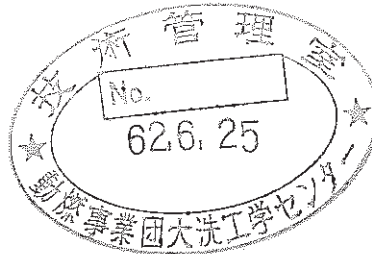


原子炉容器モデル熱過渡強度試験

第12報 き裂の解析と評価

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動力炉・核燃料開発事業団 (Power Reactor and Nuclear Fuel Development Corporation)

原子炉容器モデル熱過渡強度試験

第12報 き裂の解析と評価

齋藤 利之* 渡士 克己* 今津 彰*

要 旨

構造物強度確性試験施設(TTS)を用いて原子炉容器モデルの熱過渡強度試験を実施した。これまでに供試体の設計製作から強度試験, 破面検査, 強度評価について一連の成果を報告してきている。本報告書は原子炉容器モデルに発生した熱疲労き裂について, 破壊力学的手法を用いて解析・評価を行った結果を述べたものである。き裂を有する軸対称あるいは3次元の有限要素モデルについて熱過渡荷重を負荷される場合の応力解析を実施した。破壊力学パラメータとしては応力拡大係数 K_I , J 積分及び \hat{J} 積分について評価した。このため軸対称及び3次元問題における破壊力学パラメータを計算するプログラム(CANIS)を開発した。

熱過渡荷重が負荷される場合には熱ひずみが板厚方向に分布し, J 積分は径路独立性を失った。しかしながら, J 積分の拡張である \hat{J} 積分は径路に独立であり, 熱応力場の破壊力学パラメータとして \hat{J} 積分が有効であることが確認された。

熱過渡下ではき裂が進展するとともに応力拡大係数範囲 ΔK_I 及び \hat{J} 積分範囲 $\Delta \hat{J}$ は, あるき裂深さで最大値を示しその後緩やかに減少した。また構造不連続による曲げの影響を受けるき裂では, その最大値がより深い位置で発生した。

さらに原子炉容器モデルに発生したいくつかのき裂についてき裂深さと ΔK_I あるいは $\Delta \hat{J}$ の関係を示して, 熱疲労き裂の進展挙動を定量的に検討した。その結果, クリープき裂進展の寄与が大きい引張最大荷重で荷重保持がある高温疲労き裂進展の材料試験結果と解析で得られた \hat{J} 積分範囲 $\Delta \hat{J}$ の関係を用いれば, 本試験で発生した熱疲労き裂の進展挙動を最も良く表した。

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Thermal Transient Test of Reactor Vessel Model

Vol.12 Analyses of Cracks under Thermal Transient Loadings

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Akira Imazu*

Abstract

A thermal transient strength test was performed on a reactor vessel model utilizing the Thermal Transient Test Facility for Structures (TTS). After the test, destructive examination of a reactor vessel model was performed, and many cracking were found. It was therefore important to assess the crack propagation behaviour.

In this paper, several cracks were considered generated in the reactor vessel model tested under thermal transient loadings. Axisymmetric and three-dimensional finite element analyses were carried out for cyclic thermal transient loadings. As the parameters of fracture mechanics, the stress intensity factor K , the J -integral and the \hat{J} -integral were selected. A program for calculating fracture mechanics parameters for axisymmetric and three-dimensional problem named "CANIS" has been developed. For thermal transient stress field, the J -integral was path-dependent, but the \hat{J} -integral was path-independent. It has been shown that the \hat{J} -integral instead of the J -integral is suitable parameter to assess the integrity of structures subjected to thermal transient loadings.

The distribution of K and \hat{J} -integral with different crack depths were obtained. It has been made clear that K and \hat{J} -integral at a certain crack depth take the maximum values, and after that they decrease gradually with crack depth.

Calculated \hat{J} -integral and Paris' law formulated from domestic material data were used for the evaluation of cycles to final crack depths shown in the test. It has been shown that crack propagation rate calculated based on load controlled condition is closest to the observed crack propagation.

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1. ま え が き

構造物強度確性試験施設(TTS)を用いて原子炉容器モデルの熱過渡強度試験を実施した。この熱過渡試験の供試体の設計製作から強度試験, 破面検査, 強度評価についてFig.1-1に示すような一連の報告がなされている。このうち第5報「伝熱・応力解析と強度評価」では, 汎用非線形構造解析システム(FINAS)による熱伝導, 弾性応力解析結果及びき裂の観察結果より「高速原型炉第1種機器の高温構造設計方針」によるクリープ疲労損傷評価が実施されている。その結果, 各試験対象部位で発生したき裂の損傷値は大きな安全裕度を有していることが明らかになっている。このクリープ疲労損傷評価は, 構造物の内外表面における工学的なき裂の発生の有無を対象としており(つまり, 現在の設計では欠陥がないことが建前), その後のき裂進展挙動を特徴づけることはできない。

一般に原子力プラントでは, 安全性は多重防護の設計思想により安全設備の設置, 使用材料・機器の厳重な品質管理, さらに高度な設計技術に支えられている。現在, 軽水炉では配管のLBB(破断前漏洩)を成立させることにより合理化を進める研究が行われており, この中には欠陥を有する配管においてもその健全性, 信頼性を維持しつつプラントの有効利用を目的とする設計も含まれている。このような設計において最も重要な項目のひとつは, 構造物の最終破損形態であり, このためにき裂の進展挙動を把握することが必要である。さらに, 本試験研究のような熱疲労き裂については, 非定常温度場においてき裂進展挙動を支配する破壊力学パラメータの評価も必要である。

熱過渡によるき裂の進展試験は, 西独のHDRプロジェクトで軽水炉の給水ノズルコーナ部について実施した試験があり^{21) 24)}, 破壊力学パラメータとして応力拡大係数Kを用いて解析・評価している。また高温における熱過渡試験では事業団が配管の熱疲労き裂について応力拡大係数Kを用いて解析・評価している²⁵⁾。本試験では最高金属温度が約600℃と高温でかつ厳しい熱過渡を受けるため破壊力学パラメータとして非線形領域まで有効なJ積分さらに非定常温度場でも有効な \hat{J} 積分について解析・評価を実施した。また応力拡大係数Kについても解析・評価を実施した。

解析対象とした熱疲労き裂は, 供試体のノズルや胴部内面から発生した周方向全周き裂及びノズルコーナ部などに発生した放射状のき裂である。

上記の解析・評価を実施するためにFINASにより実施した応力解析結果より応力拡大係数K, J積分, \hat{J} 積分及びJ'積分等の破壊力学パラメータを計算するプログラムCANIS(Crack Analysis in Structure)を開発した。ここで取扱うき裂形状は周方向全周き裂(軸対称問題)及び放射状き裂(3次元問題)である。さらに算出した破壊力学パラメータを用いて, 試験で得られた熱疲労き裂の進展挙動の定量的検討を実施した。本報告書の流れをFig.1-2に示す。

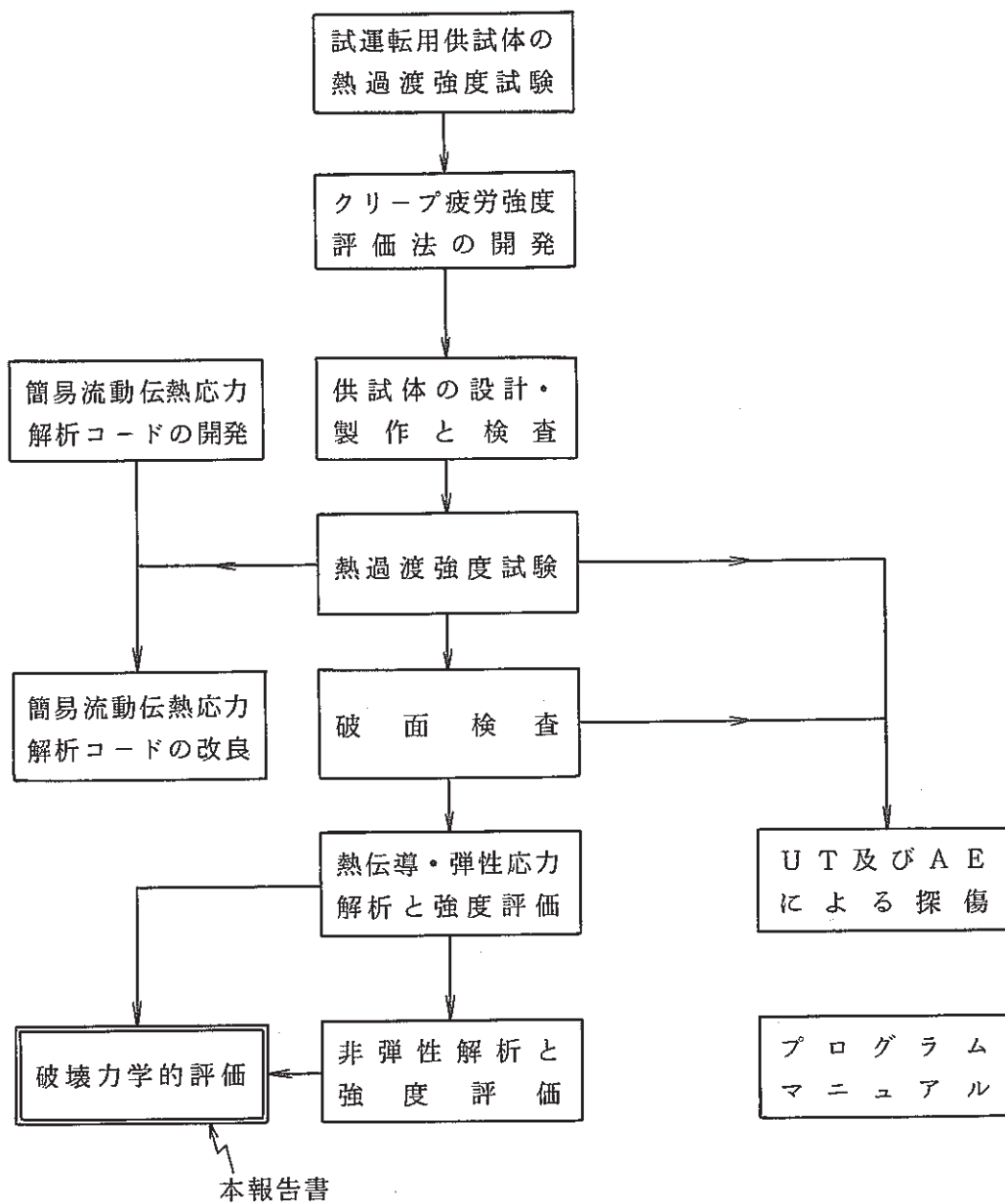


Fig. 1-1 Position of This Report in This Study

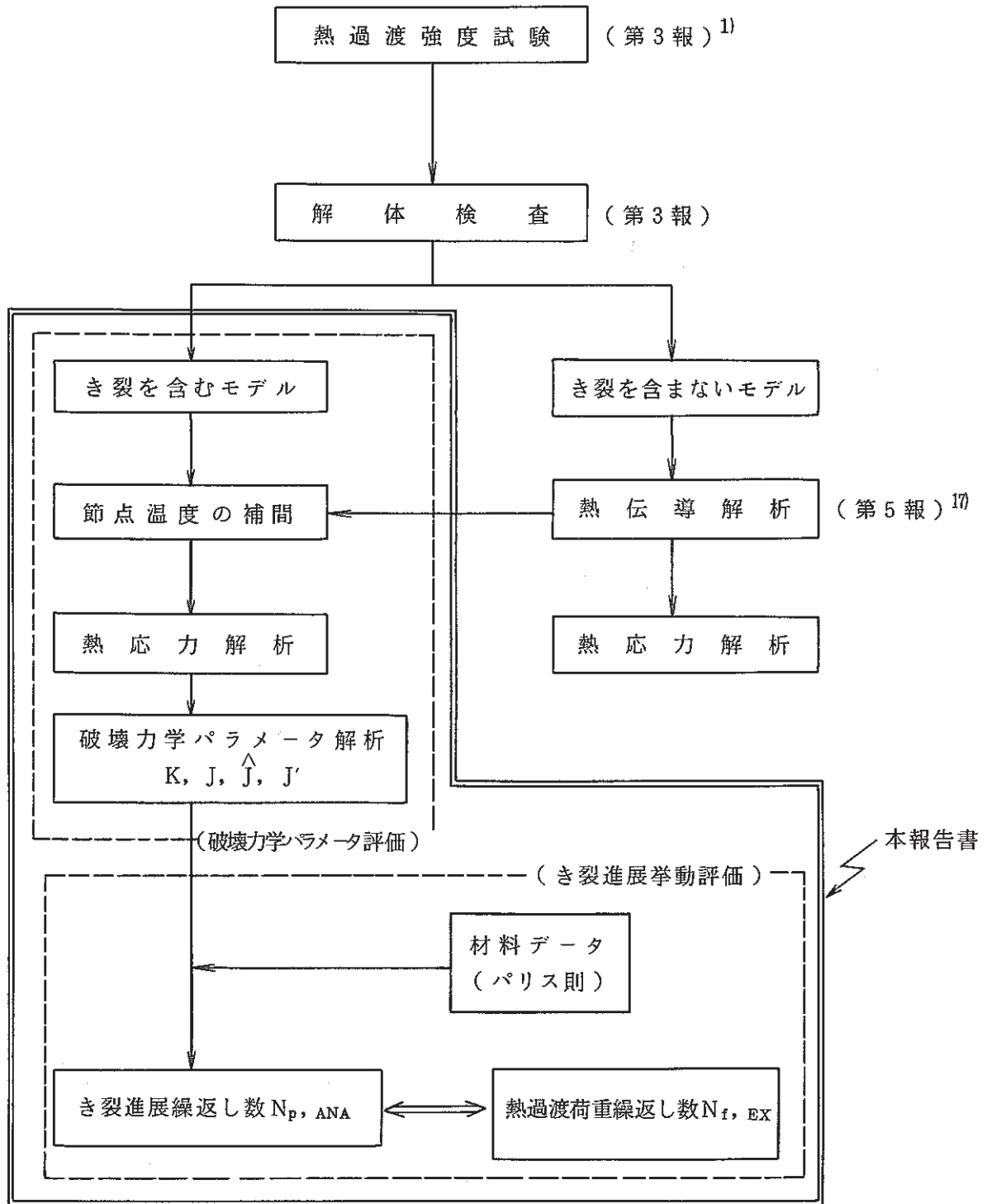


Fig. 1-2 Flow of This Study

2. 高温構造物のき裂進展を支配する破壊力学パラメータ

原子力発電プラントでは供用期間中、き裂等の有害な欠陥が存在しないよう設計、製作、検査、運転等の段階で十分管理される。しかしながら、万一供用期間中に欠陥が検出された場合には適切な方法によって構造健全性に及ぼす欠陥の影響を評価して対処方法を検討しておく必要がある。1974年、ASME Code Sec. XI に初めて破壊力学的手法による欠陥評価法が導入された。これは原子炉压力容器に対する欠陥評価基準である。さらに1983年には高靱性材料であるステンレス鋼についても破壊力学的手法による欠陥評価法が導入された³⁾。この主旨は線形破壊力学により許容寸法を超えるような欠陥について疲労き裂進展やSCCき裂進展を考慮して、次回の点検までの期間あるいはプラントの残りの設計寿命期間におけるき裂進展量を算出し、これが延性不安定破壊試験により求めた限界き裂寸法に達するような場合には運転を中止し補修あるいは交換を行い、また限界き裂寸法に達しない場合にはその期間中の運転継続を許容するというものである。

このように構造物の健全性を評価する上では、き裂の安定成長を決定することが重要であり、このためにはき裂進展速度を支配する破壊力学パラメータを把握する必要がある。ASME Code Sec. XI では、き裂進展速度を支配するパラメータとして応力拡大係数 K が適用されており、疲労き裂に対しては炭素鋼及び低合金鋼について設計線図(Fig.2-1)が記載されている。

これに対してクリープの効果が入ってくる高温構造物の場合の欠陥評価の基本的な流れをFig.2-2に示す。以下にその要点をまとめる。

- ① 非破壊検査により供用期間中の構造物に含まれる欠陥形状、寸法を明らかにする。
- ② 上述の欠陥を想定した応力解析及び破壊力学パラメータ解析を行う。
- ③ クリープ疲労き裂進展を支配する破壊力学パラメータにより、欠陥の進展量を計算する。
- ④ 欠陥が進展する場合には欠陥形状、寸法を変えて②、③のステップを繰返す。
- ⑤ ある期間に進展した欠陥形状、寸法についてプラントを運転していく上で許容できるかを評価する。ここで許容できれば運転継続であり、許容できなければ補修あるいは交換ということになる。

この欠陥評価は、前述のASME流の考え方を基に作成したものである。高速増殖炉機器では、軽水炉に比べより高温域で運転されているため、クリープ疲労き裂進展挙動を考慮しなければならない。ここでは、このクリープ疲労き裂進展速度を支配する破壊力学パラメータ、さらに繰返しの熱過渡荷重が負荷されるような非定常温度場において有効な破壊力学パラメータについて述べる。

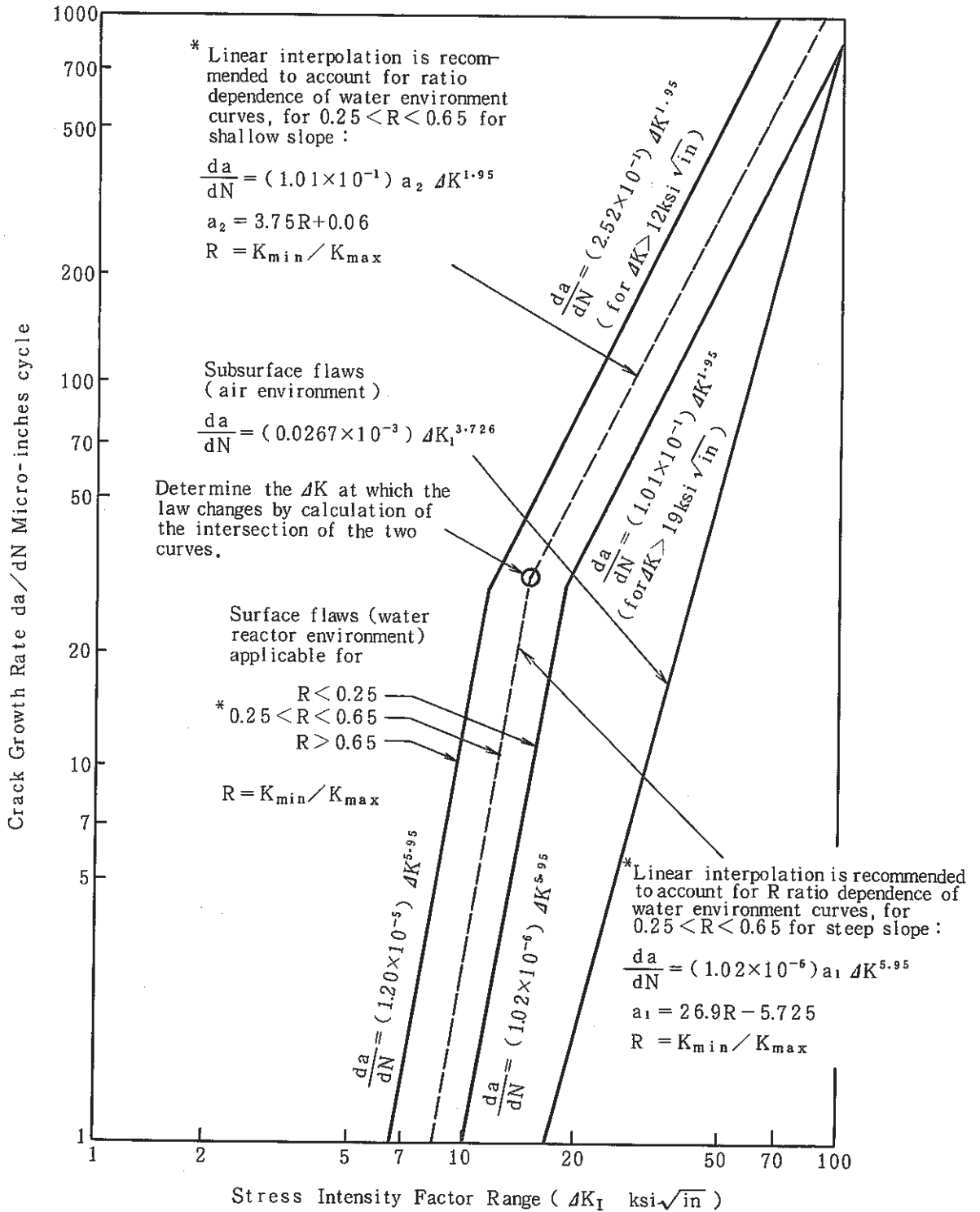


Fig. 2-1 Reference Fatigue Crack Growth Curves for Carbon and Low Alloy Ferritic Steels

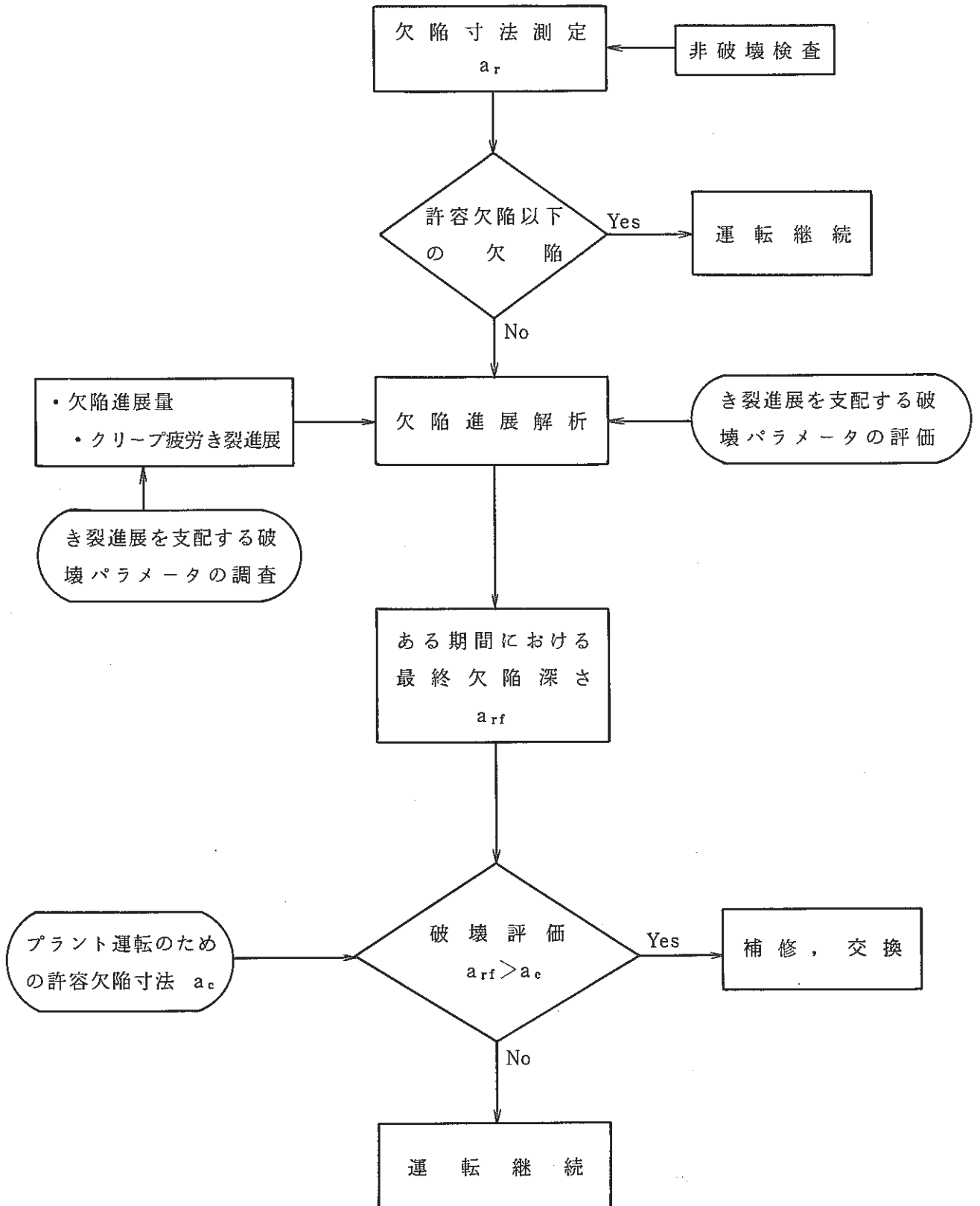


Fig. 2-2 Flaw Evaluation Concept

2.1 高温疲労き裂進展における破壊力学パラメータ

高温疲労におけるき裂進展挙動については、室温疲労き裂進展において代表的パラメータである応力拡大係数範囲 ΔK を、そのまま拡張適用する手法がある。すなわち、標準試験片を用いて、小規模降伏の条件で疲労試験を実施し、き裂進展速度を ΔK で特性づける。このような場合、温度、材料及び試験条件の広い範囲にわたって、次式の Paris 則が成立する。

$$da/dN = C(\Delta K)^m$$

ここで、 C と m は材料定数である。Fig.2.1-1⁴⁾ にオーステナイト系ステンレス鋼の 593°C (1100°F) における例を示す。このように、ある条件下では、 da/dN と ΔK は両対数紙上で直線関係にある。また、大規模降伏の領域では J 積分範囲 ΔJ が破壊力学パラメータとして用いられることが多く、この場合のき裂進展速度は次式のように示される。

$$da/dN = C'(\Delta J)^{m'}$$

ここで、 C' と m' は材料定数である。Fig.2.1-2⁵⁾ に示す低合金鋼の疲労き裂進展にみられるように、 ΔJ は、線形領域から非線形領域まで統一的に評価できる式と考えられている。

高温において繰返し荷重を受けるき裂の挙動について、小寺沢ら⁶⁾ は 304 ステンレス鋼の試験温度 550°C 及び 650°C における疲労き裂進展と応力拡大係数範囲 ΔK 、修正 J 積分 J' 及び繰返し J 積分範囲 ΔJ の関係を整理している。それらの結果を Fig.2.1-3 ~ Fig.2.1-5 に示す。これらより、き裂進展速度を支配する因子は、き裂進展速度の低い領域では ΔK 、高い領域では J' であるとしている。 ΔK 支配領域は、小規模降伏が満足されている領域と対応している。また、クリープ変形が顕著でない 250°C 及び 500°C における疲労き裂進展と応力拡大係数範囲 ΔK の関係を Fig.2.1-6 に示す。この実験でも、 ΔK が支配パラメータとなっている。

大谷ら⁷⁾ は 304 ステンレス鋼について 650°C でクリープ試験を実施し、この結果を J' で整理している (Fig.2.1-7)。この場合のき裂進展速度は

$$dl/dt [\text{mm}/\text{h}] = 1.0 \times 10^{-2} J' [\text{KN}/\text{m} \cdot \text{h}]$$

で表わされる。このように、高温クリープにおける定常き裂進展速度は、 J' が支配パラメータであるとしている。また大谷ら^{8) 9)} は彼らの行った材料試験の範囲内において、温度、荷重及び試験片形状によらずき裂進展のデータは J' を用いて統一的に整理できるとしている。

大路ら¹⁰⁾ は 304 ステンレス鋼について、クリープ条件下における繰返しき裂進展速度が繰返し数依存形のき裂進展速度と、時間依存形のき裂進展速度との線形和で与えられるものと考えて、クリープ疲労き裂進展速度の予測を行っている。

$$\begin{aligned}
 da/dN &= (da/dN)_f + (da/dN)_c \\
 &= 1.2 \times 10^{-4} \Delta J_f + 8.0 \times 10^{-3} \Delta J_c \\
 &= 8.0 \times 10^{-3} (\Delta J_c + 0.015 \Delta J_f)
 \end{aligned}$$

ΔJ_f : 繰返し J 積分範囲

J' : 修正 J 積分

$\Delta J_c = J' \times t_c$ (t_c : サイクルの時間)

Fig.2.1-8に da/dN を $(\Delta J_c + 0.015 \Delta J_f)$ に対してプロットした結果を示す。この結果より大略らは $(\Delta J_c + 0.015 \Delta J_f)$ が小さい場合を除き上式により、き裂進展が予測できるとしている。

大谷ら¹⁾は、き裂進展速度に及ぼす応力波形の効果について検討している。Fig.2.1-9は、Fig.2.1-10に示す種々の波形についてき裂進展速度と繰返し J 積分範囲の ΔJ_f の関係を示している。このように引張最大荷重で保持時間がある場合 (c-c, c-p type)、き裂進展速度は他の保持時間のない場合 (p-p type) や圧縮最大荷重で保持時間のある場合 (p-c type) の場合と比較してかなり速くなっている。また Fig.2.1-11 及び Fig.2.1-12 は日本溶接協会原子力研究委員会が動燃の委託を受けて実施した一連のクリープ疲労き裂進展試験結果の一部である。²⁾ Fig.2.1-11は、引張最大荷重で荷重保持があった場合のき裂進展速度と ΔJ_f の関係である。前述の Fig.2.1-9の引張最大荷重で荷重保持がある場合とほぼ一致する。また Fig.2.1-12は引張側最大変位で変位保持があった場合のき裂進展速度と ΔJ_f の関係である。変位保持では、変位保持のない三角波に比較してき裂進展速度は同程度もしくは少し速くなる程度である。

このように、材料試験片レベルでは K 、 J 及び J' が定常温度場においてき裂進展速度を支配するパラメータとして有効であると考えられている。つまり、高温における疲労き裂進展については小規模降伏の範囲内であれば応力拡大係数範囲 ΔK が有効であり、低サイクル疲労き裂進展については材料試験片では大規模降伏の範囲となるため繰返し J 積分範囲 ΔJ_f 、さらにクリープ現象が顕著な場合のき裂進展については修正 J 積分 J' が有効であると考えられている。現状はこれらのパラメータが材料試験において有効であるという議論にとどまっており、構造物の熱疲労き裂や3次元き裂に適用する方法を開発していく段階にある。

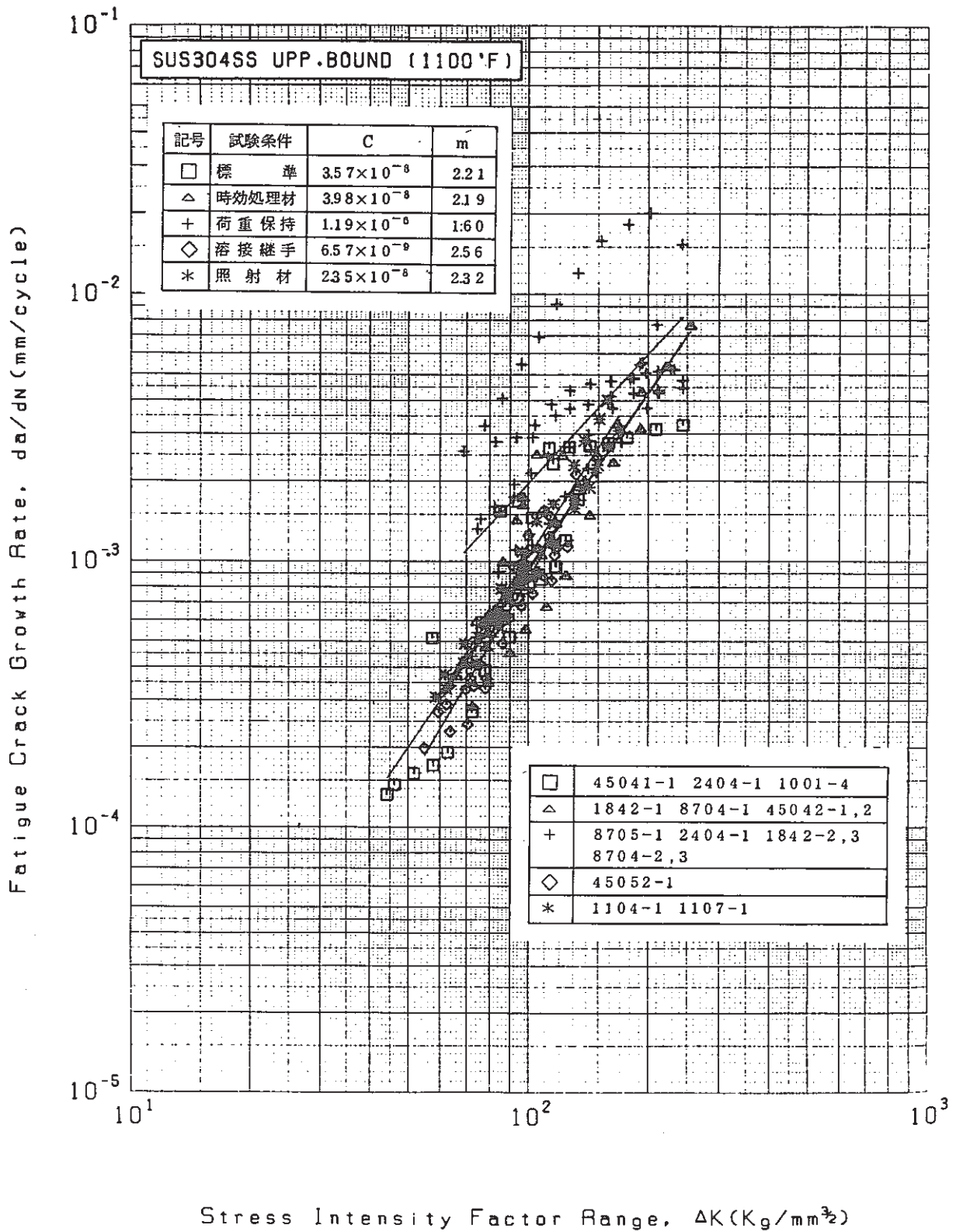


Fig. 2.1-1 Fatigue Crack Growth Rate of Type 304 Stainless Steel at 1100°F (593°C)⁴⁾

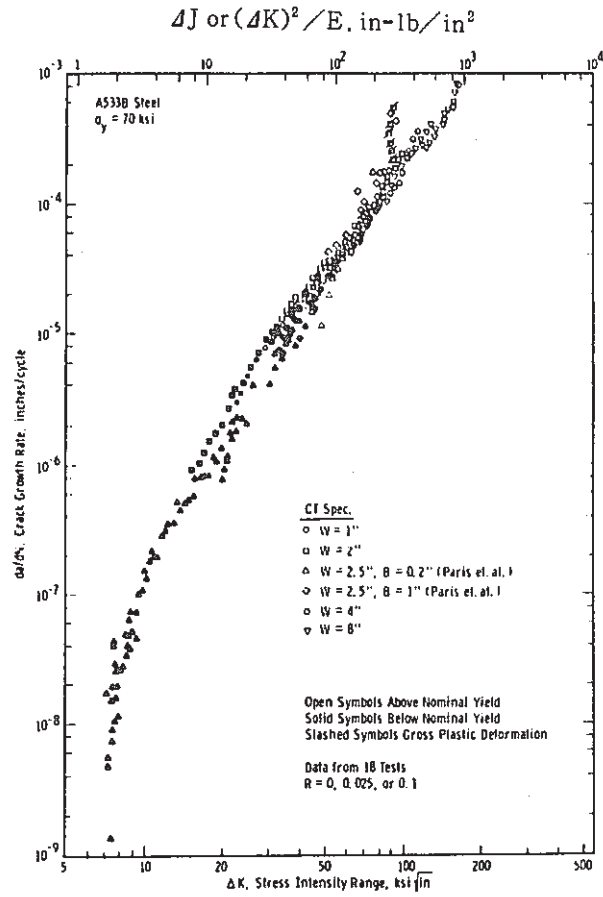


Fig. 2.1-2 Fatigue Crack Growth Rate versus Stress Intensity for Various Size Specimens of A533B Steel⁵⁾

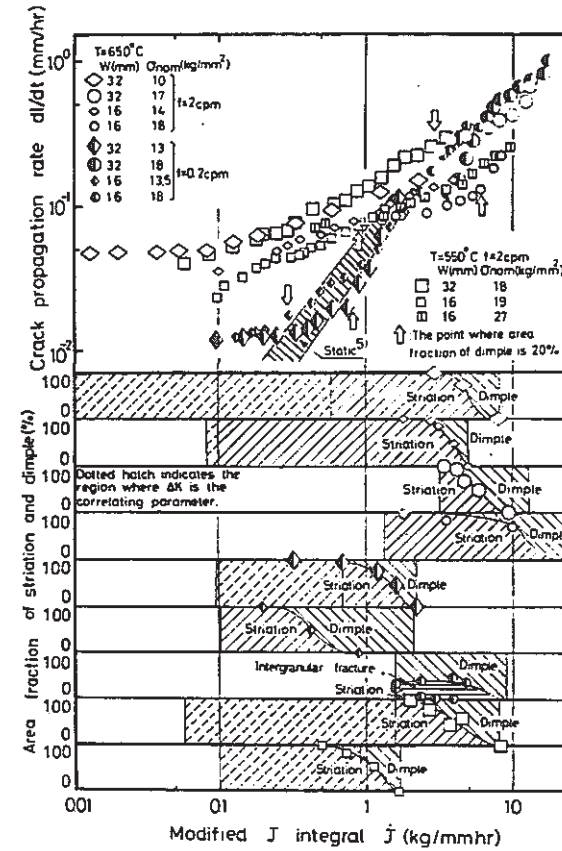
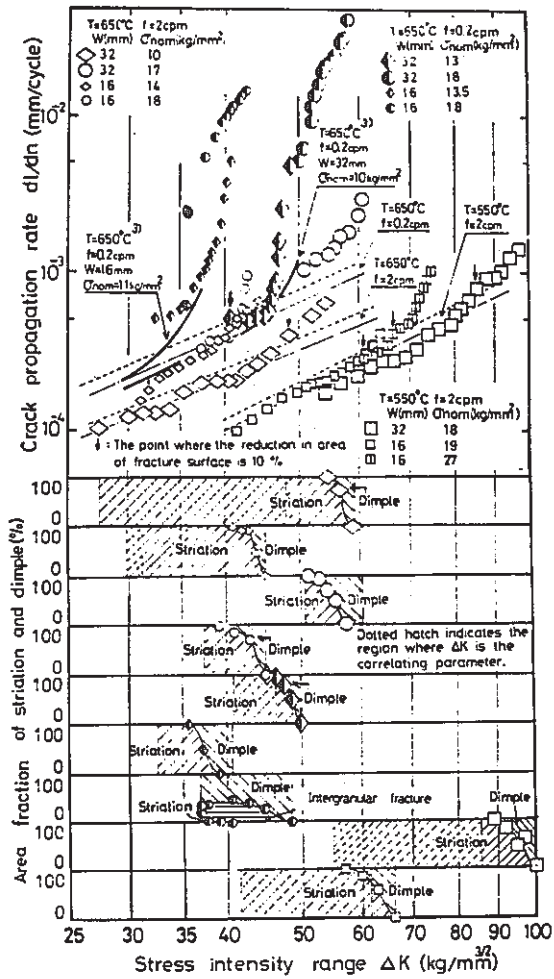


Fig. 2.1-3
Crack Propagation Rate of a 304 Stainless Steel under Repeated Load at 550 and 650°C as a Function of Stress Intensity Range⁶⁾

Fig. 2.1-4
Crack Propagation Rate of a 304 Stainless Steel under Repeated Load at 550 and 650°C as a Function of Modified J-Integral⁶⁾

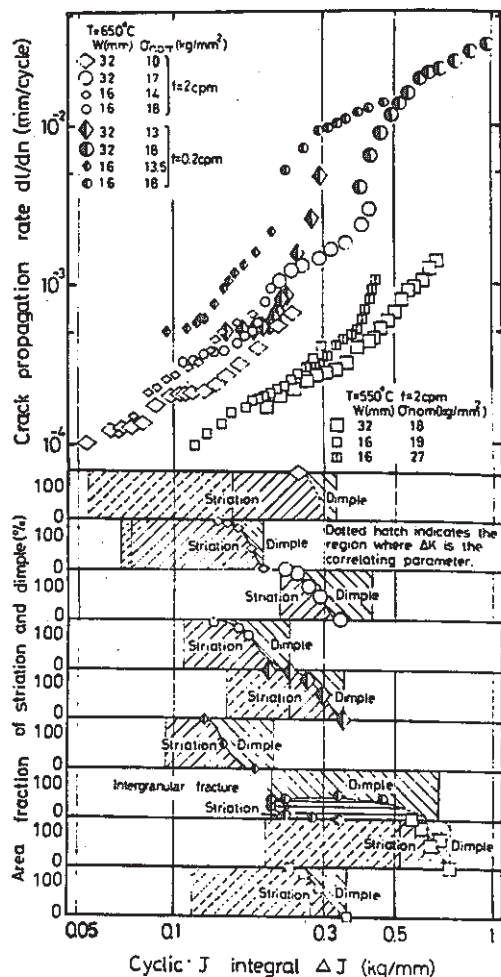


Fig. 2.1-5
Crack Propagation Rate of a 304 Stainless Steel under Repeated Load at 550 and 650°C as a Function of Cyclic J-Integral⁶⁾

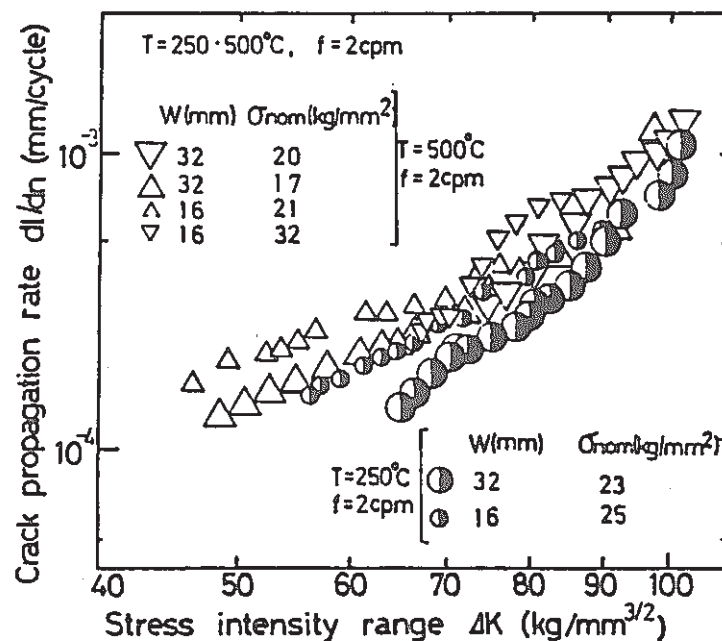


Fig. 2.1-6
Fatigue Crack Propagation Rate of a 304 Stainless Steel at 250 and 500°C as a Function of Stress Intensity Range⁶⁾

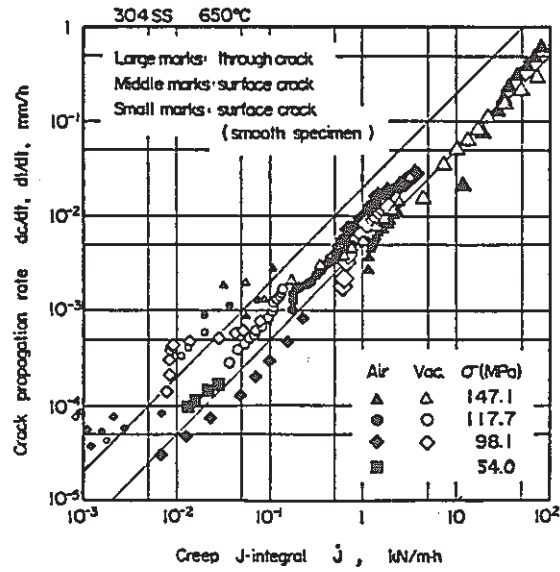


Fig. 2.1-7 Crack Propagation Rate vs. Creep J-Integral ⁷⁾

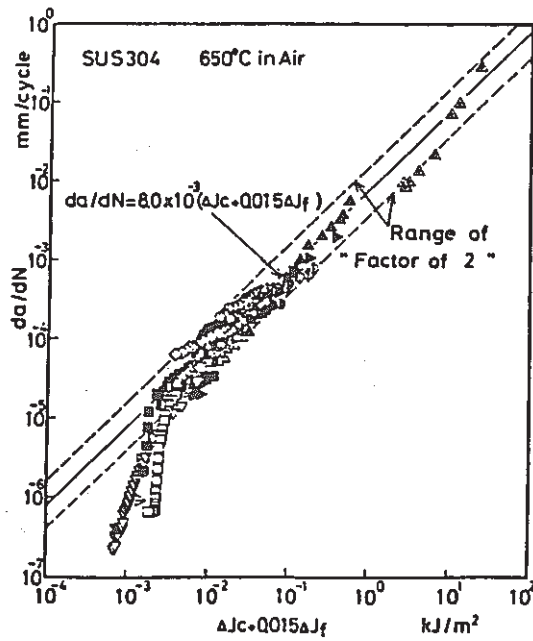


Fig. 2.1-8 Crack Propagation Rate vs. $J_c + 0.015 J_f$ ⁸⁾

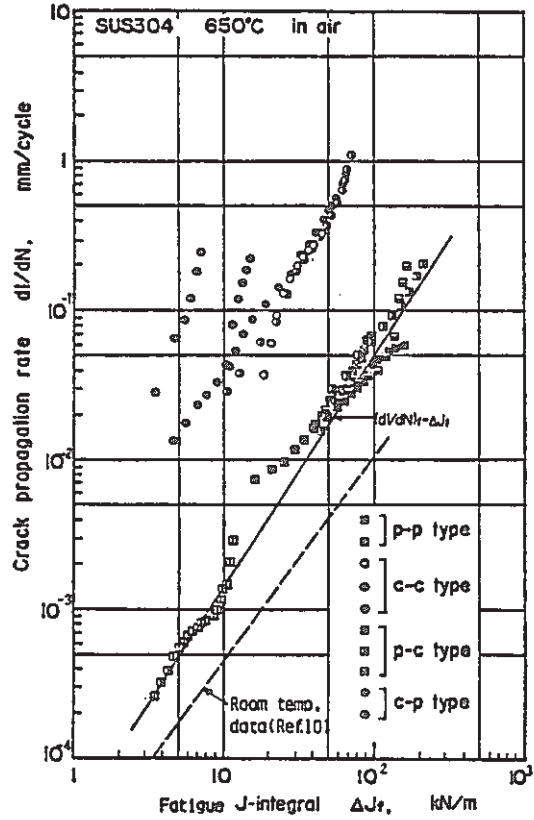


Fig. 2.1-9 Relation between da/dN and ΔJ_f ¹⁾

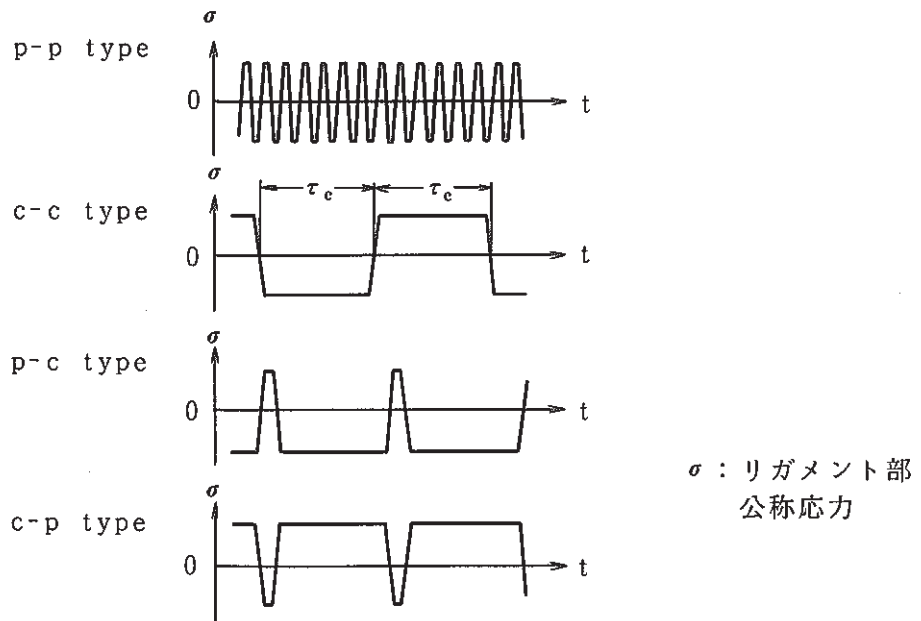


Fig. 2.1-10 Applied Wave Form for Fatigue and Cyclic Creep Tests ¹⁾

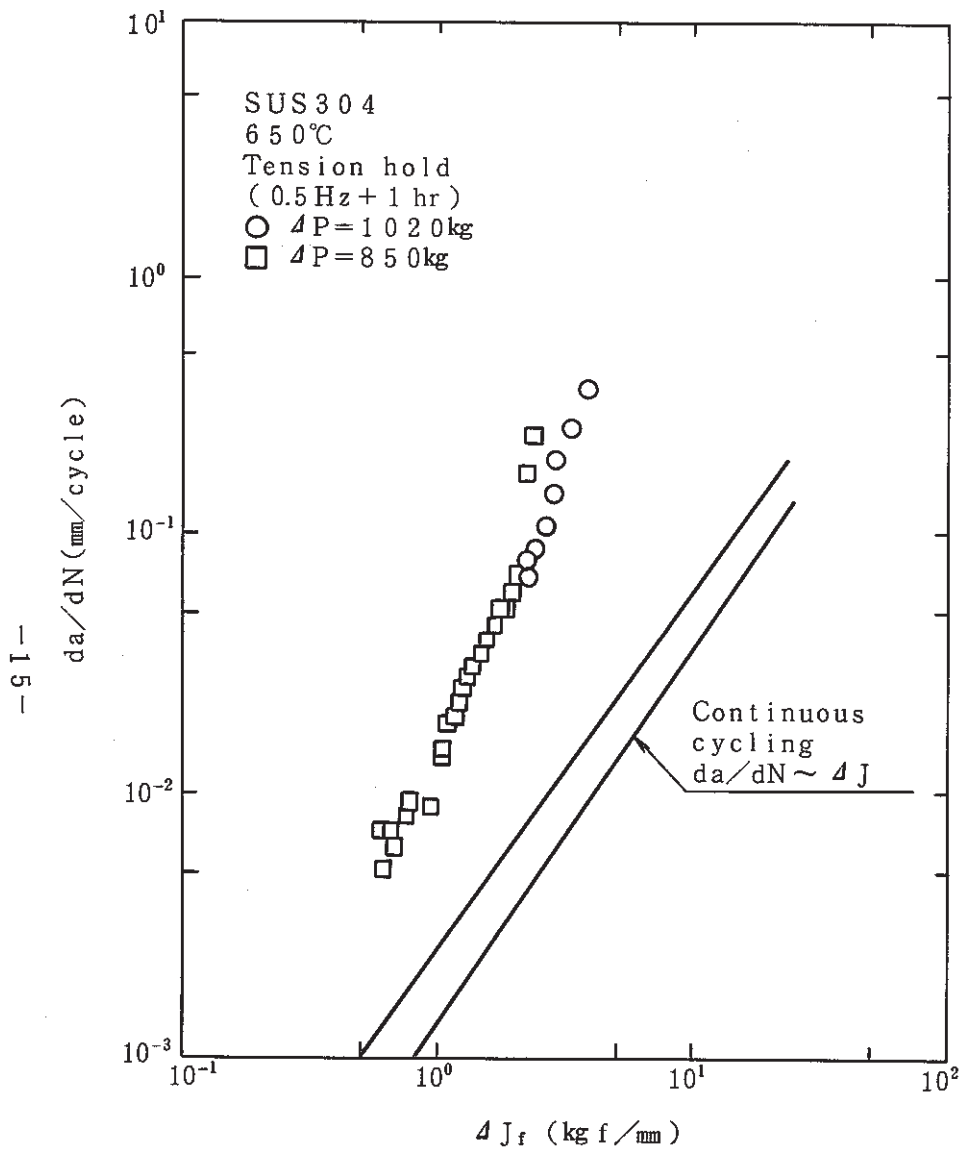


Fig. 2.1-11 Relation between da/dN and ΔJ_f under Load Controlled Tests¹²⁾

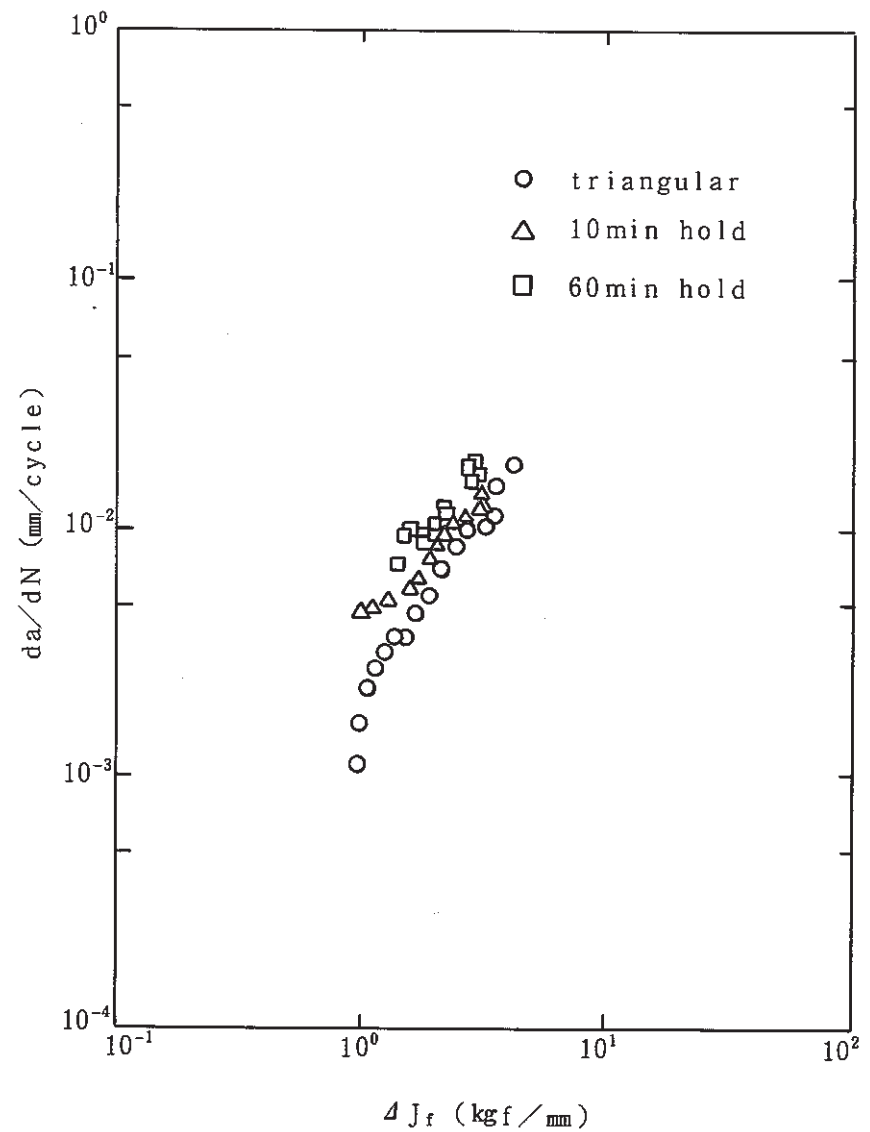


Fig. 2.1-12 Relation between da/dN and ΔJ_f under Displacement Controlled Tests¹²⁾

2.2 熱過渡荷重下における破壊力学パラメータ

熱過渡荷重を受ける構造物の破壊力学的アプローチは、軽水炉の給水ノズルコーナやサーマルスリーブ付根部に発生するき裂について実験及び解析が行われている^{18)~24)}。いずれも内圧が負荷されている状態で繰返し熱過渡を負荷させる実験である。HDRで実験された一連のノズルの熱過渡試験では、軽水炉運転条件下(110 bar, 310°C)において $\Delta T=250^\circ\text{C}$ (163 bar, 50°C)の熱過渡を負荷している。このうちBlauelらは、ノズルコーナに発生するき裂について進展評価を実施している。Paris則に基づいてき裂進展を評価しており、破壊力学パラメータとして応力拡大係数 K を適用している。なお、この応力拡大係数 K は重み関数法(weight function method)等の簡易評価式により算出している。Fig.2.2-1にノズルコーナに発生したき裂形状を示す。またTable 2.2-1とTable 2.2-2は、0~246サイクル及び246~546サイクル間における実験結果と解析結果の比較を示している。このように軽水炉については、応力拡大係数 K がかなり有効なパラメータであると思われる。

J積分は線形領域から非線形領域まで統一的に評価できる破壊力学パラメータであるが、種々の仮定の下に定義されているので、実際の構造物に適用しようとする時種々の困難が生じる。例えば、タービンロータでは遠心力や熱ひずみが存在するために、J積分は径路独立性を失う。Table 2.2-3に示すように、構造物へのJ積分の適用が困難となる場合は少なくない¹³⁾。これらのことより、J積分の拡張に関する種々の研究が行われている。前述の修正J積分は、クリープ条件下でき裂が進展する場合のJ積分の拡張である。

熱過渡荷重を繰返し負荷される試験体では、熱ひずみや塑性ひずみが存在し、そのためJ積分はエネルギー解放率としての物理的意味を失ってしまう。このような場合の破壊力学パラメータとして青木ら^{15) 16)}は、 \hat{J} 積分を提案している。 \hat{J} 積分とき裂の進展速度を関連づけた論文は見当たらないが、青木ら^{13) 14)}は非定常不均一な熱ひずみ ϵ^t_{ij} が存在する場合の有限要素法解析を実施している。Fig. 2.2-2に示す中央き裂をもつ平板の左右面を基準温度から $\theta = -100^\circ\text{C}$ まで急冷する場合のJ及び \hat{J} 積分を算出している。Fig.2.2-3に定常温度場(時間 $t \rightarrow \infty$)における \hat{J} 積分の種々の径路に対する計算値(○印)及びJ積分(×印)を示す。 \hat{J} 積分は径路依存せずまた石田の解から得られる値と良く一致している。一方、J積分は径路に依存している。Fig. 2.2-4に非定常温度場における \hat{J} 積分の各径路に対する計算結果を示す。不均一温度場においても、 \hat{J} 積分は径路独立性を示しており、き裂先端近傍の応力・ひずみの特異性が \hat{J} 積分により特徴づけられる。熱ひずみ ϵ^t_{ij} は、弾性ひずみ ϵ^e_{ij} 及び塑性ひずみ ϵ^{p}_{ij} の特異性に影響を与えるが、 ϵ^t_{ij} はき裂先端近傍で特異性を持たない。したがって、き裂先端では ϵ^t_{ij} は ϵ^e_{ij} や ϵ^{p}_{ij} に比べて無視できるので次式が成立する。

$$\hat{J} = \lim_{\rho \rightarrow 0} J \quad \dots\dots\dots (2.2-1)$$

ここで ρ はき裂先端に中心を持つ半径である。非定常温度場における \hat{J} 積分はき裂先端ではJ

積分と同一であり，き裂進展速度を特徴づけている J 積分をそのまま \hat{J} 積分に置き換えることができると考えられる。

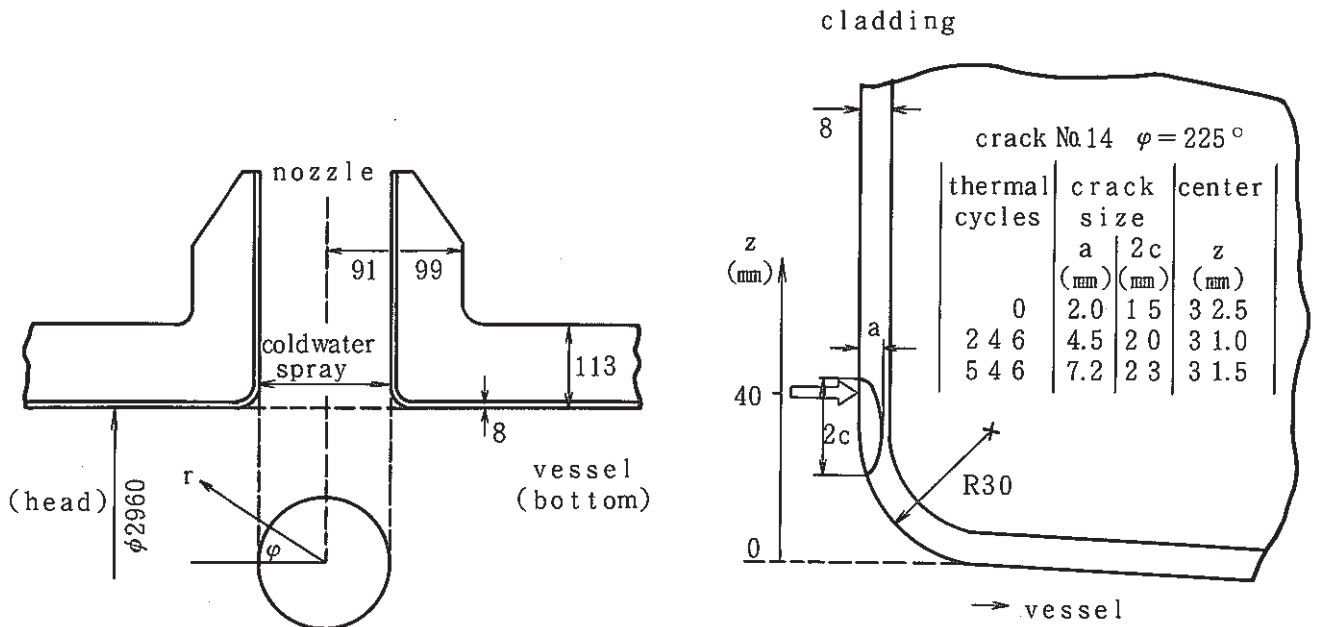


Fig. 2.2-1 Geometry of HDR Nozzle A2, Location and Size of NDT-Indication No.14²⁴⁾

Table 2.2-1 Crack Growth Prediction for Test Series V66.0 as ²⁴⁾

Cooling	Stresses	Method of Calculation	Prediction			EXPERIMENT
			AUST. CLADDING R=0.2	BASE MATERIAL(FERRITIC)		
				ASME AIR	ASME WATER R≤0.25	
Number N _r of cycles for a ₀ = 2 + a ₁ = 4.5 mm						
Line	σ(x)	cf plastic	84	647	281	246
Line	σ(x, y)	wf elastic		2765	607	
Line	σ(x)	cf plast. cor	794	5228	831	
area	σ(x, y)	wf elastic	62	480	240	
area	σ(x, y)	cf elastic	51	410	221	
Crack length 2c ₁ (mm) after N ₁ cycles						
Line	σ(x)	cf elastic	18.1	18.1	18.7	20
Line	σ(x, y)	wf elastic		16.7	17.7	
Line	σ(x)	cf plast. cor	16.5	16.6	17.6	
area	σ(x, y)	wf plastic	18.4	18.4	19.0	
area	σ(x, y)	cf elastic	18.3	18.3	18.6	

Table 2.2-2 Crack Growth Prediction for Test Series V66.1 as ²⁴⁾

Cooling	Stresses	Method of Calculation	Prediction			EXPERIMENT
			AUST. CLADDING R=0.2	BASE MATERIAL(FERRITIC)		
				ASME AIR	ASME WATER R≤0.25	
Number N ₂ of cycles for a ₁ = 4.5 + a ₂ = 8 mm						
Line	σ(x)	cf elastic	133	1026	473	300
Line	σ(x, y)	wf elastic				
Line	σ(x)	cf plast. cor		4870	959	
area	σ(x, y)	wf elastic	57	462	281	
area	σ(x, y)	cf elastic	39	328	234	
Crack length 2C ₂ (mm) after N ₂ cycles						
Line	σ(x)	cf elastic	34.6	34.1	30.4	23-28
Line	σ(x, y)	wf elastic				
Line	σ(x)	cf plast. cor	29.4	29.2	28	
area	σ(x, y)	wf elastic	28.5	28.4	27.7	
area	σ(x, y)	cf elastic	26.8	26.8	26.4	

Table 2.2-3 Impossible Case of J-Integral Application¹³⁾

1. 慣性力・物体力が存在する場合 ……遠心力(物体力), 電磁力(物体力), 衝撃荷重(慣性力), 高速き裂(慣性力)
2. 熱ひずみ・初期ひずみが存在する場合 ……温度こう配(熱ひずみ) 残留応力(初期ひずみ)
3. 全ひずみ塑性論以外の構成関係を持つ材料の場合 ……ひずみ増分論に従う弾塑性体, ひずみ速度に依存する材料 材料定数が温度に依存する材料, 不均質物体
4. 破壊進行領域の大きさが無視できない場合 ……延性破壊

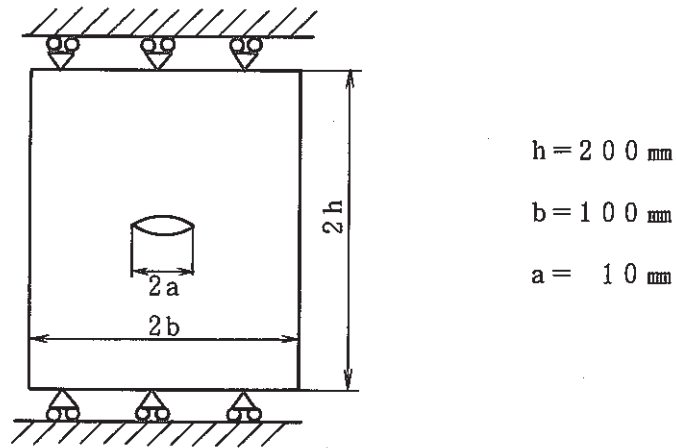


Fig. 2.2-2 Geometry of Center Cracked Plate¹⁵⁾

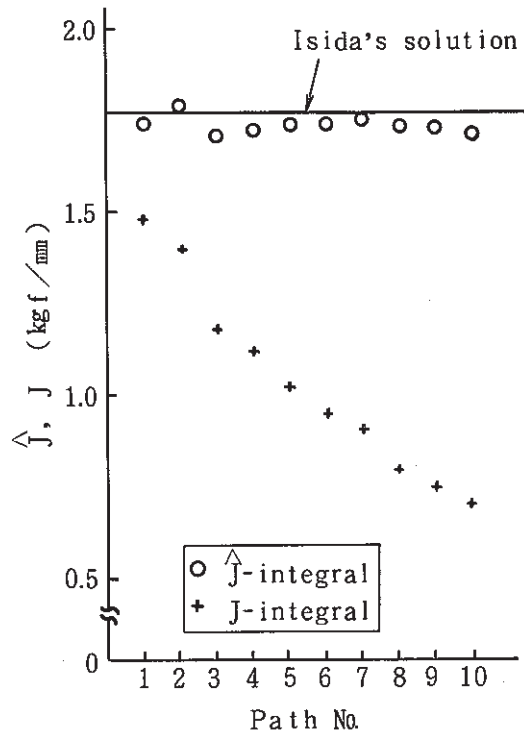


Fig. 2.2-3 Comparison of \hat{J} with J (Elastic Problem)¹⁵⁾

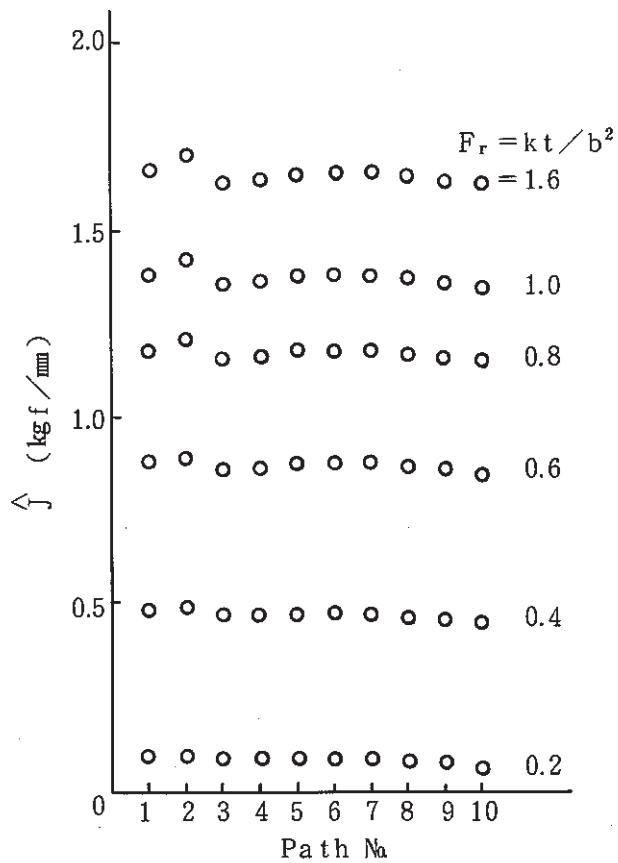


Fig. 2.2-4 \hat{J} vs. Paths for Transient Temperature Field¹⁵⁾
(Elastic Problem)

3. 破壊力学パラメータの解析

構造物が Fig.3-1 に示すような温度変化を受けると、例えば厚肉円筒がその内表面に同図中に示すような熱応力が発生する。応力はコールドショックにおいて引張側の極値を示し、ホットショックにおいては圧縮側の極値さらに続いて引張応力が現われる。ここではこのような応力の変化に伴う破壊力学パラメータを原子炉容器モデルについて算出し、破壊力学的検討を実施する。対象とした解析モデルは、Fig.3-2 に示す最終溶接部、入口ノズル、シンニング部、コニカル・下部鏡部及び出口ノズル部の円周き裂、スタッドボルト付根部のき裂及び計装ノズルコーナ部に発生した放射状き裂である。本解析で用いたき裂深さは、解体検査により得られた最終き裂深さ $a_{f.exp}$ と最終き裂深さ $a_{f.exp}$ に達するまでのき裂深さを適宜に 1～5 ケース想定した。Fig.3-3 に破壊力学パラメータ解析の手法を示すが、本解析においては、き裂の進展解析を行うのではなくき裂深さを一定として熱過渡 1 サイクル（非弾性では 1.5 サイクル）に対する熱応力解析を行い、各時点における破壊力学パラメータを算出するものである。熱伝導解析については、第 5 報「伝熱・応力解析と強度評価」¹⁷⁾ の熱伝導解析結果を用いた。すなわち、本解析における有限要素分割モデルはき裂を含むモデルであり、き裂近傍の要素分割を細かくしているため第 5 報で用いた部分モデルの有限要素分割とは異なるものであるが、熱伝導解析は両者の節点を対応させることにより補間して行った。熱応力解析は、補間した節点温度を用いて、汎用非線形構造システム（FINAS）により熱応力解析を行った。さらに熱応力解析のポストファイルを用いて破壊力学パラメータの算出を行った。この計算は、軸対称及び 3 次元問題において破壊力学パラメータを算出するプログラム；CANIS を用いて行った。

附録 A 及び附録 B は軸対称及び 3 次元問題における応力拡大係数 K 、 J 積分及び J' 積分等の破壊力学パラメータの算出式を示す。

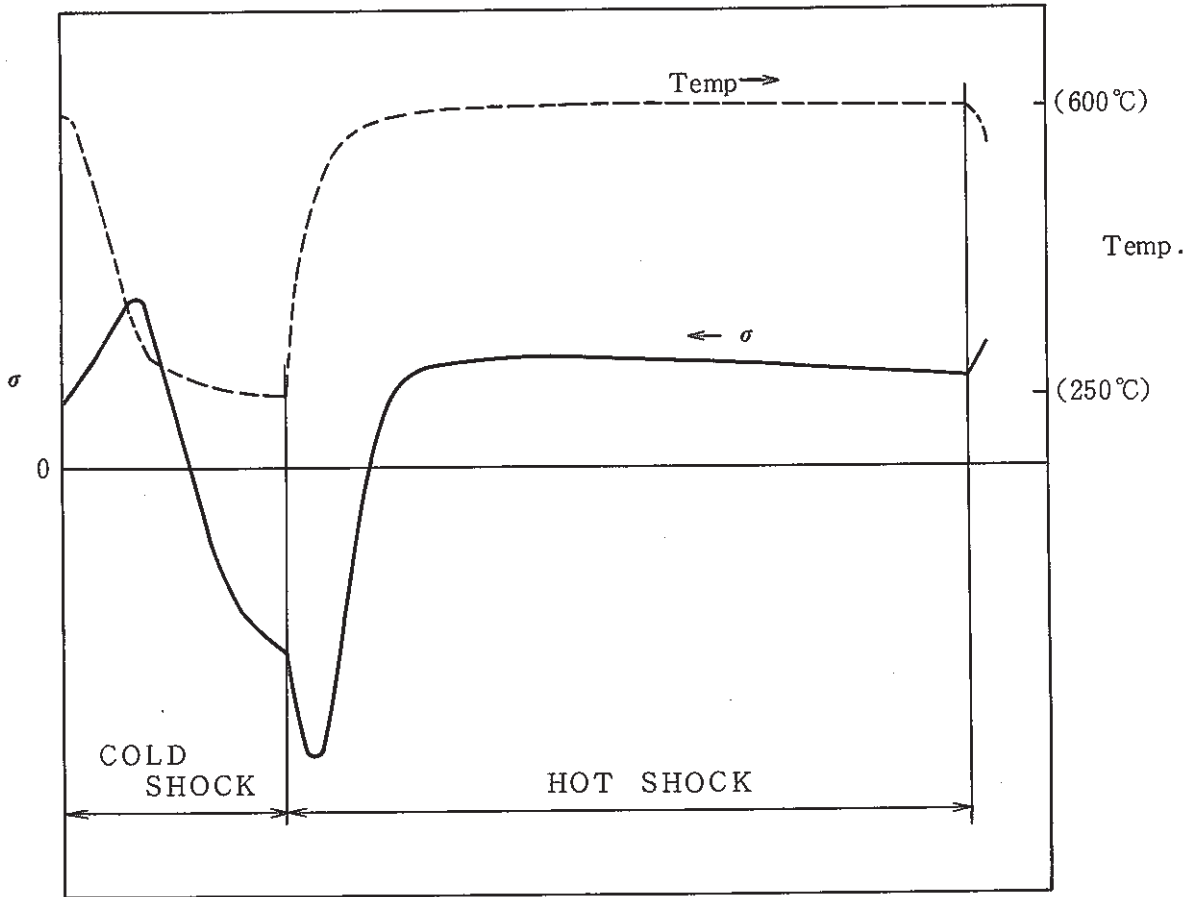


Fig. 3-1 Typical Thermal and Stress History

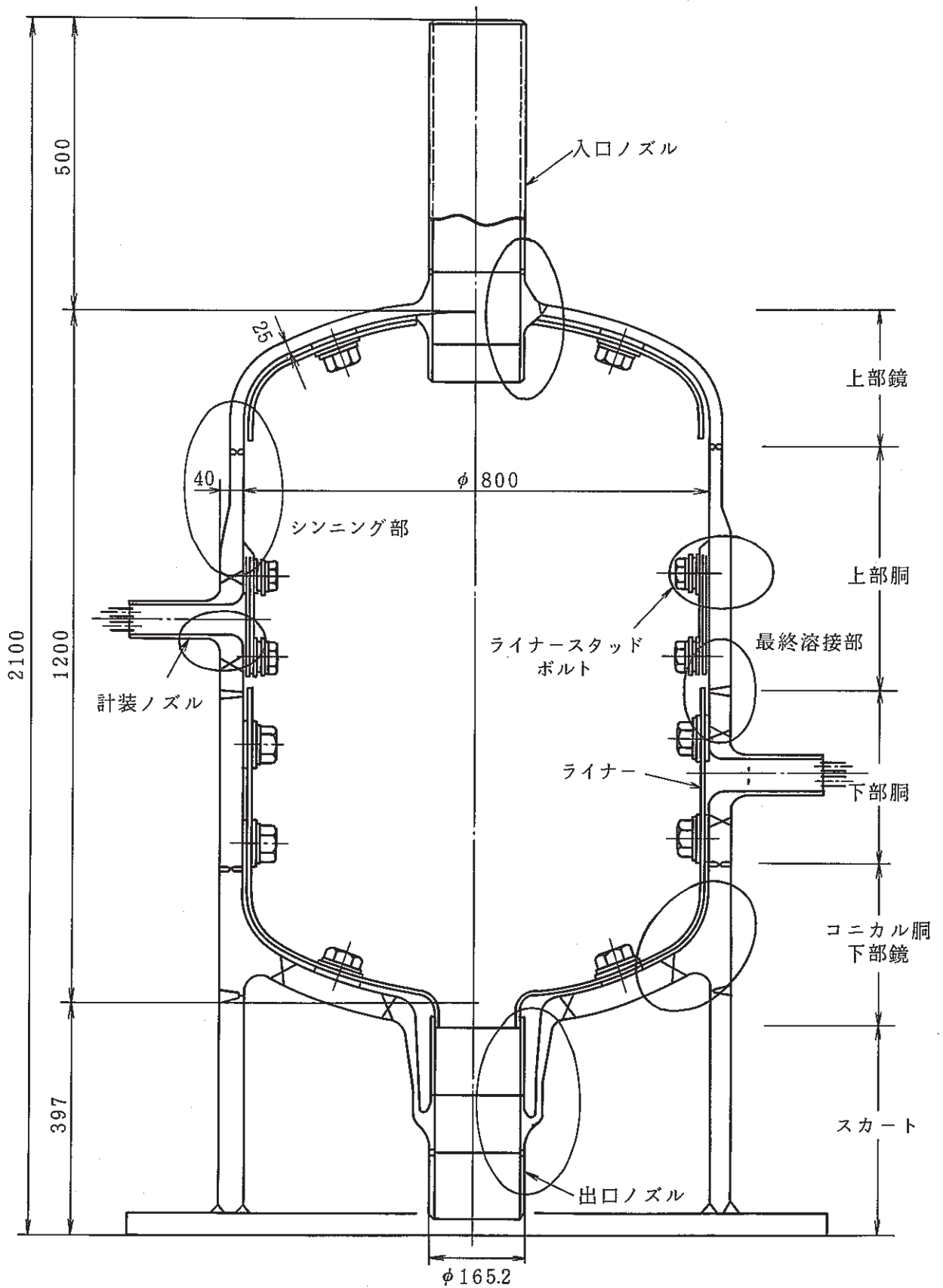


Fig. 3-2 Configuration of Reactor Vessel Model

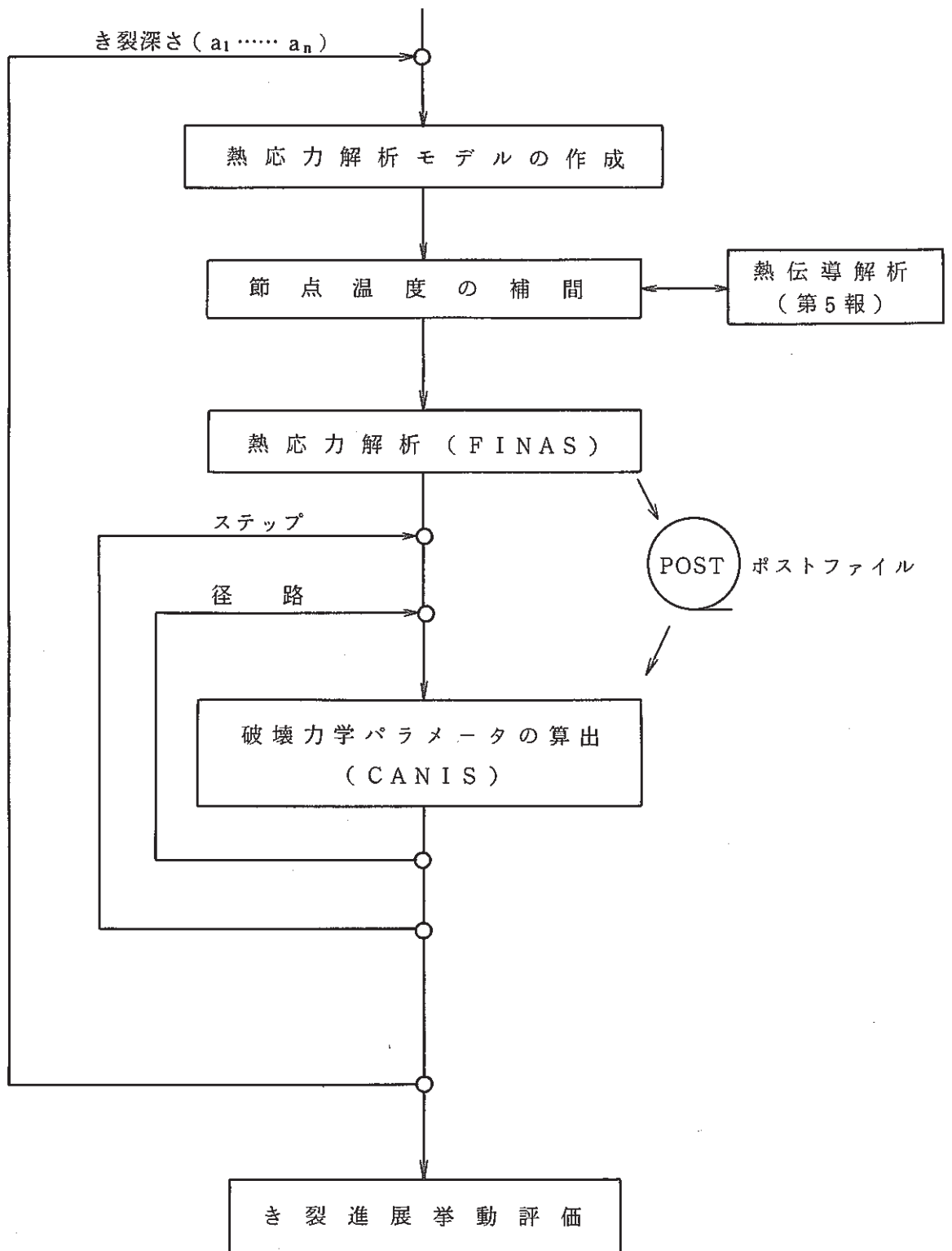


Fig. 3-3 Procedure of Fracture Mechanics Parameter Analysis

3.1 解析モデル

対象とした解析モデルは Fig.3-2 に示す最終溶接部, 入口ノズル, シンニング部, コニカル・下部鏡部, 出口ノズル, スタッドボルト部及び計装ノズル部である。解析モデルの形状・寸法は第5報「伝熱・応力解析と強度評価」, 第6報「非弾性解析と強度評価」で用いた有限要素モデルと同一であり, 本解析で用いたき裂を含むモデルではき裂近傍の有限要素分割を細かくしている。対象とした解析モデルの境界条件及び有限要素分割を Fig.3.1-1 ~ Fig.3.1-14 に示す。計算で使用した物理定数及び境界条件は, 第5報「伝熱・応力解析と強度評価」に準じた。なお, 軸対称モデルにおいて, き裂は想定したき裂位置の同一座標点で節点を2重に定義している。応力解析の境界条件としてある深さまで両節点変位を自由としてき裂を導入し, 残りのリガメント部の両節点変位を一定としてモデル化した。き裂面において接触要素は考慮していない。使用要素は軸対称モデルでは8節点四辺形軸対称要素QAX 8及び6節点三角形軸対称要素TAX 6, 3次元モデルでは20節点六面体要素HEX 20及び15節点五面体要素PENT 15である。使用コードはFINAS V.9.0である。

(a) 最終溶接部

上部胴と下部胴の最終溶接部近傍には, 全周にわたって2本のき裂が発生したが, 本解析で対象としたのは下部胴側の深い方のき裂(深さ27mm)である。き裂の位置と境界条件を Fig.3.1-1 に示す。このき裂に対して Fig.3.1-2 に示すように6つの軸対称の有限要素モデルを作成した。想定したき裂深さは, 1, 5, 10, 15, 20及び27mmである。

(b) 入口ノズル

入口ノズル内表面に全周き裂及び多数の微細き裂が発生したが, 本解析で対象としたのはそのうち代表的なき裂3ヶ所である。き裂の位置と境界条件を Fig.3.1-3 に示す。さらにこれらのき裂に対して Fig.3.1-4 に示すように3つの軸対称の有限要素モデルを作成した。想定したき裂深さは $(a_1, a_2, a_3) = (1, 1, 1), (2, 2.65, 2), (4, 5.3, 4)$ である。

(c) シンニング部

上部胴シンニング部では多数のき裂が発生していたが, 本解析で対象としたのはき裂深さ約9mm, 15mmの全周き裂である。き裂の位置と境界条件を Fig.3.1-5 に示す。さらにこれらのき裂に対して Fig.3.1-6 に示すように4つの軸対称の有限要素モデルを作成した。想定したき裂深さは $(a_1, a_2) = (1, 1), (4, 5), (7, 10), (9.4, 15)$ である。

(d) コニカル・下部鏡部

コニカル・下部鏡の溶接部近傍には, 本供試体の中で最も深いき裂が全周にわたって発生した。本解析ではこのき裂(深さ約32mm)を解析の対象としており, き裂の位置と境界条件を Fig.3.1-7 に示す。このき裂に対して Fig.3.1-8 に示すように3つの軸対称の有限要素モデルを作成した。想定したき裂深さは1, 15及び32mmである。

(e) 出口ノズル

出口ノズル部は最深き裂でも約3mmであり、1mm以下の浅いき裂が多かったが、本解析ではこれらのうち代表的な3つなき裂を解析の対象とした。き裂の位置と境界条件をFig. 3.1-9に示す。これらなき裂に対してFig. 3.1-10に示すように2つの軸対称の有限要素モデルを作成した。想定なき裂深さは $(a_1, a_2, a_3) = (1.45, 1.55, 0.70)$, $(2.9, 3.1, 1.4)$ である。

(f) スタッドボルト

下部鏡に溶接のスタッドボルトには、その隅肉溶接部において約13mm深さなき裂が発生しているものがあつた。き裂の位置と境界条件をFig. 3.1-11に示す。このき裂に対してFig. 3.1-12に示すように4つの軸対称の有限要素モデルを作成した。想定なき裂深さは1, 7, 10及び13mmである。

(g) 計装ノズル

計装ノズルコーナ部に放射状なき裂が多数発生した。本解析ではこのき裂形状を円弧上と想定して3次元解析を行った。解析モデルは20°モデルであり、き裂形状と境界条件をFig. 3.1-13に示す。このき裂についてFig. 3.1-14に示すように3つの3次元の有限要素モデルを作成した。想定なき裂の半径 r は9.6, 12.8及び16.0mmである。

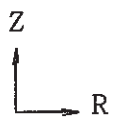
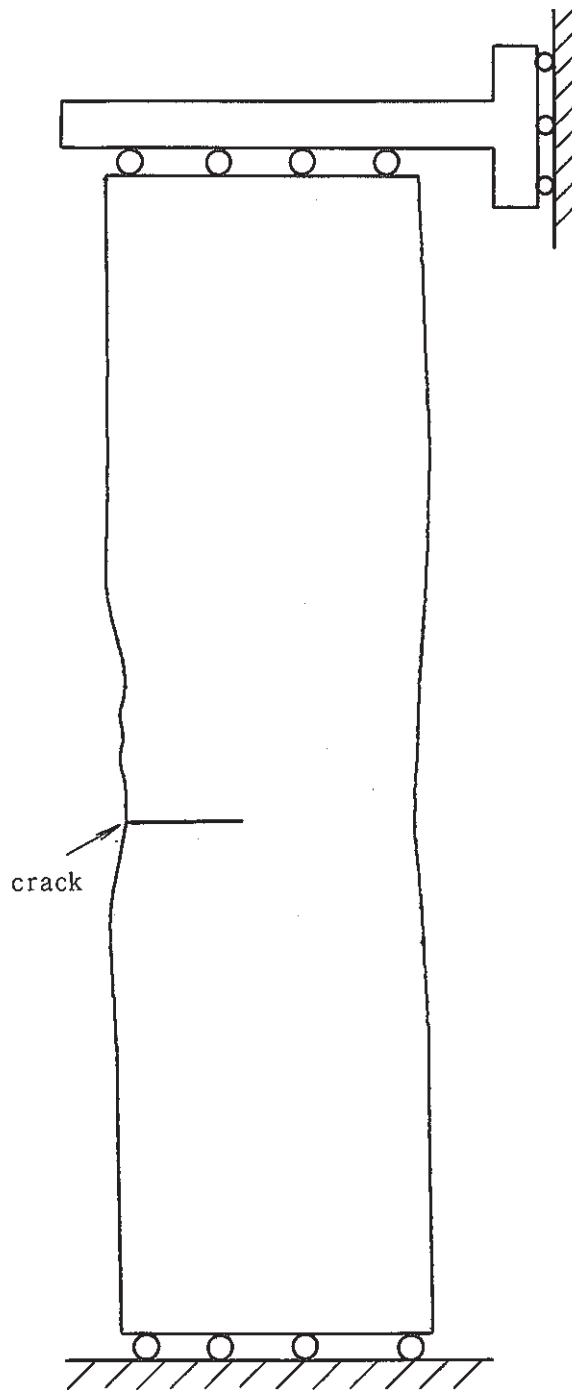


Fig. 3.1-1 Mechanically Boundary Condition of Finally Welded Joint

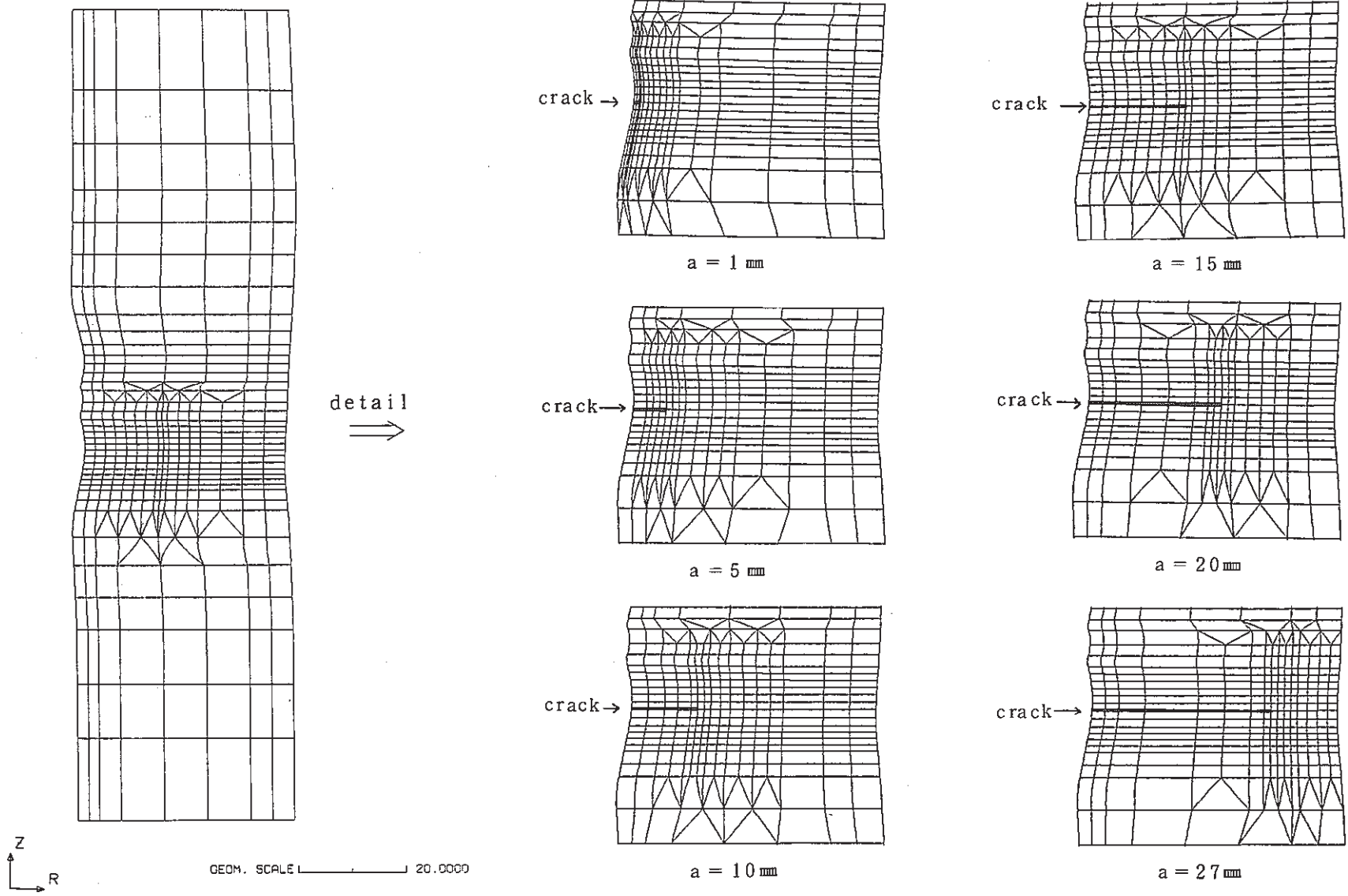


Fig. 3.1-2 Finite Element Models for Finally Welded Joint

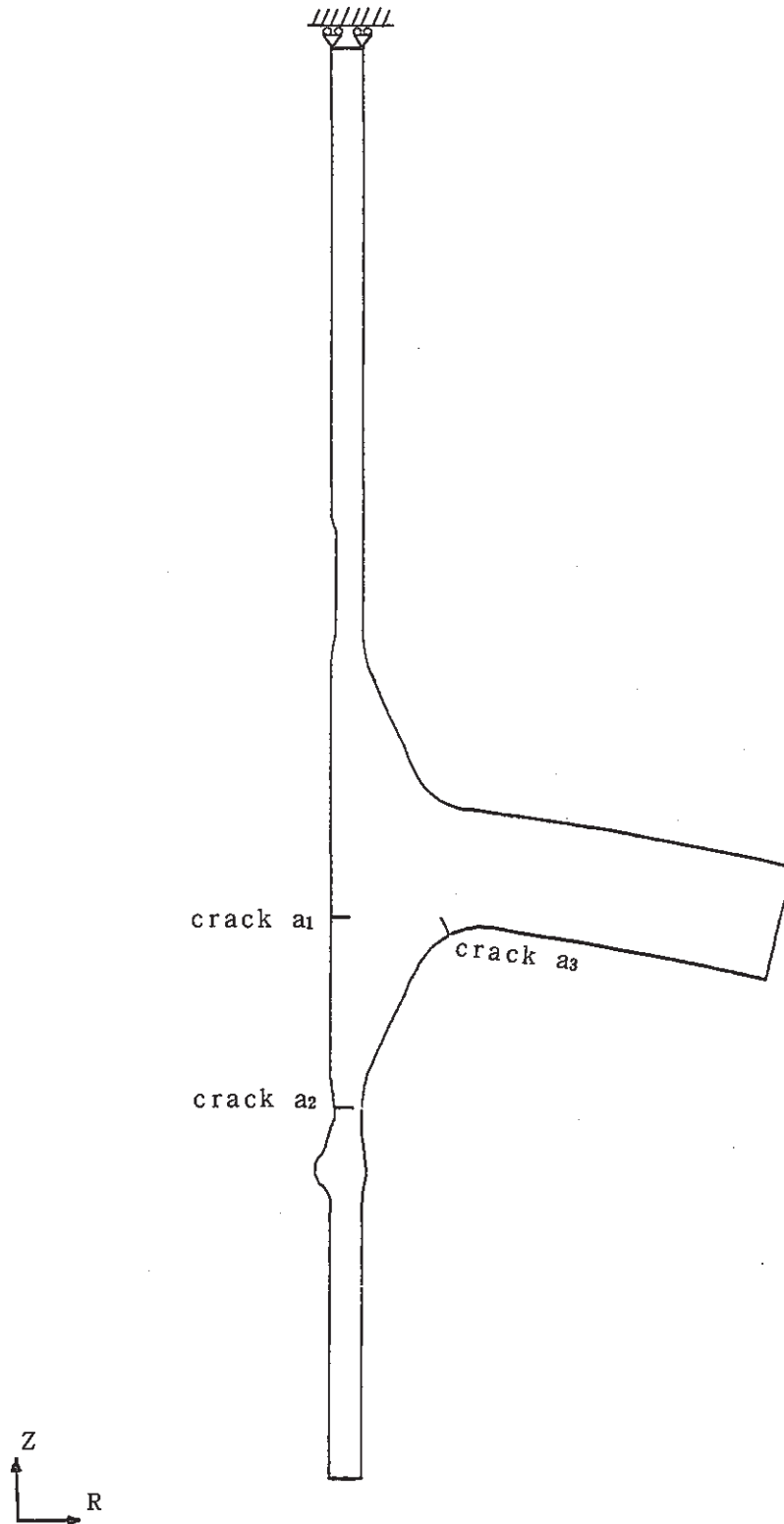


Fig. 3.1-3 Mechanically Boundary Condition of Inlet Nozzle

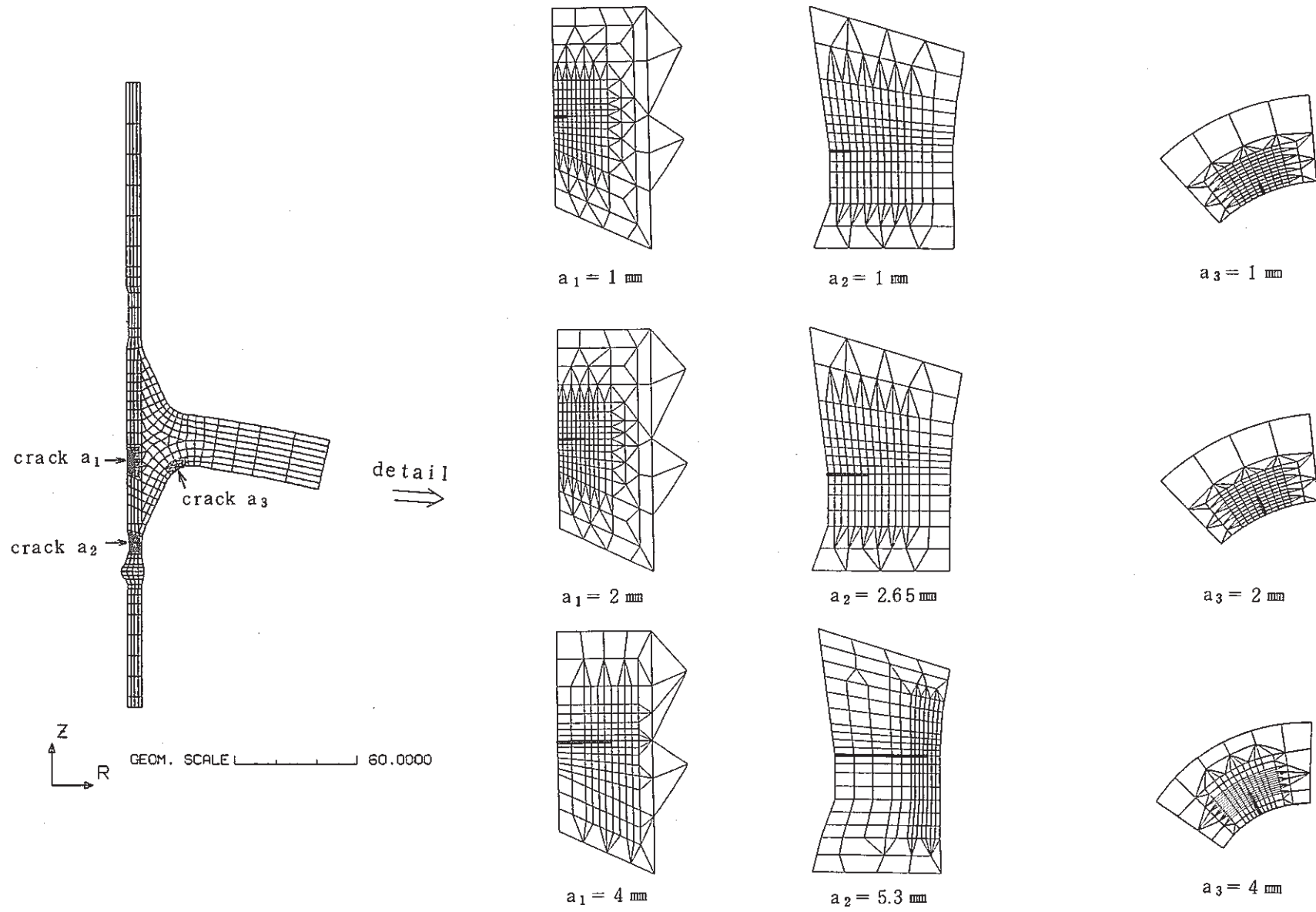


Fig. 3.1-4 Finite Element Models for Inlet Nozzle

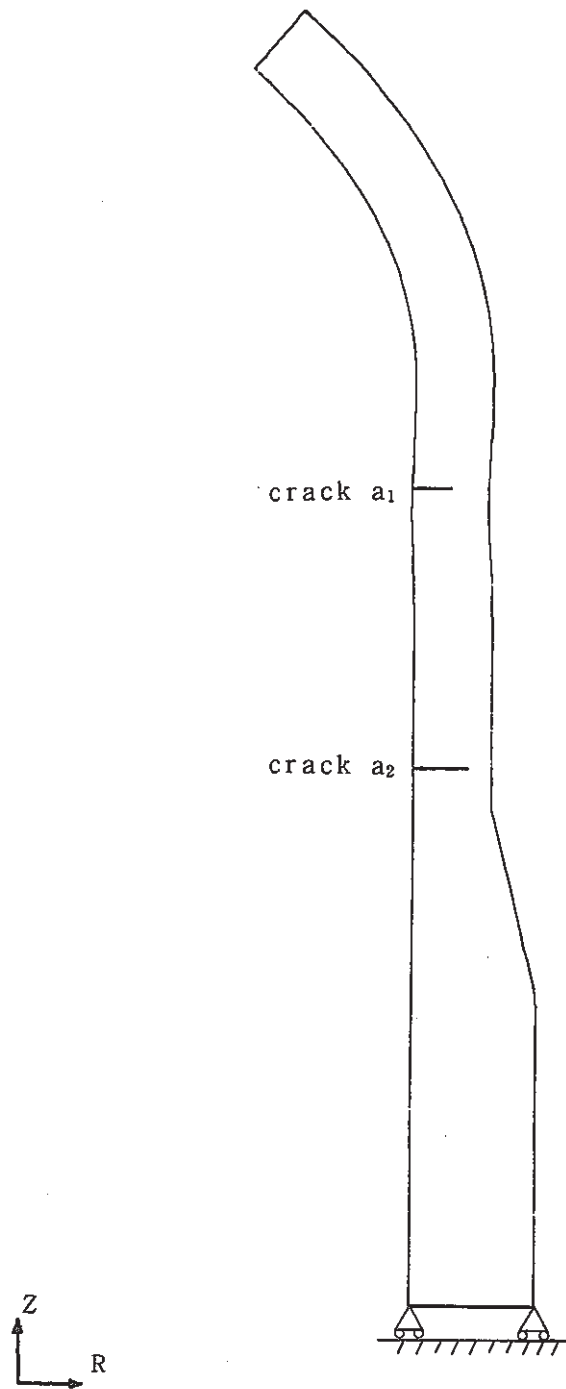


Fig. 3.1-5 Mechanically Boundary Condition of Thinning Portion

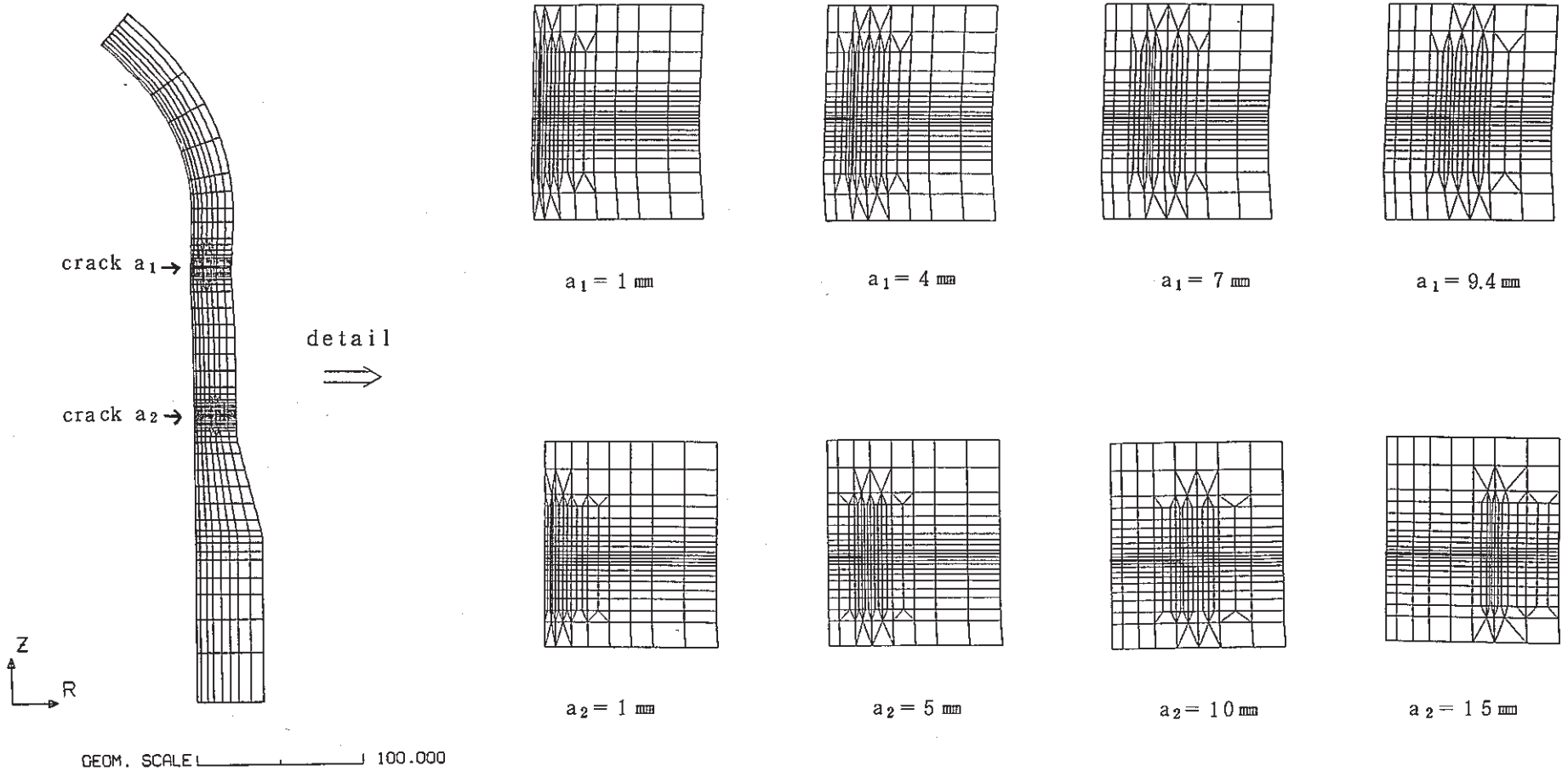


Fig. 3.1-6 Finite Element Models for Thinning Portion

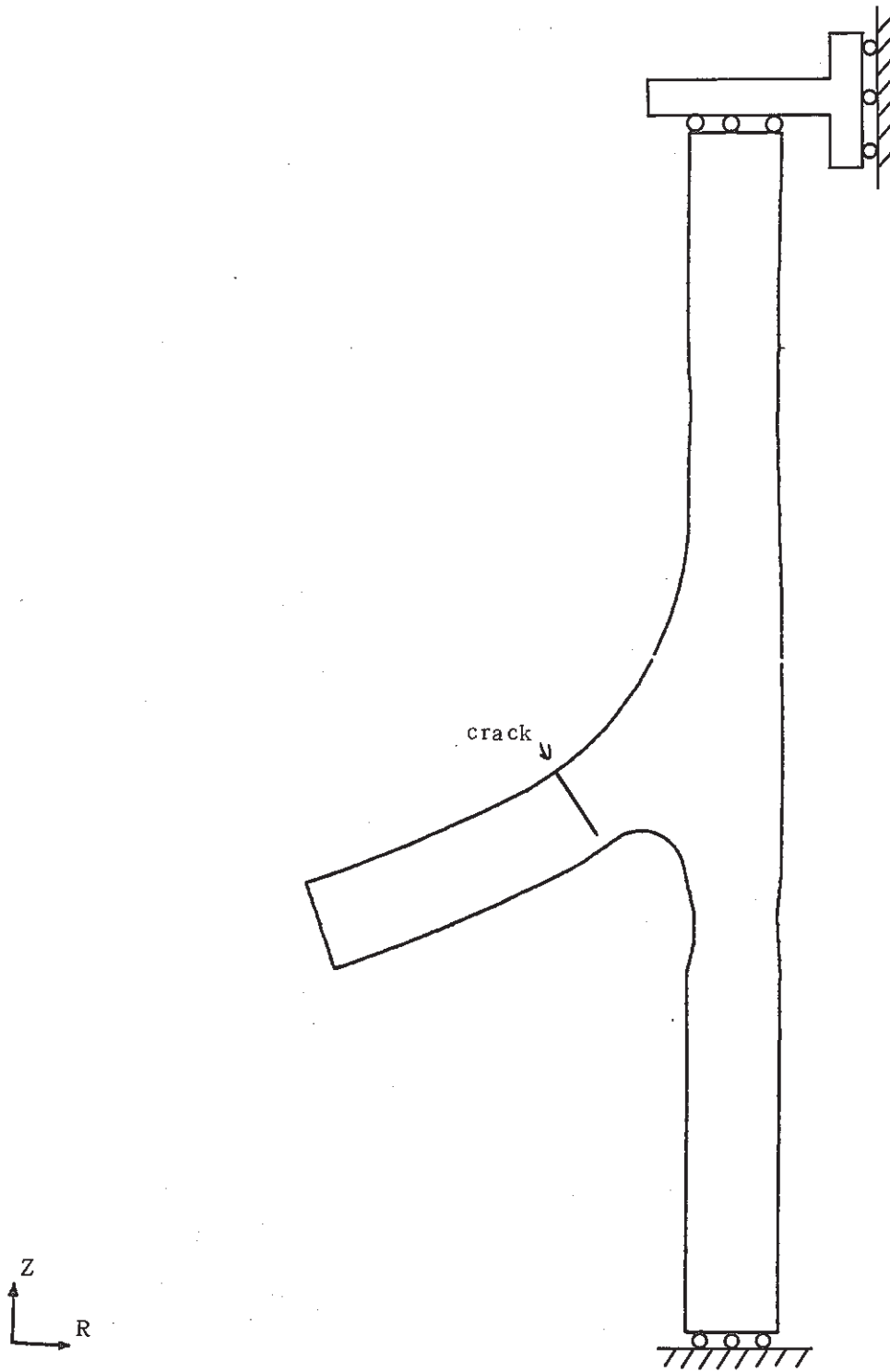


Fig. 3.1-7 Mechanically Boundary Condition of Conical-Bottom Head

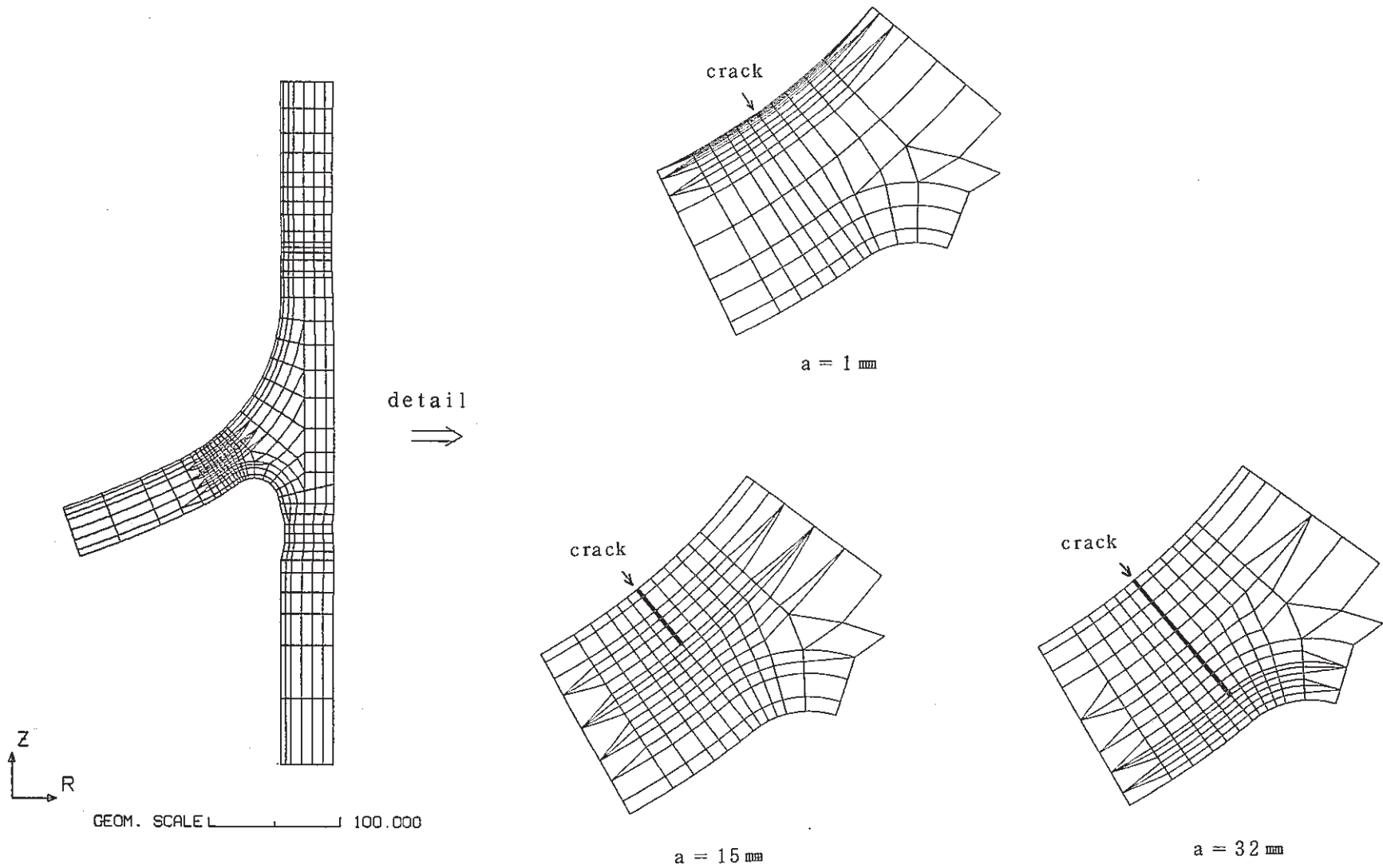


Fig. 3.1-8 Finite Element Models for Conical-Bottom Head

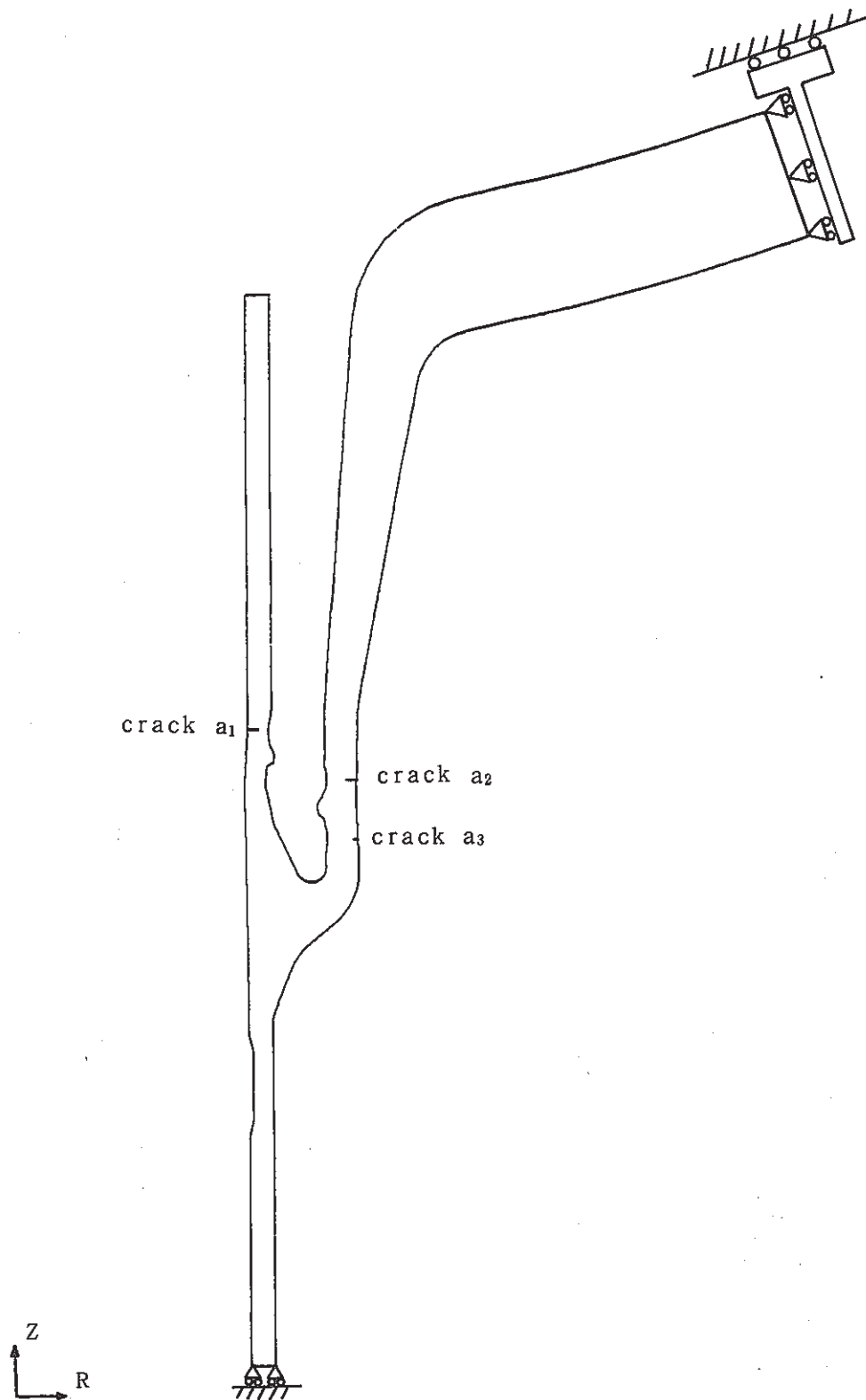


Fig. 3.1-9 Mechanically Boundary Condition of Outlet Nozzle

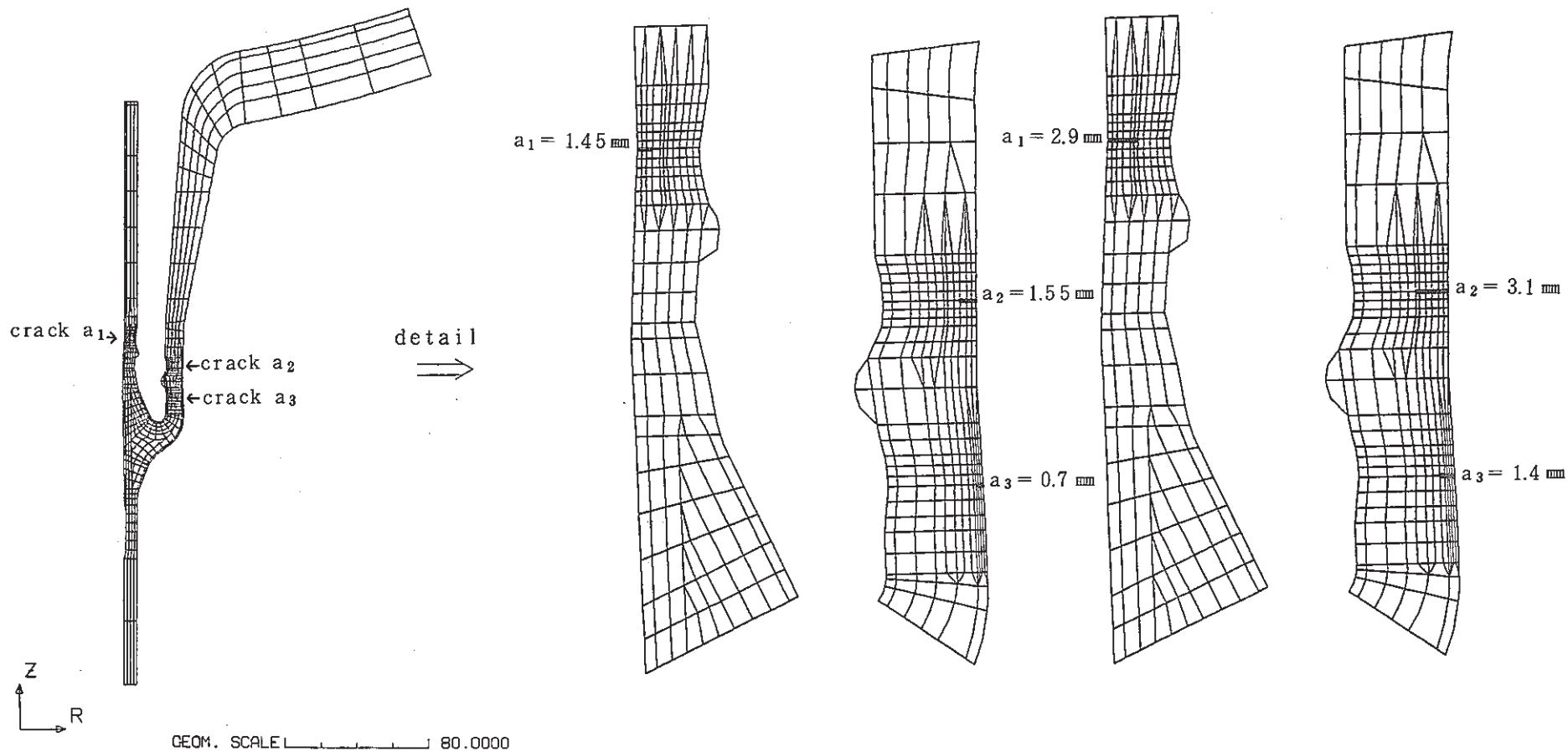


Fig. 3.1.-10 Finite Element Models for Outlet Nozzle

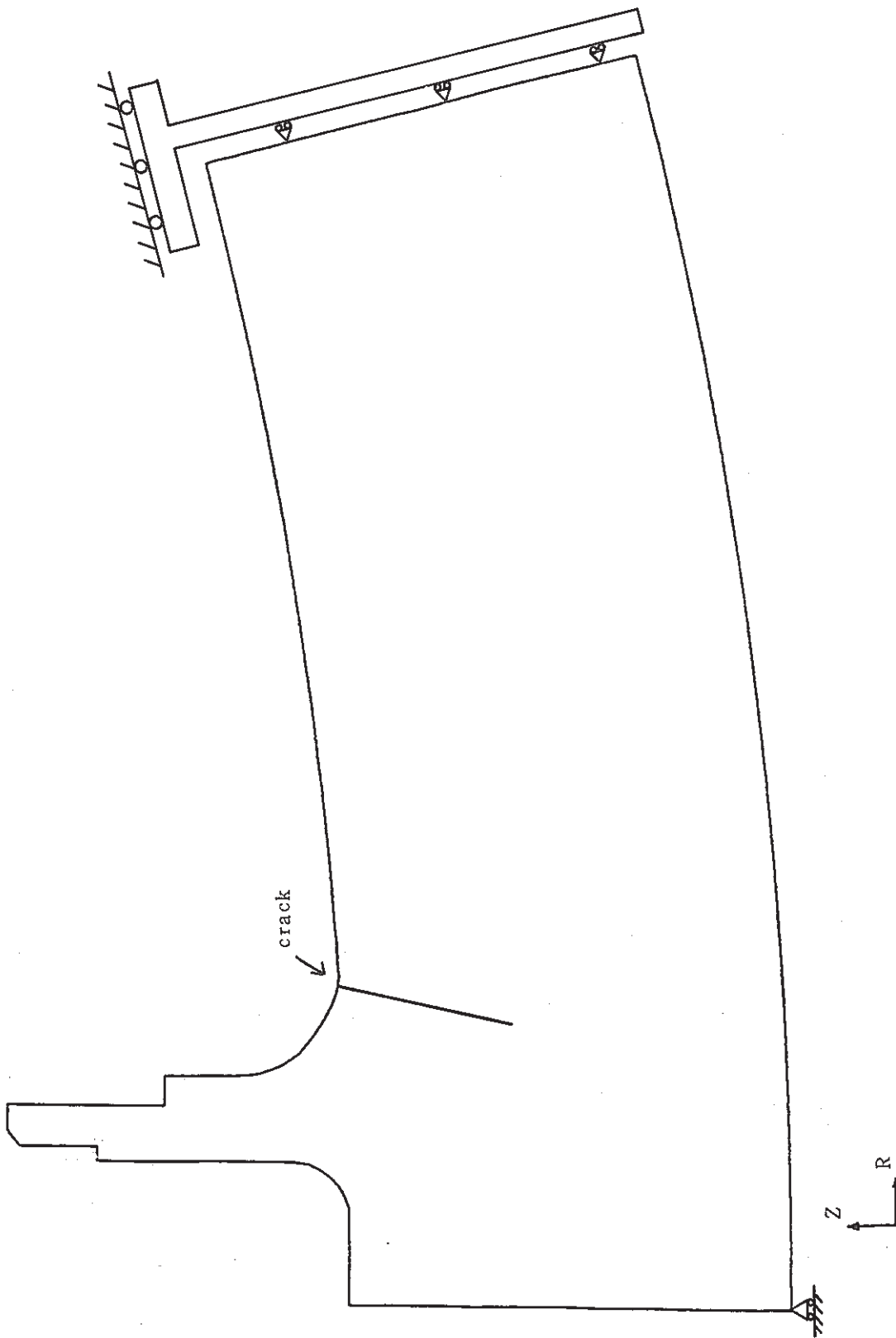


Fig. 3.1-11 Mechanically Boundary Condition of Stud Bolt

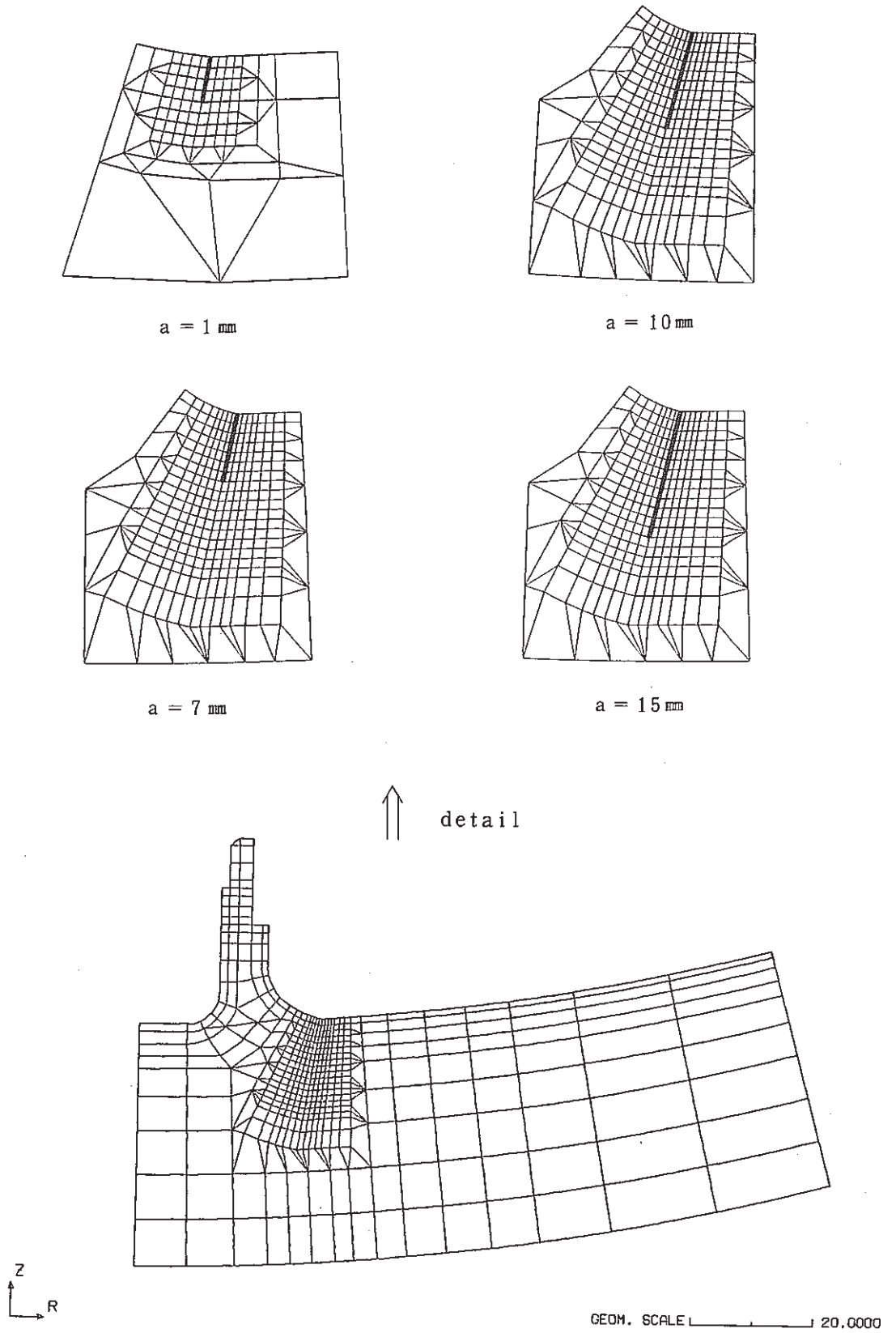
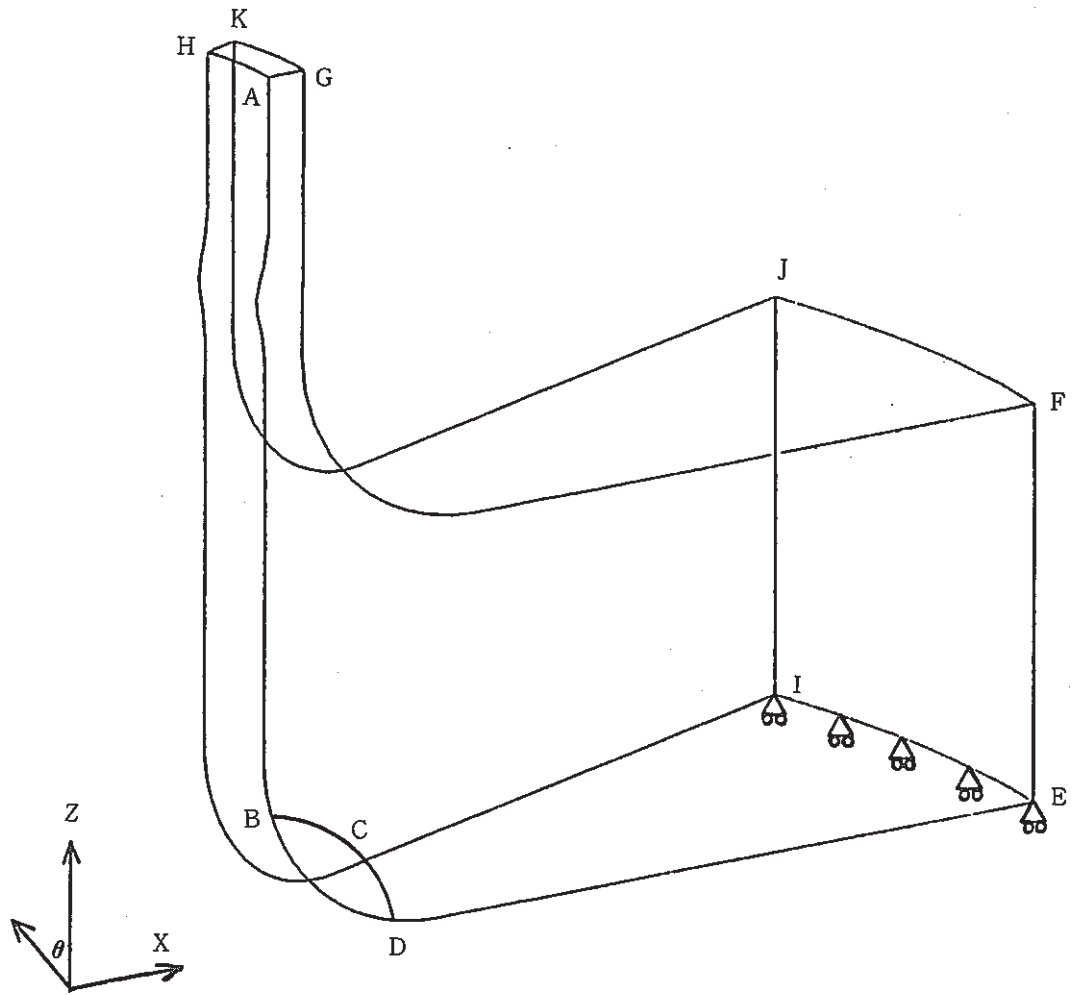


Fig. 3.1-12 Finite Element Models for Stud Bolt



- ① 面-ABCDEFGおよび面-HIJKにおける節点の周方向変位を拘束
- ② 辺-EIにおける節点の軸方向変位を拘束
- ③ 面-EFJIにおける節点については半径方向を一樣変位

Fig. 3.1-13 Mechanically Boundary Condition of Instrumental Nozzle

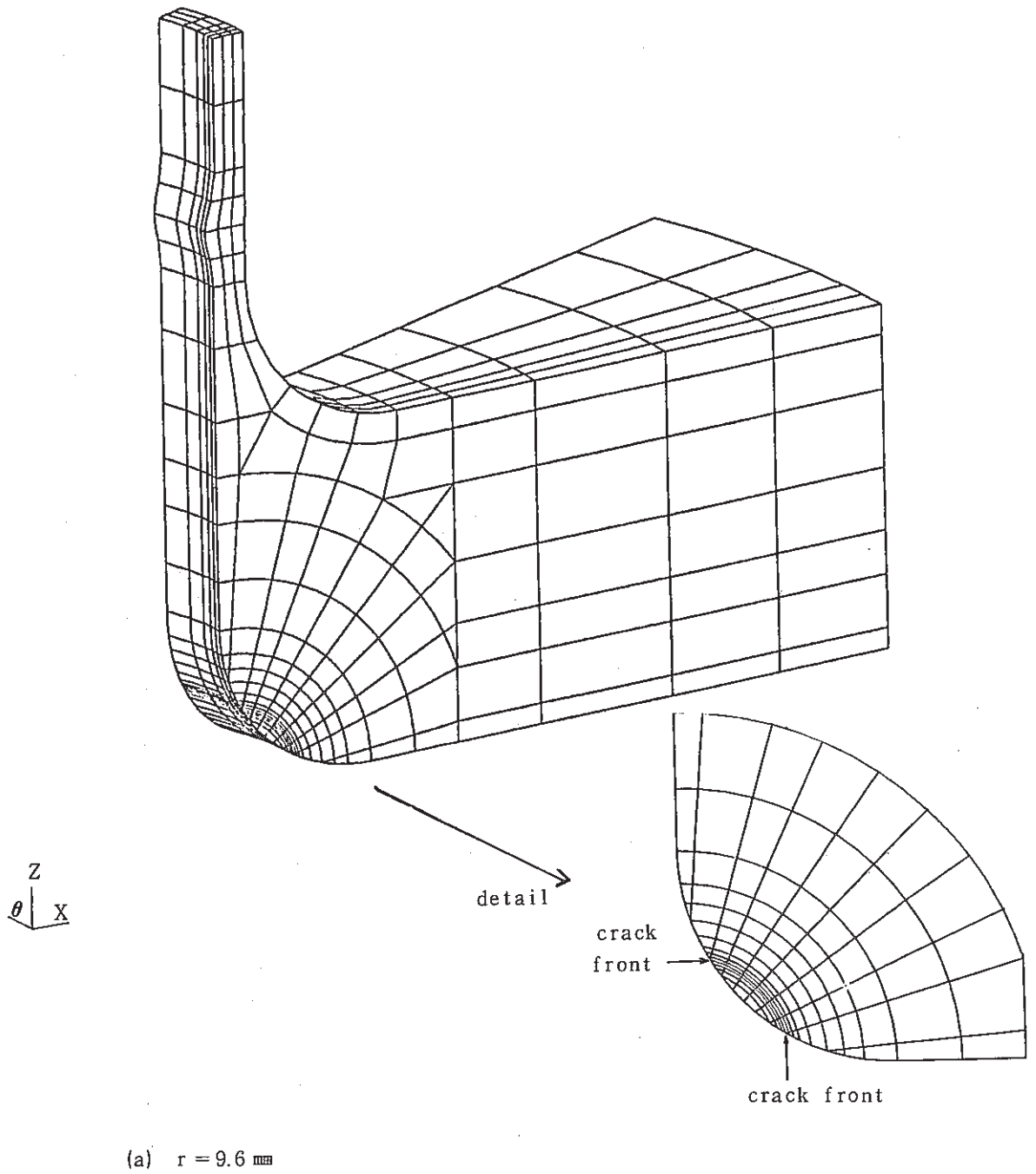
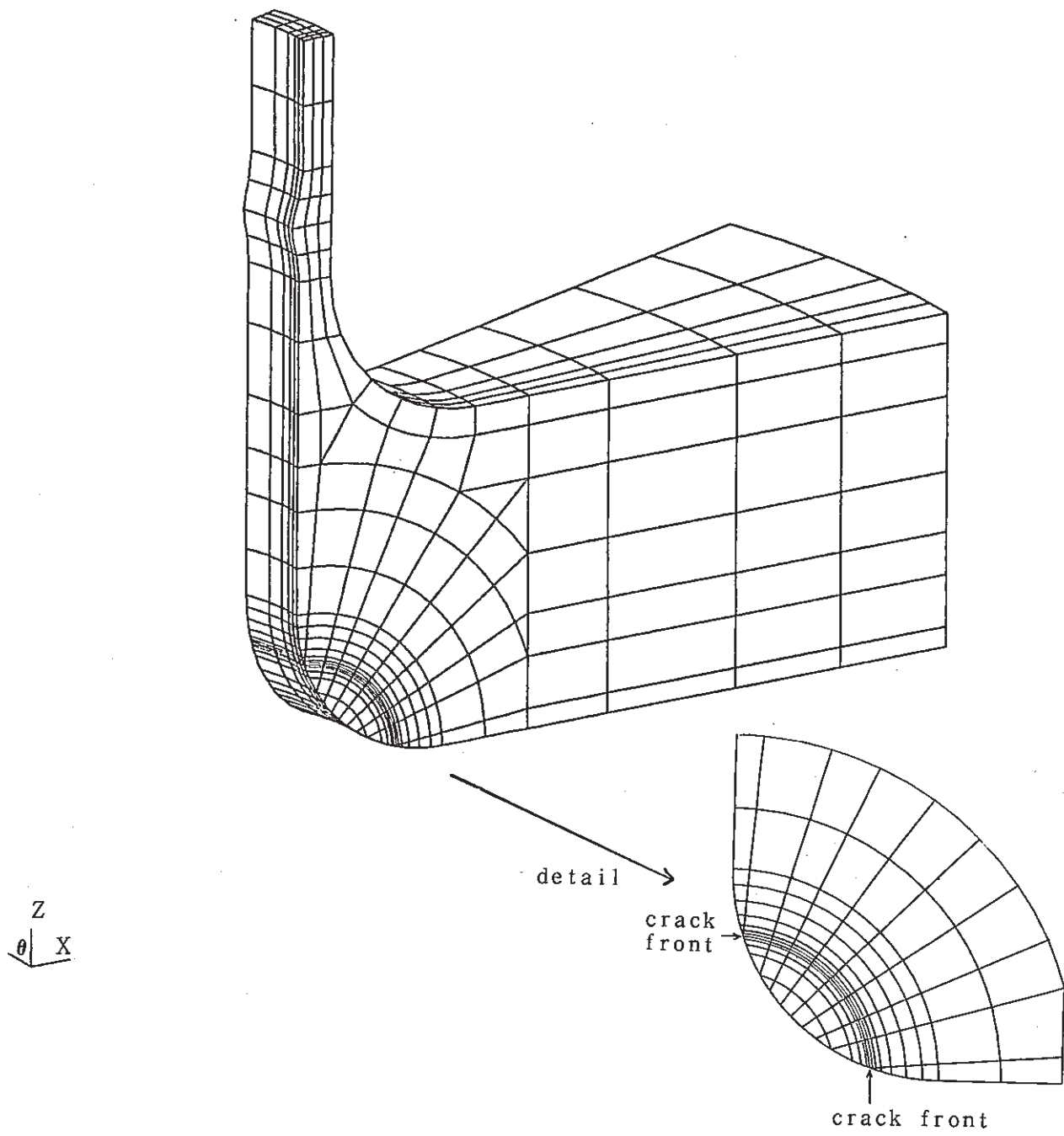
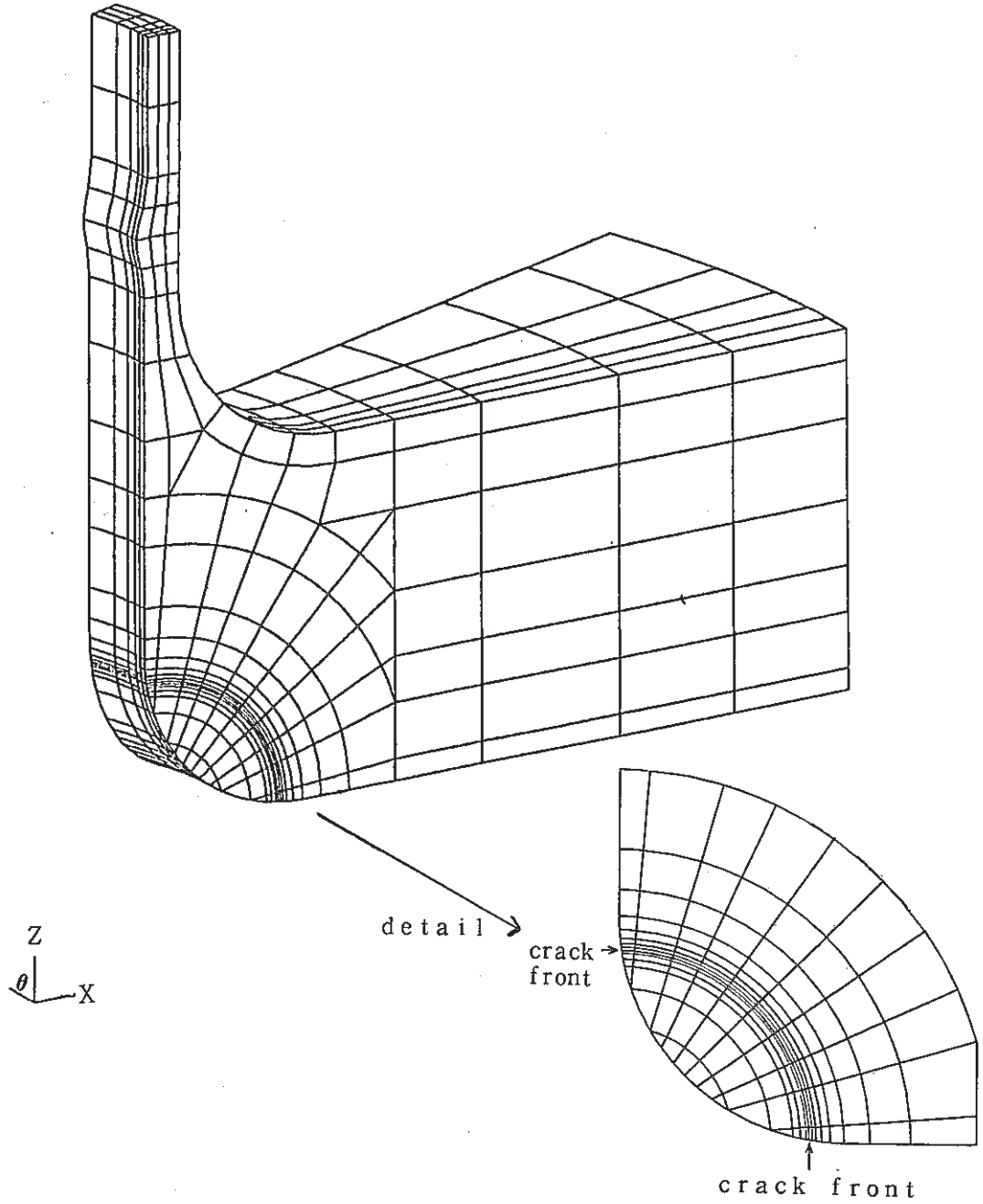


Fig. 3.1-14 Finite Element Models for Instrumental Nozzle



(b) $r = 12.8 \text{ mm}$

Fig. 3.1-14 Cont'd



(c) $r = 16.0 \text{ mm}$

Fig. 3.1-14 Cont'd

3.2 弾性解析に基づく破壊力学パラメータの解析

軸対称及び3次元問題において破壊力学パラメータを計算した。 \hat{J} 積分は、附録Aに示したように熱過渡荷重下でも径路独立性を示すので、これ以降対象とする破壊力学パラメータとして \hat{J} 積分、さらに応力拡大係数はき裂面に垂直な応力成分よりき裂先端に外挿した K_I 値を選んだ。弾性解析及び破壊力学パラメータの解析結果の詳細を附録C、Eに示す。

Table 3.2-1～Table 3.2-7は、各モデルのき裂深さごとの応力拡大係数範囲 ΔK_I 及び \hat{J} 積分範囲である。

(a) 最終溶接部

Fig.3.2-1(1)は各き裂の熱過渡に対する応力拡大係数 K_I の時間変化である。き裂深さが15mmで最も大きな値を示す。Fig.3.2-1(2)は \hat{J} 積分の時間変化であるが、この場合もき裂深さ15mmで最も大きな値を示す。Fig.3.2-1(3)及びFig.3.2-1(4)はき裂深さと応力拡大係数範囲 $\Delta K (= K_{max} - K_{min})$ 、 \hat{J} 積分範囲 $\Delta \hat{J} (= \hat{J}_{COLD,MAX} + \hat{J}_{HOT,MAX})$ である。このようにき裂深さが10～15mmで ΔK 、 $\Delta \hat{J}$ とも最大を示しその後緩やかに減少している。

(b) 入口ノズル

Fig.3.2-2(1)～Fig.3.2-2(6)に、各き裂(a_1 、 a_2 及び a_3 き裂)の K_I 値及び \hat{J} 積分値の時間変化を示す。さらにFig.3.2-2(7)とFig.3.2-2(8)にはき裂深さと各き裂の ΔK_I 、 $\Delta \hat{J}$ との関係を示す。このように、入口ノズル内表面側から発生なき裂 a_1 及び a_2 はある深さで最大値を示し、その後減少している。しかしながら a_3 き裂は、浅いき裂では ΔK_I 、 $\Delta \hat{J}$ は小さいがき裂深さとともに大きくなっており減少する傾向は今回の解析範囲ではみられなかった。

(c) シンニング部

Fig.3.2-3(1)～Fig.3.2-3(4)に各き裂(a_1 、 a_2 き裂)の K_I 値及び \hat{J} 積分値の時間変化を示す。 a_1 き裂ではき裂深さが7mmで K_I 値、 \hat{J} 積分値とも最大を示す。 a_2 き裂では、 K_I 値はき裂深さ10mmが最大であり、 \hat{J} 積分値はき裂深さ15mmが最大を示す。Fig.3.2-3(5)、Fig.3.2-3(6)は、き裂深さと ΔK_I 及び $\Delta \hat{J}$ の関係である。 a_2 き裂は a_1 き裂に比べて ΔK_I 及び $\Delta \hat{J}$ とも大きな値であり、さらにこれらの値の最大がより深い位置にある。 a_2 き裂では肉厚変動部(25mm～40mm)の影響が大きいと思われる。

(d) コニカル・下部鏡

Fig.3.2-4(1)はき裂深さごとの応力拡大係数 K_I の時間変化である。き裂深さが15mmで最も大きな値を示している。Fig.3.2-4(2)は \hat{J} 積分の時間変化である。このように、コールドショック時に比較してホットショック時の K_I 値及び \hat{J} 積分値がかなり大きい。附録C Fig.C.4.1-1,2,3にみられるように、このき裂先端ではホットショックにおいてかなり大きな圧縮応力が発生している。これは純粋な熱過渡によるものでなく、温度応答の遅いスカート部からのたが締め効果が大きいと思われる。

Fig.3.2-4(3)、Fig.3.2-4(4)にき裂深さと応力拡大係数範囲 ΔK_I 及び \hat{J} 積分範囲の関係

を示す。 ΔK_I については、き裂深さが約 15 mm で最大を示しその後減少するが、 \hat{J} 積分では、き裂深さ 32 mm でもき裂深さ 15 mm の値とほとんど同値であり減少傾向は緩やかではない。

(e) 出口ノズル部

Table 3.2-5 に示すように、出口ノズル部に想定した 3 つのき裂の K_I 値 及び \hat{J} 積分値は、極めて小さい。また想定したき裂深さも各き裂 2 つであるため、き裂深さと ΔK_I 、 $\Delta \hat{J}$ の関係が明確でない。

(f) スタッドボルト

Fig. 3.2-5(1), Fig. 3.2-5(2) はき裂深さごとの応力拡大係数 K_I 、 \hat{J} 積分値の時間変化である。両者ともき裂深さが 7 mm で最大を示す。Fig. 3.2-5(3), Fig. 3.2-5(4) はき裂深さと ΔK_I 、 $\Delta \hat{J}$ の関係であるが、き裂深さに対する最大値は、5 mm 前後の浅いき裂において発生している。

(g) 計装ノズル

Fig. 3.2-6(1) は、コールドショック時におけるき裂半径ごとのき裂縁に沿った K_I 値の分布である。このよういき裂が進展すると容器側 ($\varphi = 90^\circ$) で最大を示すようになる。Fig. 3.2-6(2) はホットショック時のき裂縁に沿った K_I 値の分布であり、容器側で、負の最大を示す。Fig. 3.2-6(3), Fig. 3.2-6(4) はき裂縁に沿った \hat{J} 値の分布であり、 K_I 値と同様き裂の進展に従い容器側 ($\varphi = 90^\circ$) で最大を示すようになる。Fig. 3.2-6(5), Fig. 3.2-6(6) は $\varphi = 20^\circ, 50^\circ$ 及び 70° 方向にき裂が進展する場合の ΔK_I 及び $\Delta \hat{J}$ とき裂半径の関係である。さらに、Fig. 3.2-6(7) には、コールドショック時における \hat{J} 積分値の変化を示す。このように、き裂が深まるにつれて容器側 ($\varphi = 90^\circ$) の \hat{J} 積分値が大きくなり、き裂は容器側を優先的に進展する傾向を示している。破面観察において、き裂は容器側がノズル側よりも長く解析結果と良く一致した。(附録 G 参照)

Table 3.2-1 K_I and \hat{J} -Integral Range for Finally Welded Joint

Crack Depth (mm)	Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm		
	$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$
1	1 1 9.5 (152 sec)	-1 3 5.3 (990 sec)	2 5 4.8	0.6 1 6 6 (152 sec)	0.7 2 6 2 (990 sec)	1.3 4 2 8
5	1 6 8.3 (152 sec)	-1 8 9.6 (990 sec)	3 5 7.9	1.7 9 3 0 (152 sec)	2.1 1 4 0 (990 sec)	3.9 0 7 0
10	1 9 1.3 (152 sec)	-2 1 3.9 (990 sec)	4 0 5.2	2.3 2 1 0 (152 sec)	2.7 0 3 0 (1020 sec)	5.0 2 4 0
15	1 9 3.2 (152 sec)	-2 1 6.4 (1020 sec)	4 0 9.6	2.3 6 9 0 (152 sec)	2.7 5 2 0 (1020 sec)	5.1 2 1 0
20	1 7 4.5 (174 sec)	-1 9 5.4 (1020 sec)	3 6 9.9	2.0 6 6 0 (152 sec)	2.4 5 3 0 (1020 sec)	4.5 1 9 0
27	1 5 6.0 (174 sec)	-1 7 5.8 (1020 sec)	3 3 1.8	1.3 9 1 0 (152 sec)	1.6 3 2 0 (1020 sec)	3.0 2 3 0

Table 3.2-2 K_I and \hat{J} -Integral Range for Inlet Nozzle

Crack Depth (mm)	Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm		
	$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$
a ₁	1 (9.5 sec)	-1 0 8.9 (9 0 9 sec)	1 8 5.5	0.3 0 6 8 (12 sec)	0.5 7 3 8 (9 0 9 sec)	0.8 8 0 6
	2 (12 sec)	-1 1 8.7 (9 1 0 sec)	1 9 8.5	0.3 4 9 7 (12 sec)	0.7 3 1 4 (9 1 0 sec)	1.0 8 1 1
	4 (12 sec)	-1 3 1.3 (9 1 0 sec)	2 0 7.0	0.2 7 9 9 (12 sec)	0.8 0 1 6 (9 1 0 sec)	1.0 8 1 5
a ₂	1 (12 sec)	-1 1 6.4 (9 1 0 sec)	2 4 1.2	0.8 0 1 7 (12 sec)	0.6 1 2 5 (9 1 0 sec)	1.4 1 4 2
	2.65 (12 sec)	-1 1 4.8 (9 1 0 sec)	2 4 2.3	0.9 8 2 7 (12 sec)	0.7 1 6 0 (9 1 0 sec)	1.6 9 8 7
	5.3 (14 sec)	-7 8.4 (9 1 0 sec)	1 6 7.4	0.3 2 9 2 (12 sec)	0.2 2 1 2 (9 1 0 sec)	0.5 5 0 4
a ₃	1 (90 sec)	-5 7.2 (1020 sec)	1 5 3.9	0.5 8 4 8 (90 sec)	0.1 9 8 6 (1020 sec)	0.7 8 3 4
	2 (120 sec)	-6 2.7 (1020 sec)	1 6 8.1	0.8 0 5 3 (90 sec)	0.2 7 5 2 (1020 sec)	1.0 8 0 5
	4 (120 sec)	-9 8.0 (1020 sec)	2 6 3.8	1.2 7 8 0 (120 sec)	0.4 3 6 2 (1080 sec)	1.7 1 4 2

Table 3.2-3 K_I and \hat{J} -Integral Range for Thinning Portion

Crack Depth (mm)	Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm			
	$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$	
a ₁	1 (138 sec)	57.5 (960 sec)	-85.6 (960 sec)	143.1	0.1718 (138 sec)	0.3253 (960 sec)	0.4971
	4 (138 sec)	93.3 (960 sec)	-135.2 (960 sec)	228.5	0.5026 (138 sec)	0.9456 (975 sec)	1.4482
	7 (152 sec)	101.3 (975 sec)	-147.0 (975 sec)	248.3	0.5897 (138 sec)	1.1263 (975 sec)	1.7160
	9.4 (152 sec)	87.9 (975 sec)	-129.0 (975 sec)	216.9	0.4704 (152 sec)	0.9257 (975 sec)	1.3961
a ₂	1 (138 sec)	88.6 (960 sec)	-122.2 (960 sec)	210.8	0.4266 (120 sec)	0.4851 (975 sec)	0.9117
	5 (138 sec)	162.9 (975 sec)	-220.9 (975 sec)	383.8	1.5919 (138 sec)	2.5988 (975 sec)	4.1907
	10 (138 sec)	200.0 (975 sec)	-263.7 (975 sec)	463.7	2.4410 (138 sec)	3.8856 (975 sec)	6.3266
	15 (138 sec)	192.1 (975 sec)	-247.7 (975 sec)	439.8	2.7569 (138 sec)	4.2149 (975 sec)	6.9718

Table 3.2-4 K_I and \hat{J} -Integral Range for Conical-Bottom Head

Crack Depth (mm)	Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm		
	$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$
1	35.5 (60 sec)	-88.8 (960 sec)	124.3	0.0358 (90 sec)	0.2532 (990 sec)	0.2884
15	65.1 (90 sec)	-218.1 (990 sec)	283.2	0.2256 (90 sec)	2.5452 (990 sec)	2.7708
32	49.3 (120 sec)	-123.4 (1020 sec)	172.7	0.3667 (120 sec)	2.4019 (1020 sec)	2.7686

Table 3.2-5 K_I and \hat{J} -Integral Range for Outlet Nozzle

Crack Depth (mm)		Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm		
		$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$
a ₁	1.45	5 0.8 (60 sec)	-6 6.5 (952.5 sec)	1 1 7.3	0.1 2 0 3 (60 sec)	0.1 9 2 6 (95 2.5 sec)	0.3 1 2 9
	2.9	4 5.1 (60 sec)	-6 0.0 (952.5 sec)	1 0 5.1	0.1 8 4 3 (60 sec)	0.2 9 5 8 (95 2.5 sec)	0.4 8 0 1
a ₂	1.55	-1.2 4 (90 sec)	2.9 2 (972 sec)	4.1 6	-	-	-
	3.1	-3.7 0 (90 sec)	5.4 1 (972 sec)	9.1 1	-	-	-
a ₃	0.7	4.2 6 (66 sec)	-5.4 3 (1000 sec)	9.6 9	-	-	-
	1.4	7.2 5 (66 sec)	-9.1 7 (1000 sec)	1 6.4 2	-	-	-

NOTE. \hat{J} Value of Crack a₂ and a₃ are less than 0.01

Table 3.2-6 K_I and \hat{J} -Integral Range for Stud Bolt

Crack Depth (mm)		Stress Intensity Factor, $kg/mm^{3/2}$			\hat{J} , kg/mm		
		$K_{I,COLD,max}$	$K_{I,HOT,max}$	ΔK_I	$\hat{J}_{COLD,max}$	$\hat{J}_{HOT,max}$	$\Delta \hat{J}$
1		1 1 6.3 (150 sec)	-1 4 0.9 (1000 sec)	2 5 7.2	0.7 0 4 4 (150 sec)	0.8 5 2 4 (1000 sec)	1.5 5 6 8
7		1 3 7.0 (150 sec)	-1 5 8.1 (1000 sec)	2 9 5.1	1.1 5 9 0 (150 sec)	1.3 3 8 0 (1020 sec)	2.4 9 7 0
10		1 1 8.0 (150 sec)	-1 3 5.4 (1020 sec)	2 5 3.4	0.8 4 6 1 (150 sec)	0.9 6 2 7 (1020 sec)	1.8 0 8 8
13		9 4.1 (150 sec)	-1 0 6.7 (1020 sec)	2 0 0.8	0.4 7 2 8 (150 sec)	0.5 3 1 3 (1020 sec)	1.0 0 4 1

Table 3.2-7 K_I and \hat{J} -Integral Range for Instrumental Nozzle

Crack Radius (mm)	φ	Stress Intensity Factor, $\text{kg}/\text{mm}^{3/2}$			\hat{J} , kg/mm		
		$K_{I, \text{COLD, max}}$ (150 sec)	$K_{I, \text{HOT, max}}$ (1000 sec)	ΔK_I	$\hat{J}_{\text{COLD, max}}$ (150 sec)	$\hat{J}_{\text{HOT, max}}$ (1000 sec)	$\Delta \hat{J}$
9.6	20°	70.3 (150 sec)	-82.9 (1000 sec)	153.2	0.2676 (150 sec)	0.3160 (1000 sec)	0.5836
	50°	92.4 (150 sec)	-110.0 (1000 sec)	202.4	0.4909 (150 sec)	0.5836 (1000 sec)	1.0745
	70°	78.1 (150 sec)	-95.4 (1000 sec)	173.5	0.3277 (150 sec)	0.4199 (1000 sec)	0.7476
12.8	20°	99.5 (150 sec)	-112.7 (1000 sec)	212.2	0.5735 (150 sec)	0.6217 (1000 sec)	1.1952
	50°	112.7 (150 sec)	-130.3 (1000 sec)	243.0	0.7281 (150 sec)	0.8338 (1000 sec)	1.5619
	70°	125.7 (150 sec)	-150.7 (1000 sec)	276.4	0.9185 (150 sec)	1.107 (1000 sec)	2.0255
16.0	20°	89.0 (150 sec)	-96.9 (1000 sec)	185.9	0.4528 (150 sec)	0.4612 (1000 sec)	0.9140
	50°	106.7 (150 sec)	-120.0 (1000 sec)	226.7	0.6506 (150 sec)	0.7154 (1000 sec)	1.3660
	70°	132.7 (150 sec)	-157.0 (1000 sec)	289.7	1.028 (150 sec)	1.219 (1000 sec)	2.247

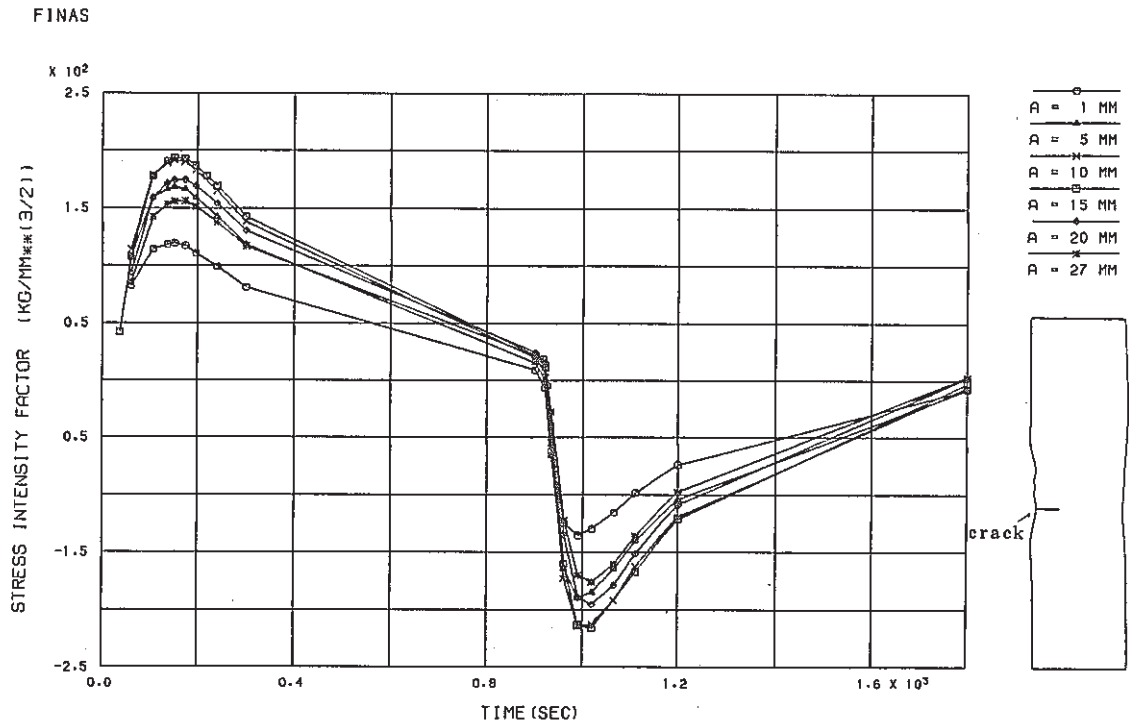


Fig. 3.2-1(1) History of Stress Intensity Factor for Finally Welded Joint

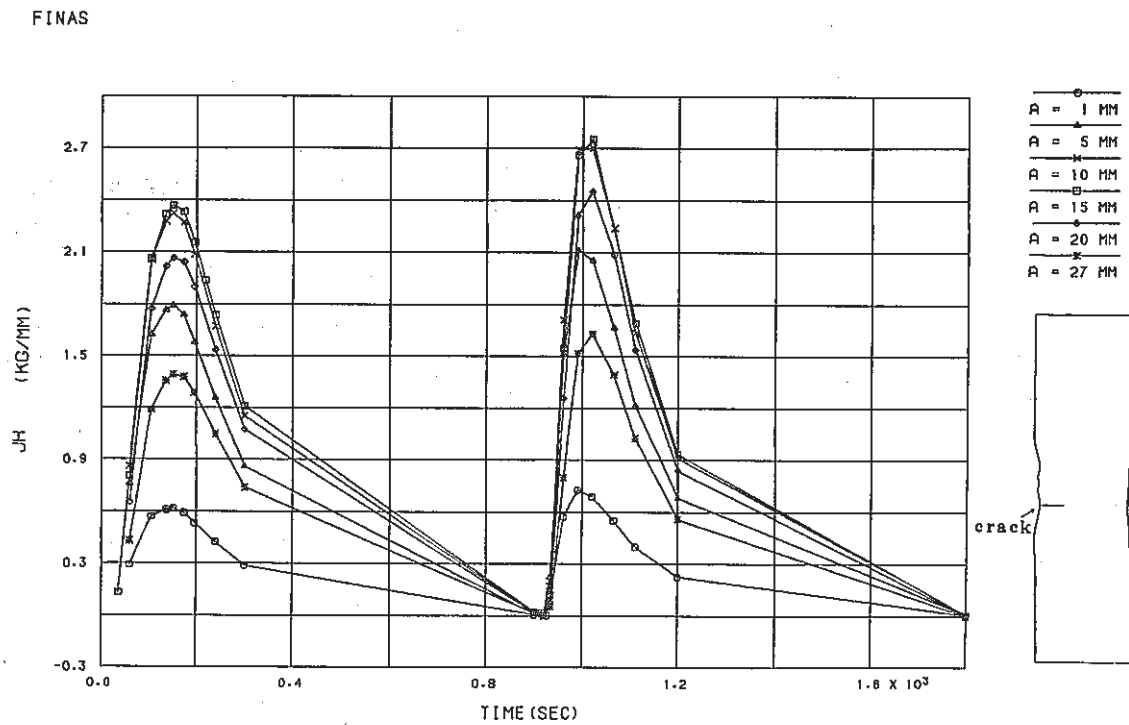


Fig. 3.2-1(2) History of \hat{J} -Integral for Finally Welded Joint

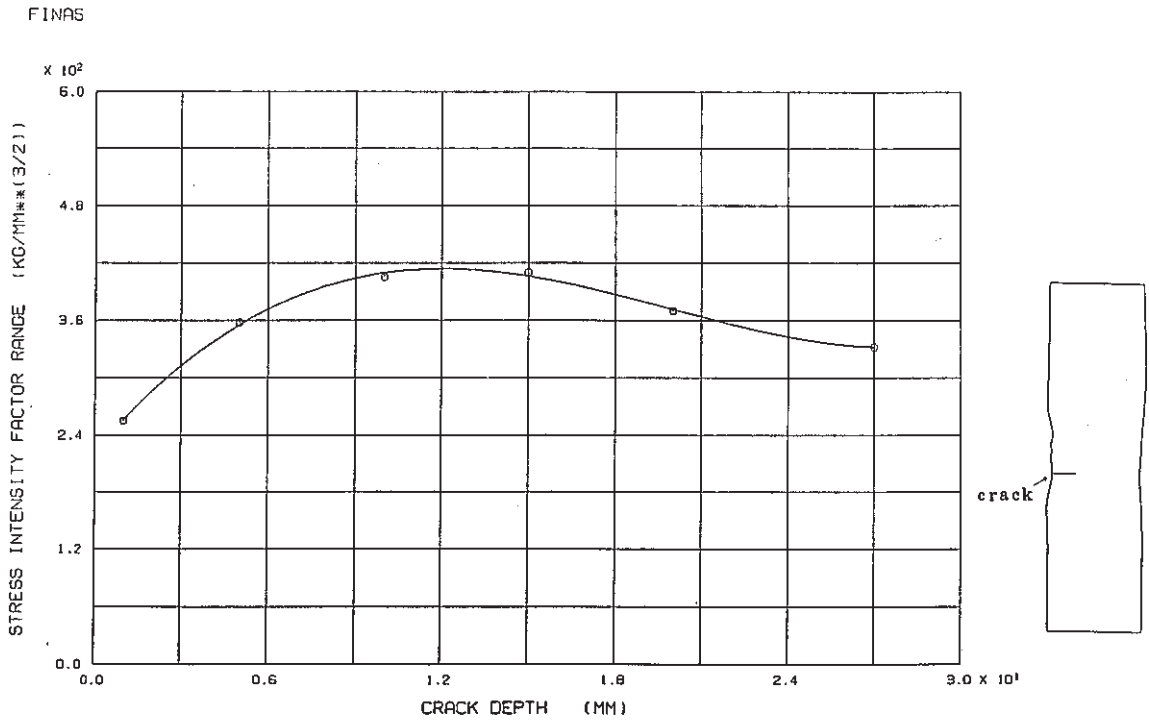


Fig. 3.2-1(3) Relation between Stress Intensity Factor Range and Crack Depth for Finally Welded Joint

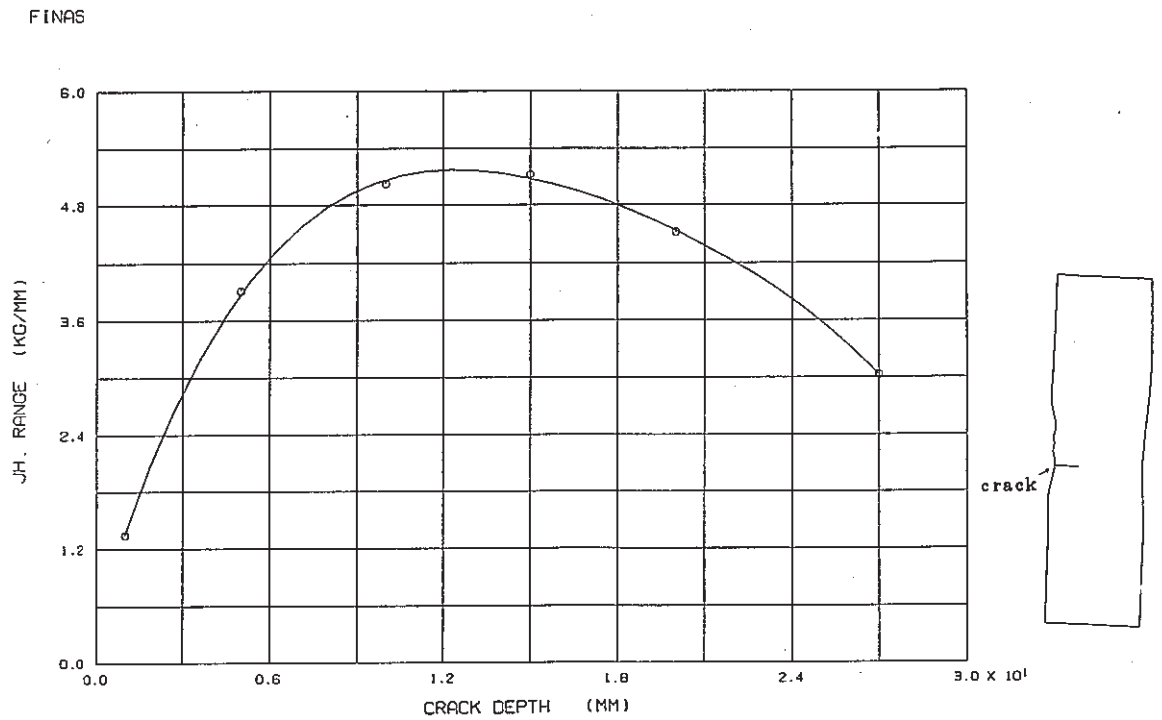


Fig. 3.2-1(4) Relation between \hat{J} -Integral Range and Crack Depth for Finally Welded Joint

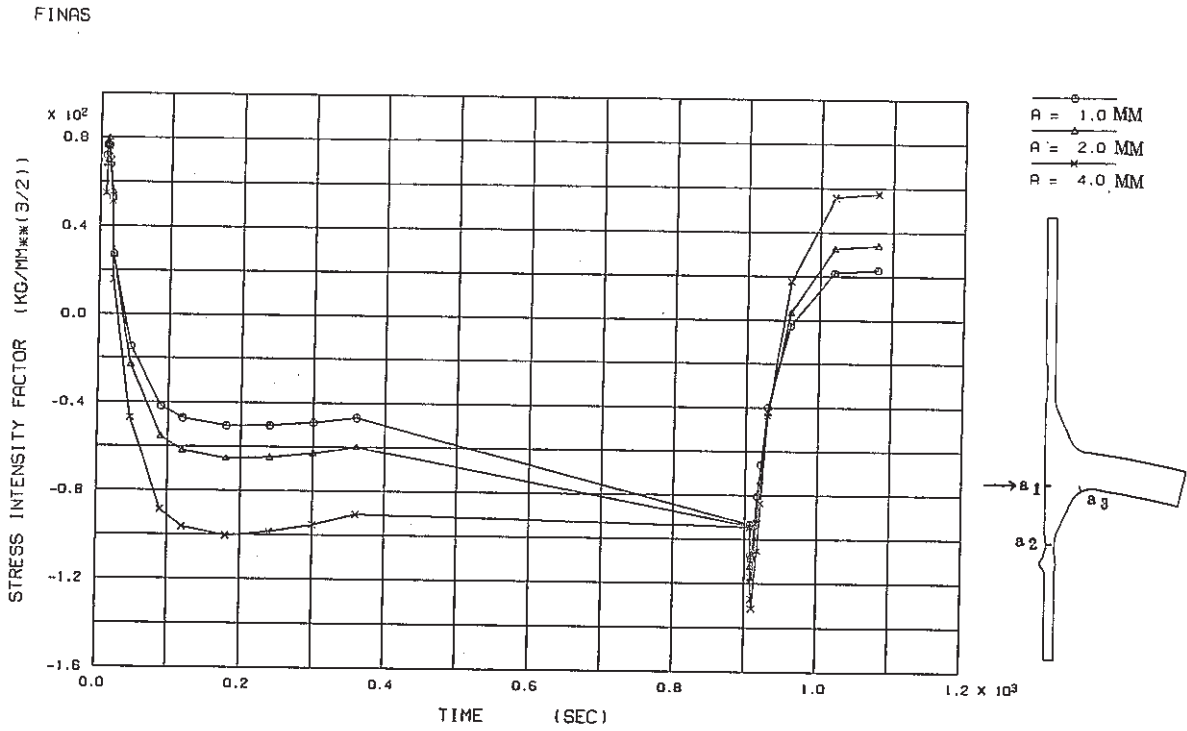


Fig. 3.2-2(1) History of Stress Intensity Factor for Inlet Nozzle, crack a_1

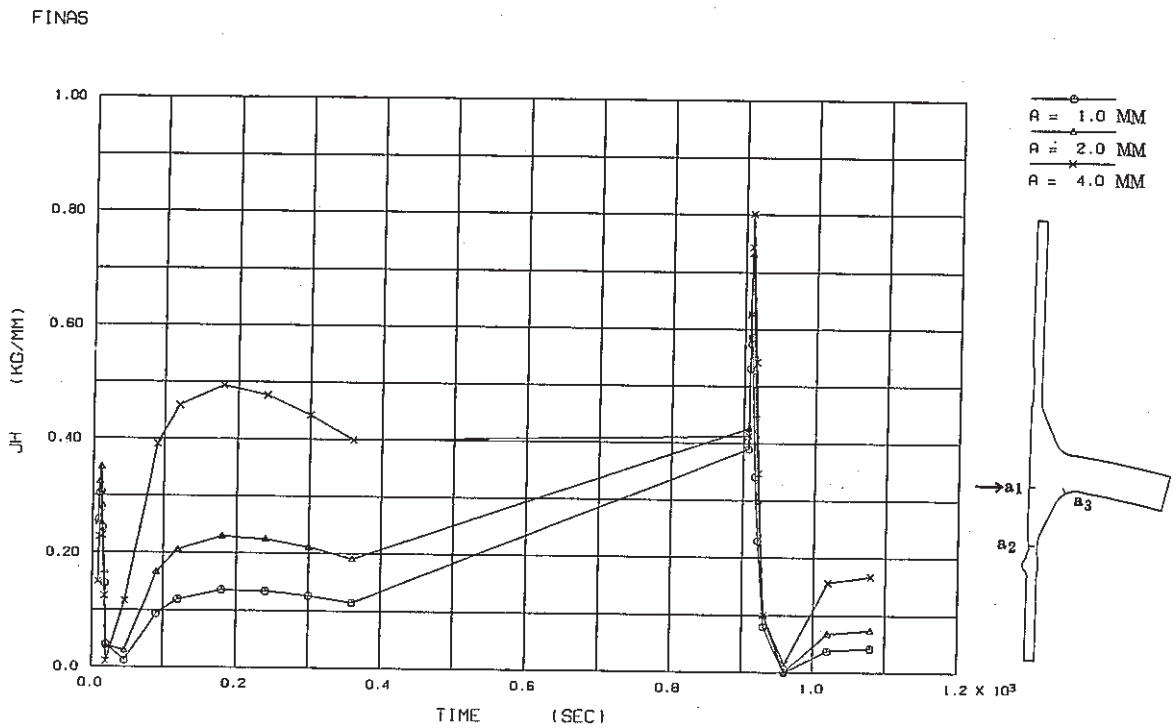


Fig. 3.2-2(2) History of \hat{J} -Integral for Inlet Nozzle, crack a_1

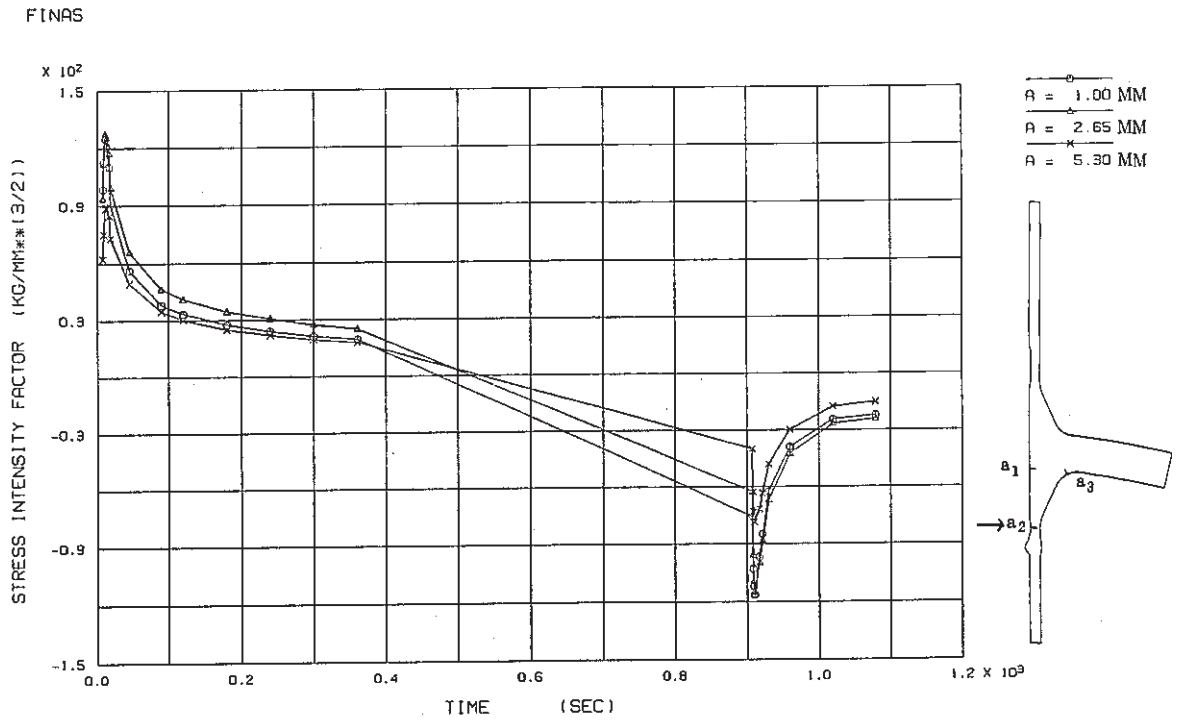


Fig. 3.2-2(3) History of Stress Intensity Factor for Inlet Nozzle, crack a₂

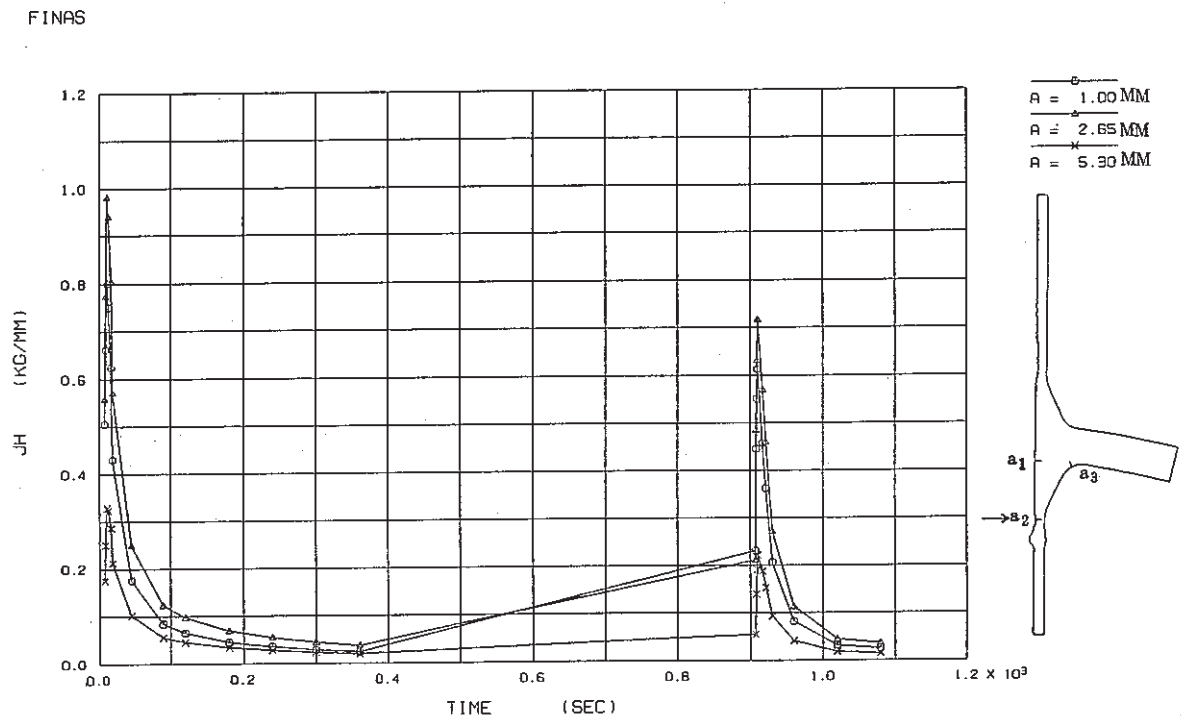


Fig. 3.2-2(4) History of \hat{J} -Integral for Inlet Nozzle, crack a₂

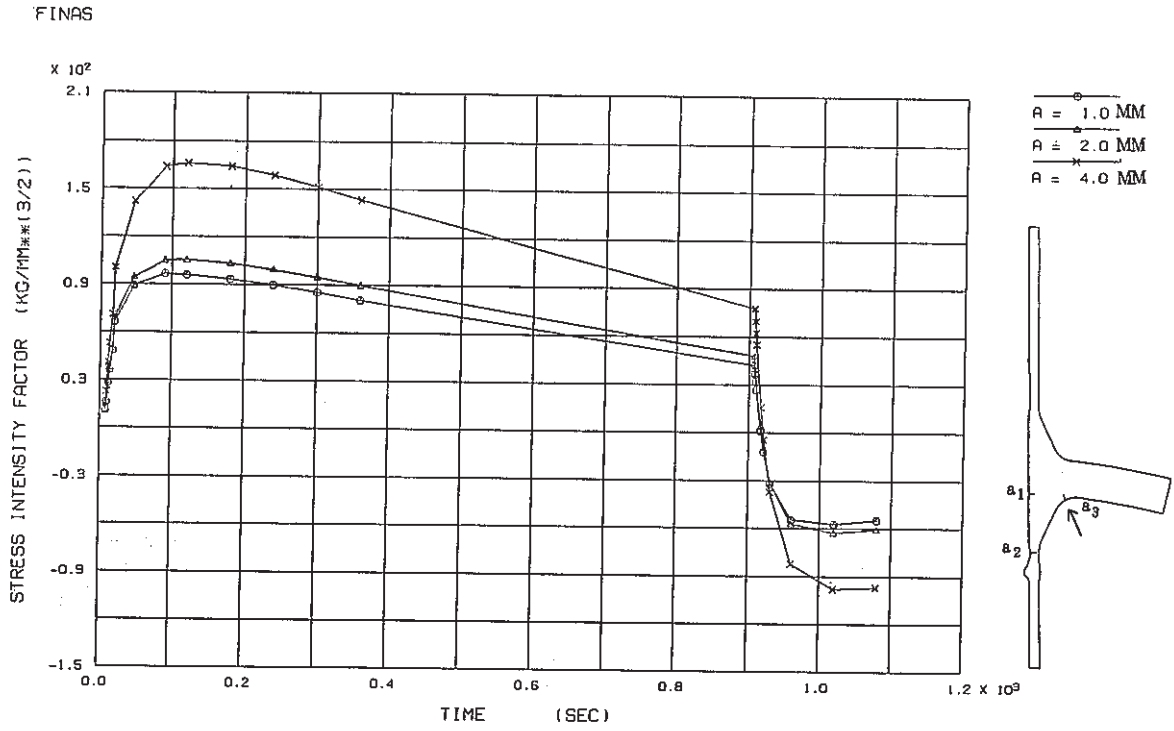


Fig. 3.2-2(5) History of Stress Intensity Factor for Inlet Nozzle, crack a₃

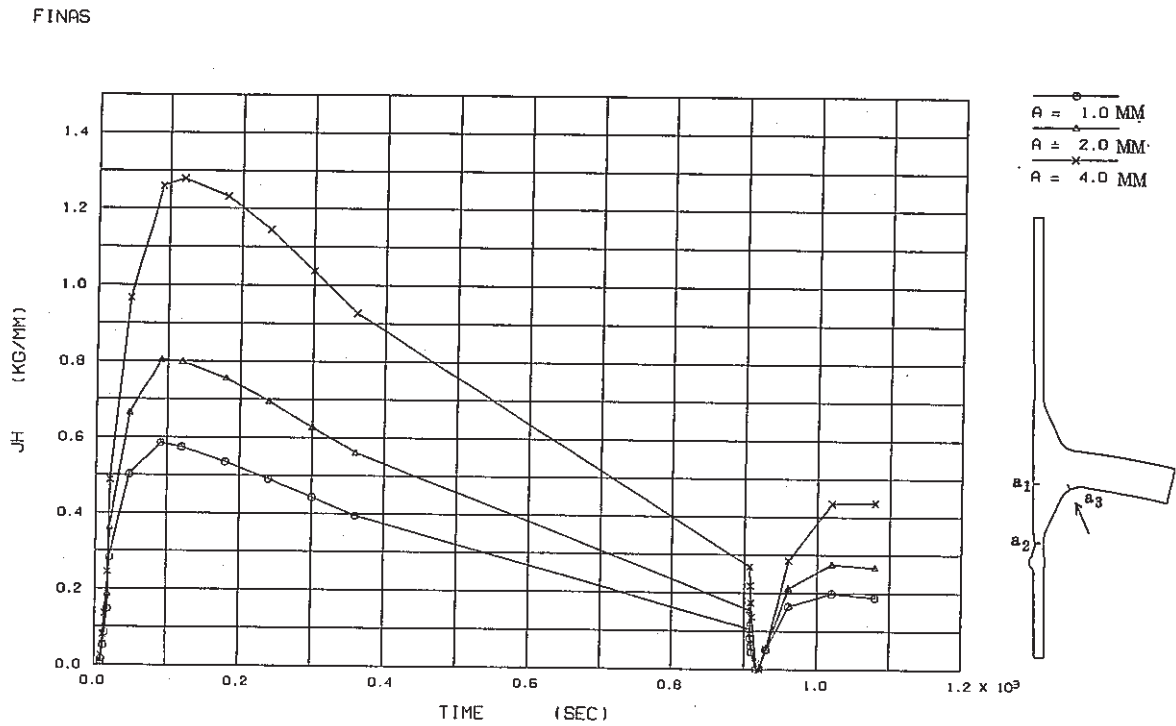


Fig. 3.2-2(6) History of \hat{J} -Integral for Inlet Nozzle, crack a₃

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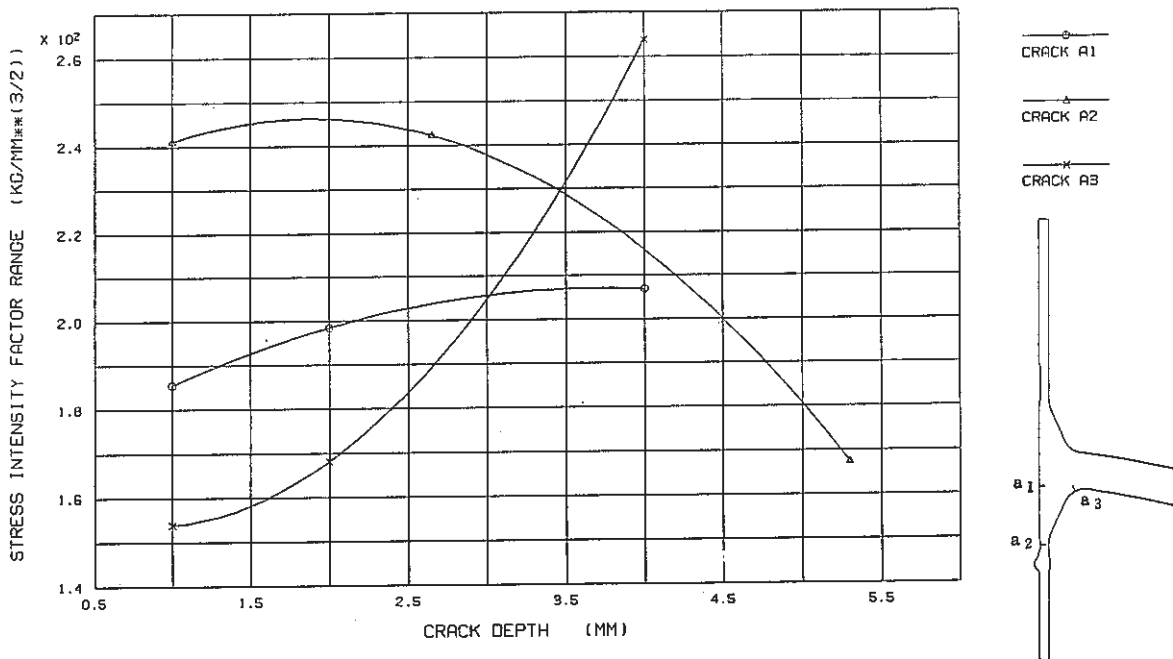


Fig. 3.2-2(7) Relation between Stress Intensity Factor Range and Crack Depth for Inlet Nozzle

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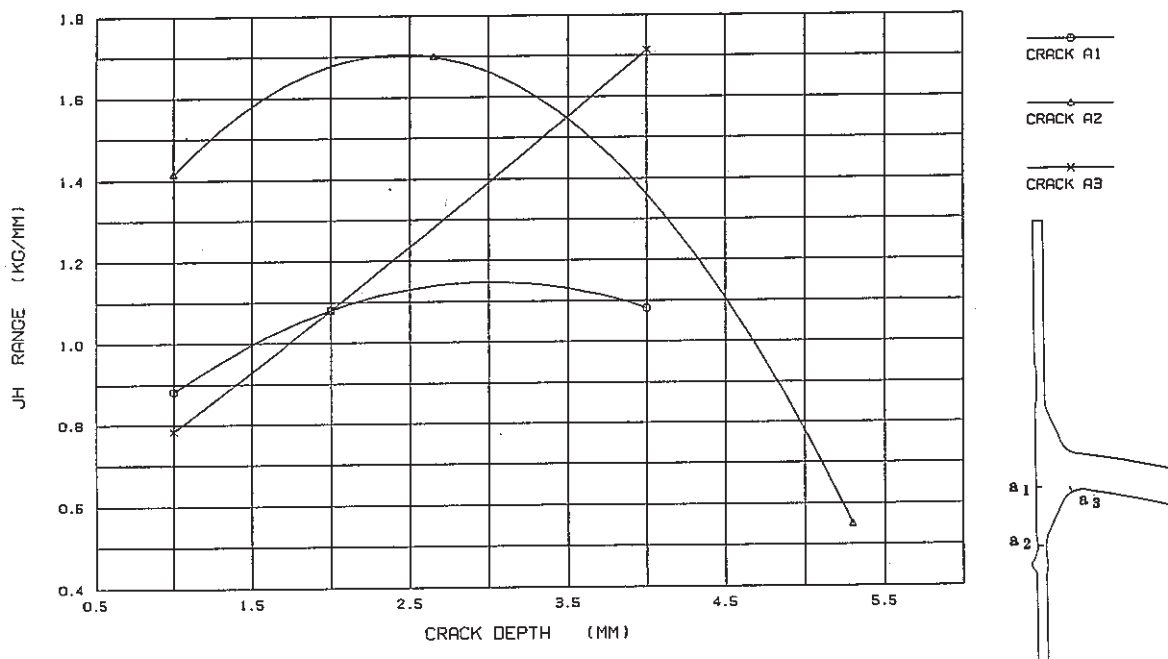


Fig. 3.2-2(8) Relation between \hat{J} -Integral Range and Crack Depth for Inlet Nozzle

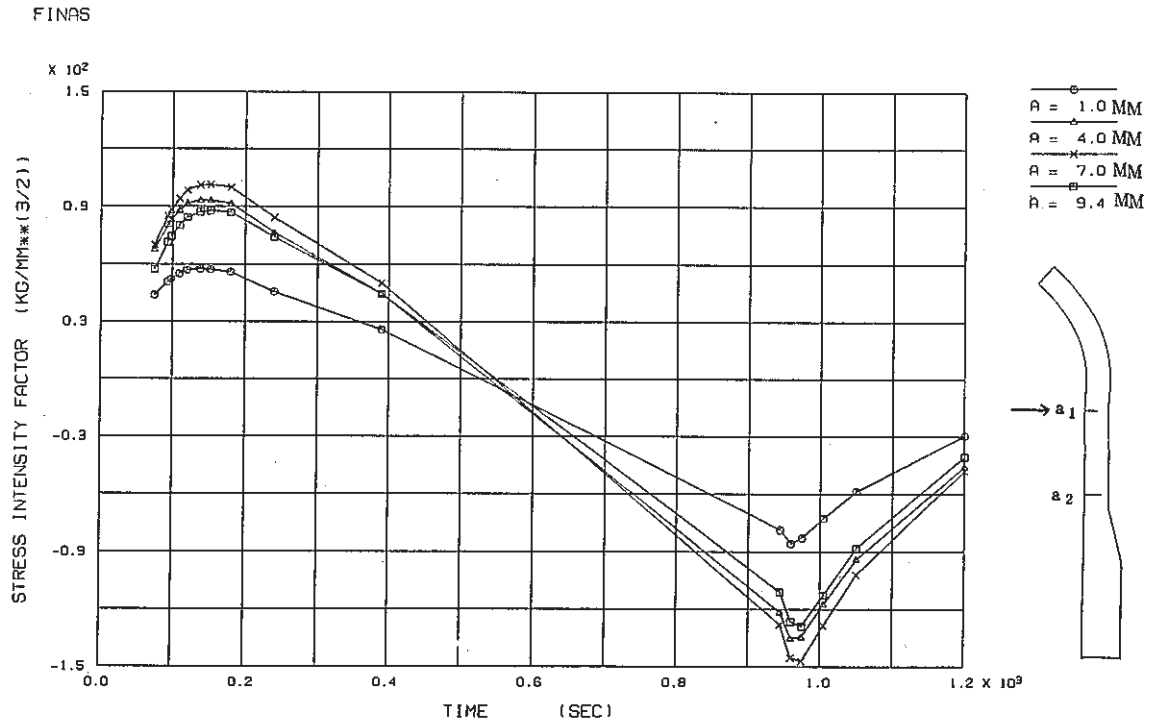


Fig. 3.2-3(1) History of Stress Intensity Factor for Thinning Portion, crack a_1

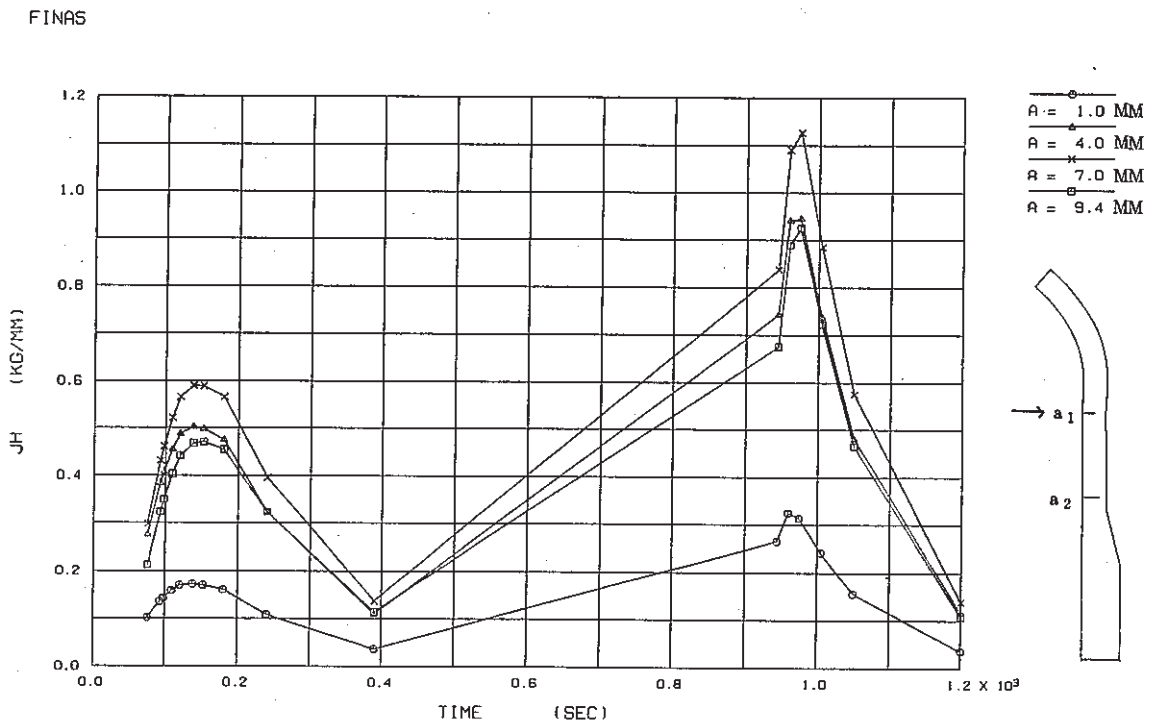


Fig. 3.2-3(2) History of \hat{J} -Integral for Thinning Portion, crack a_1

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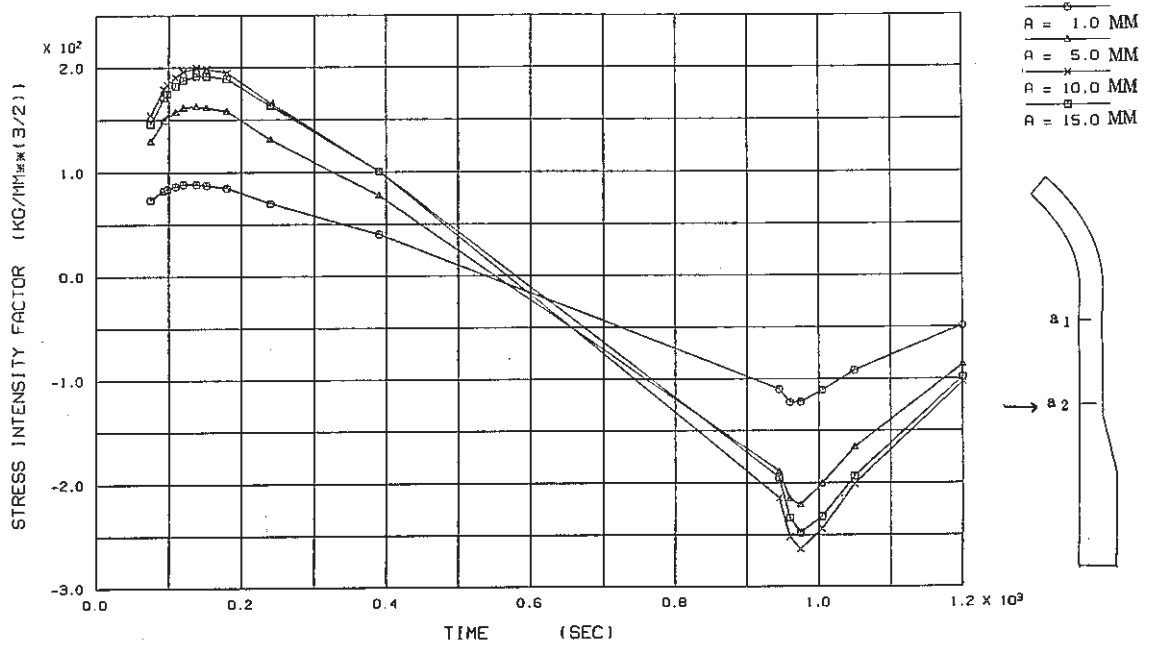


Fig. 3.2-3(3) History of Stress Intensity Factor for Thinning Portion, crack a₂

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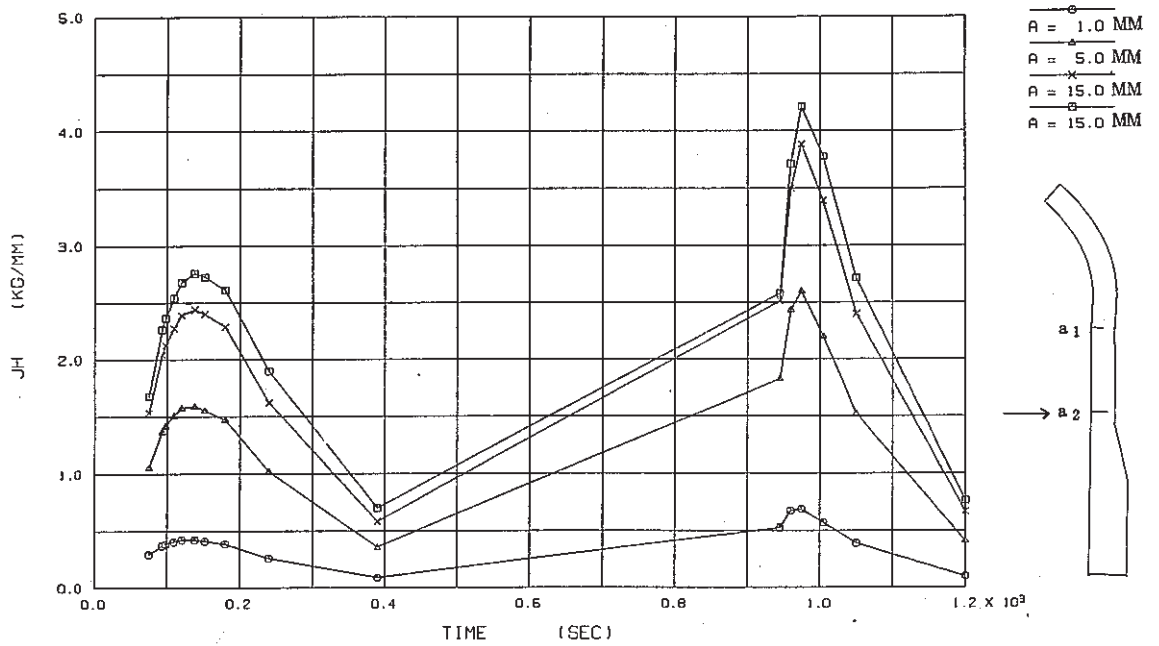


Fig. 3.2-3(4) History of \hat{J} -Integral for Thinning Portion, crack a₂

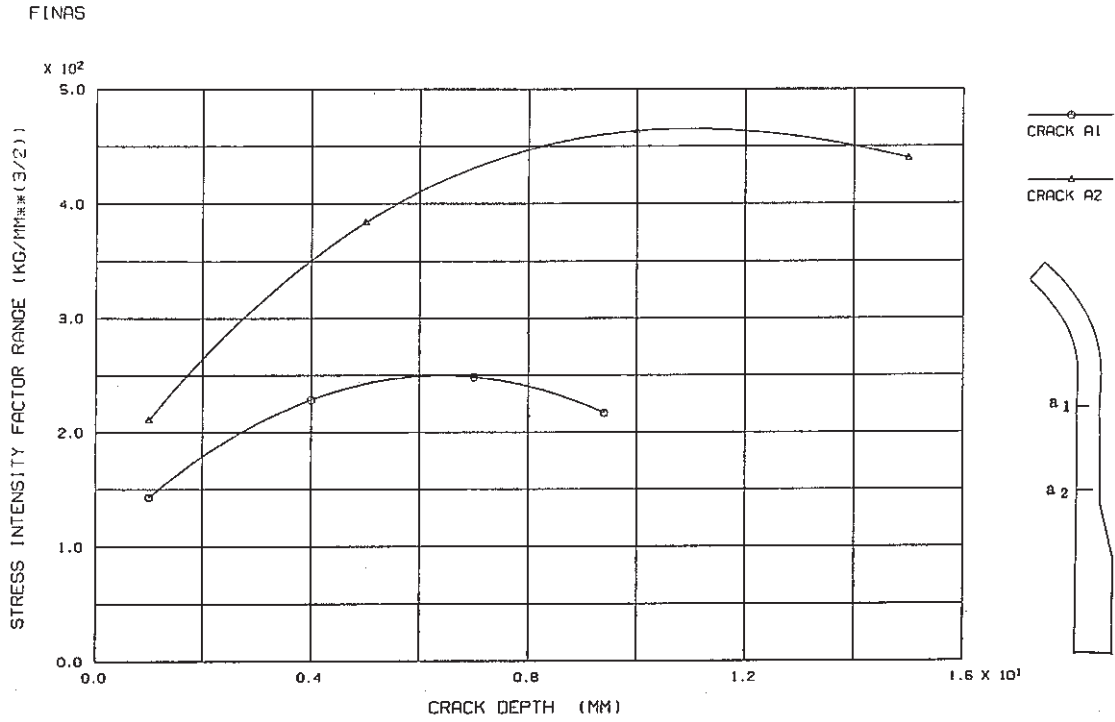


Fig. 3.2-3(5) Relation between Stress Intensity Factor Range and Crack Depth for Thinning Portion

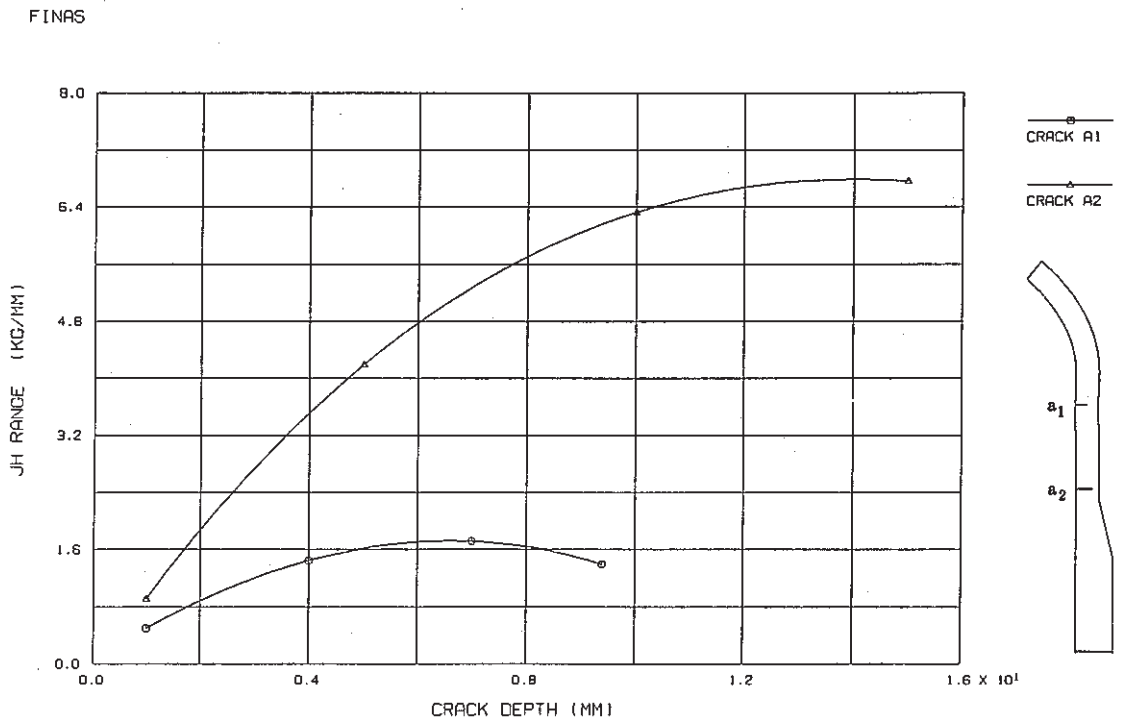


Fig. 3.2-3(6) Relation between \hat{J} -Integral Range and Crack Depth for Thinning Portion

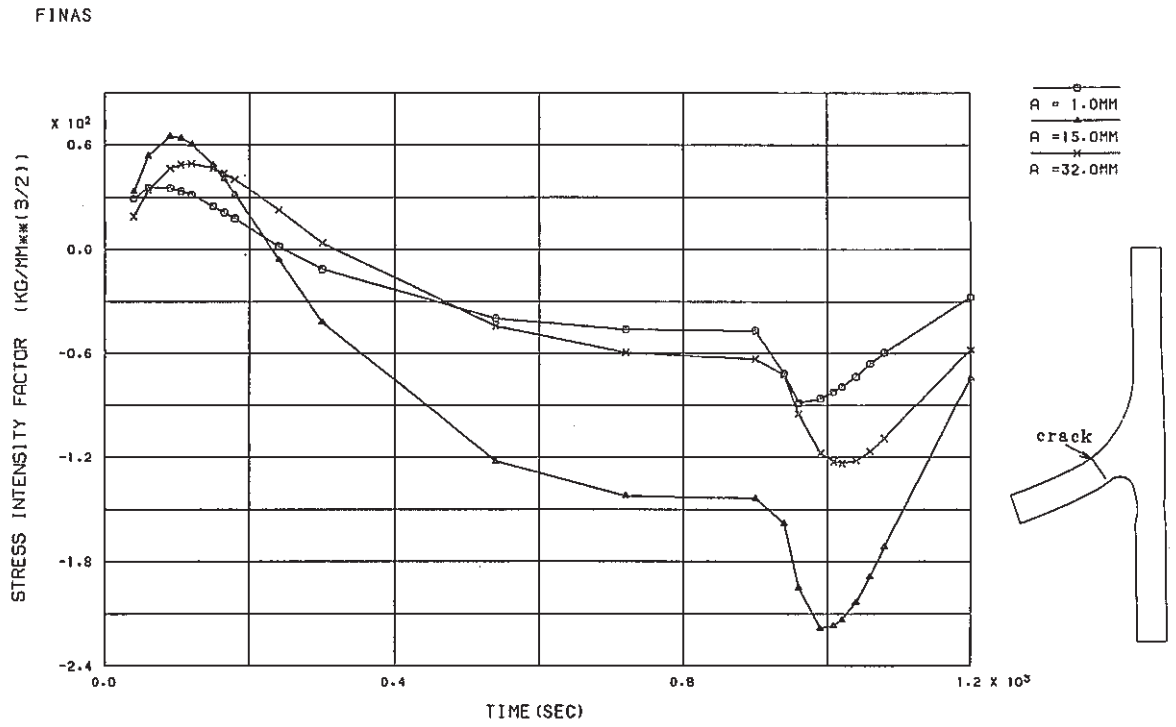


Fig. 3.2-4(1) History of Stress Intensity Factor for Conical-Bottom Head

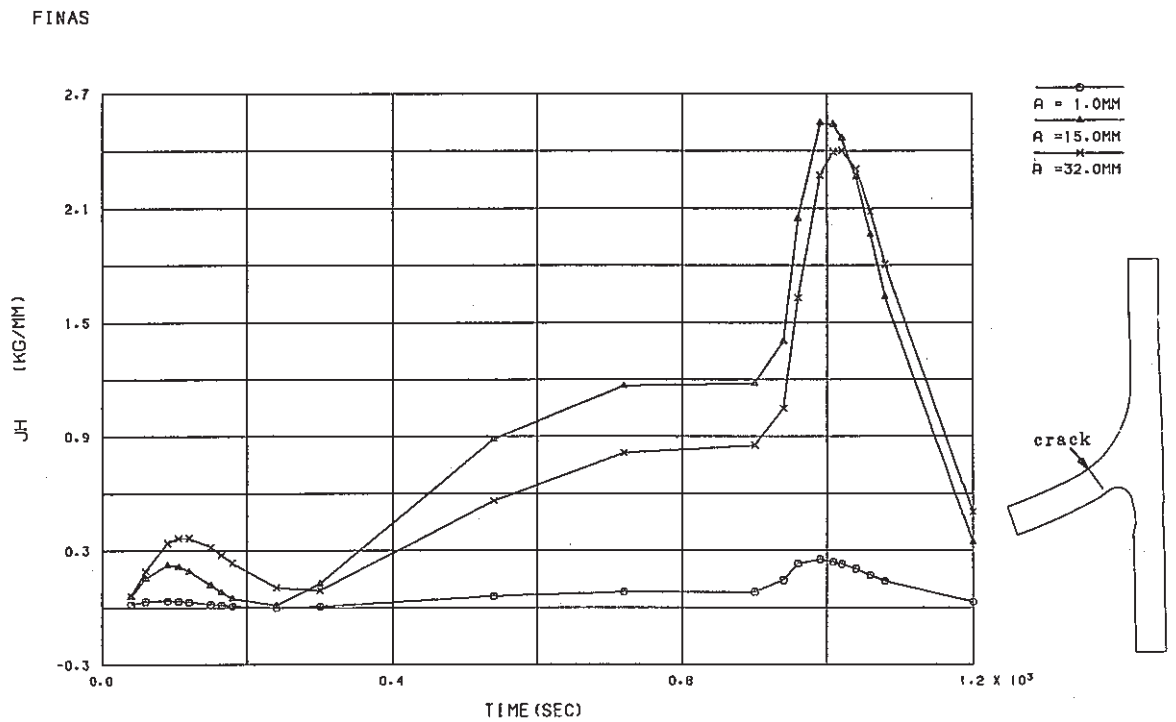


Fig. 3.2-4(2) History of \hat{J} -Integral for Conical-Bottom Head

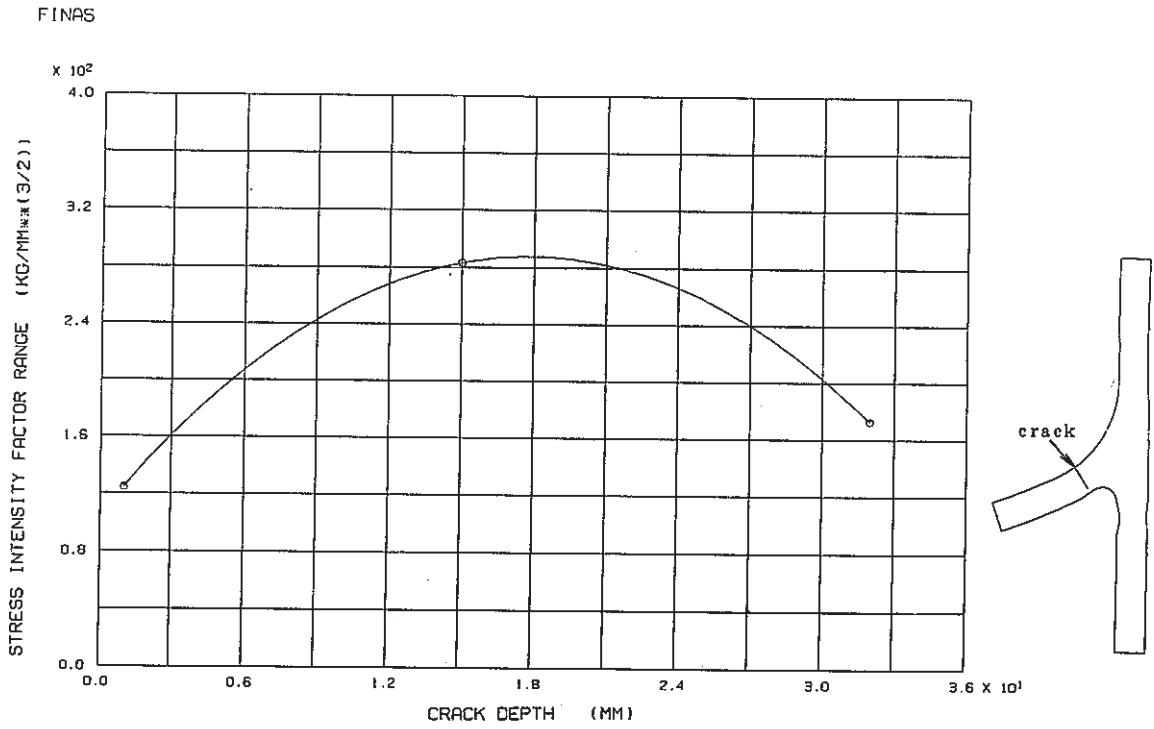


Fig. 3.2-4(3) Relation between Stress Intensity Factor Range and Crack Depth for Conical-Bottom Head

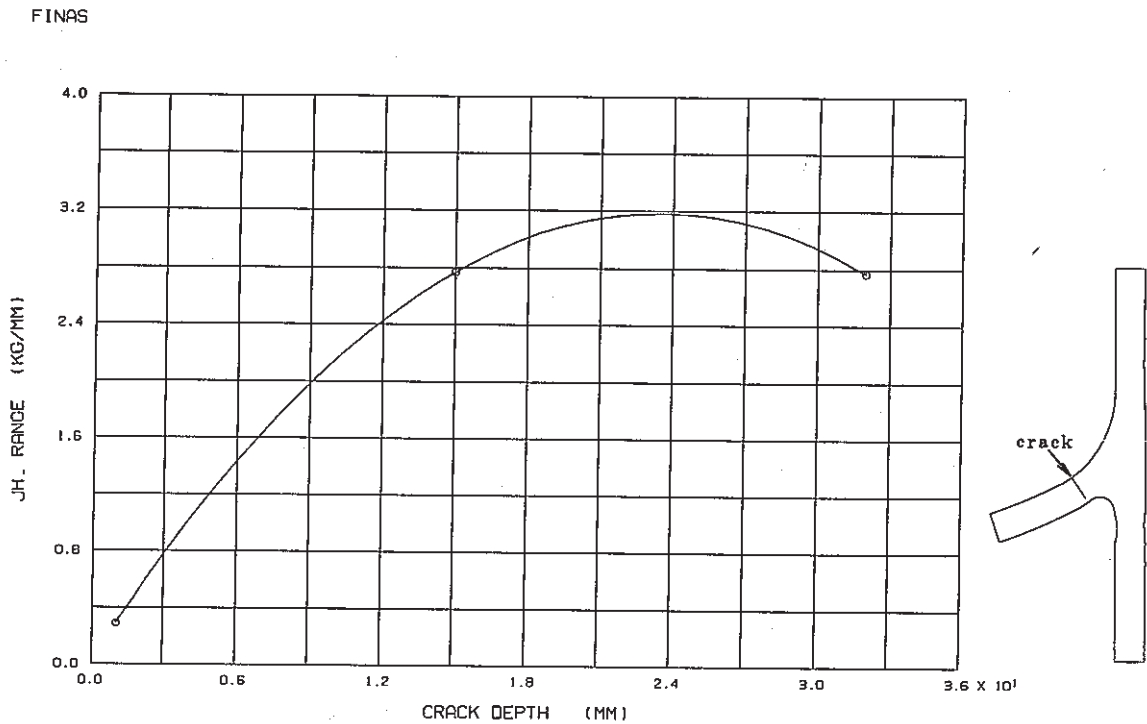


Fig. 3.2-4(4) Relation between \hat{J} -Integral Range and Crack Depth for Conical-Bottom Head

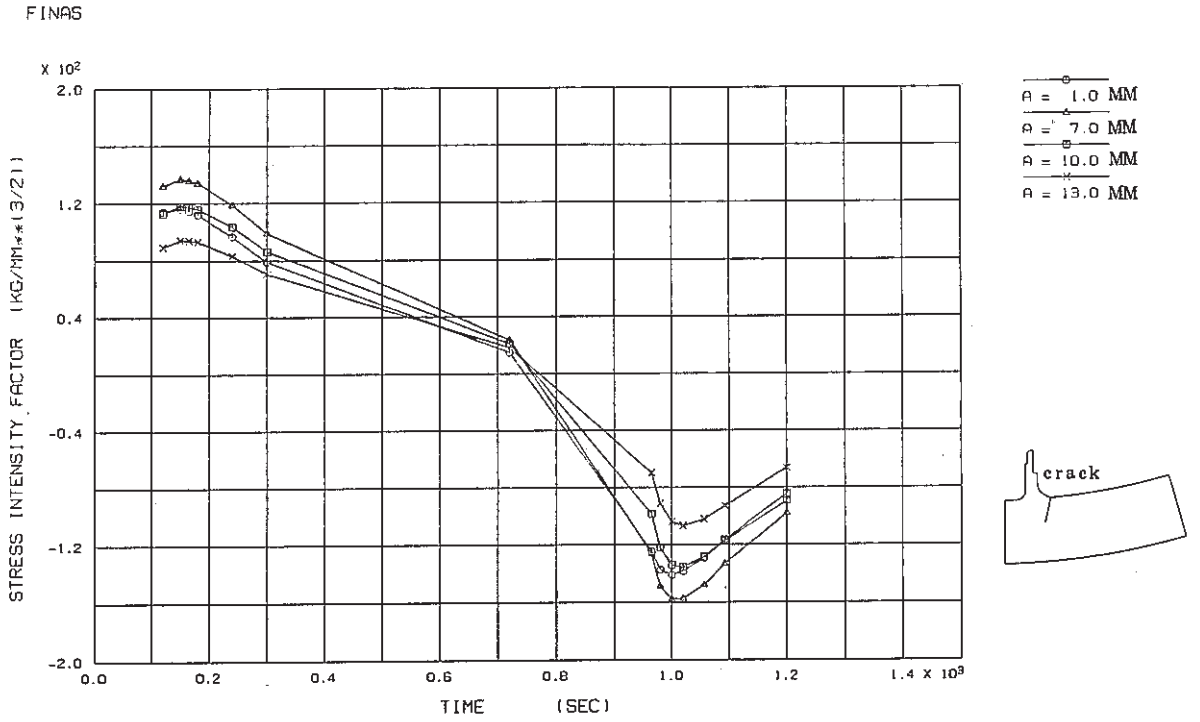


Fig. 3.2-5(1) History of Stress Intensity Factor for Stud Bolt

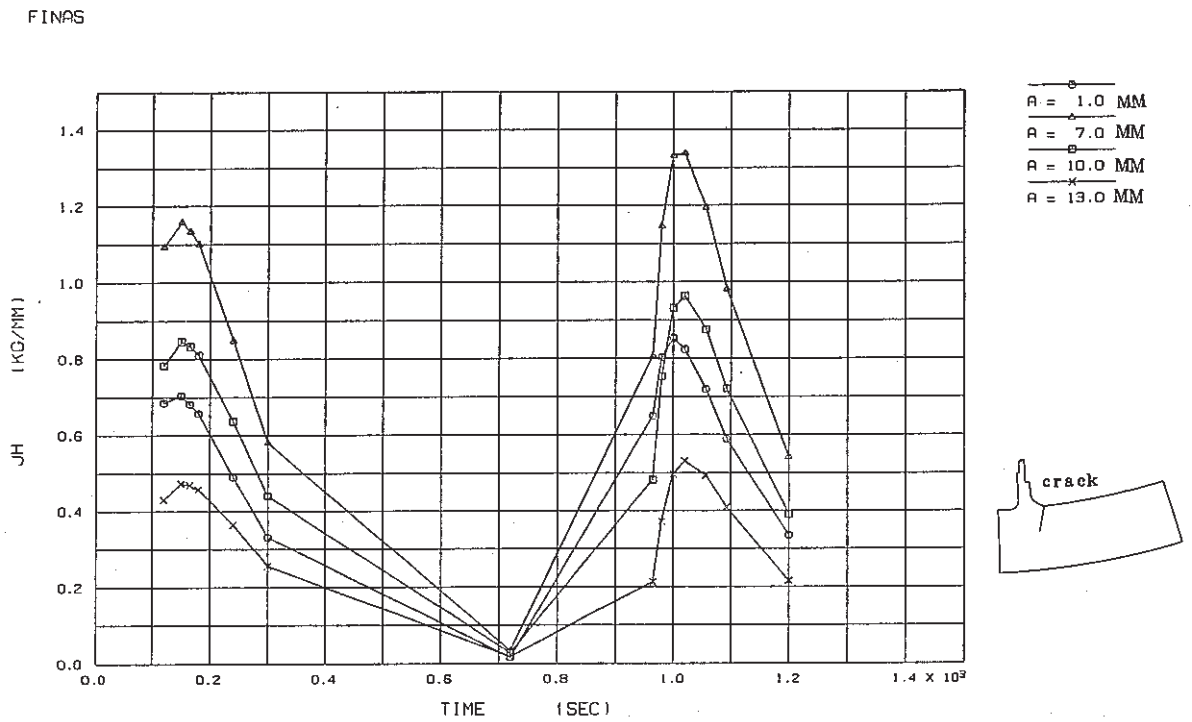


Fig. 3.2-5(2) History of \hat{J} -Integral for Stud Bolt

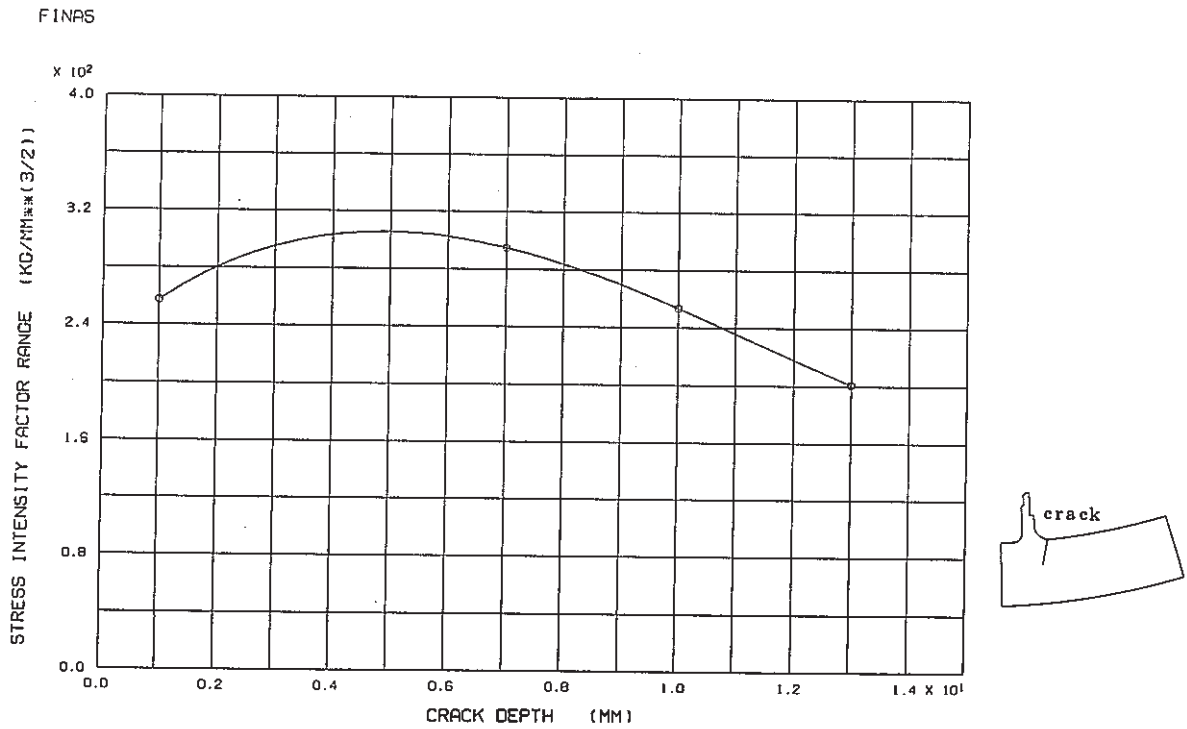


Fig. 3.2-5(3) Relation between Stress Intensity Factor Range and Crack Depth for Stud Bolt

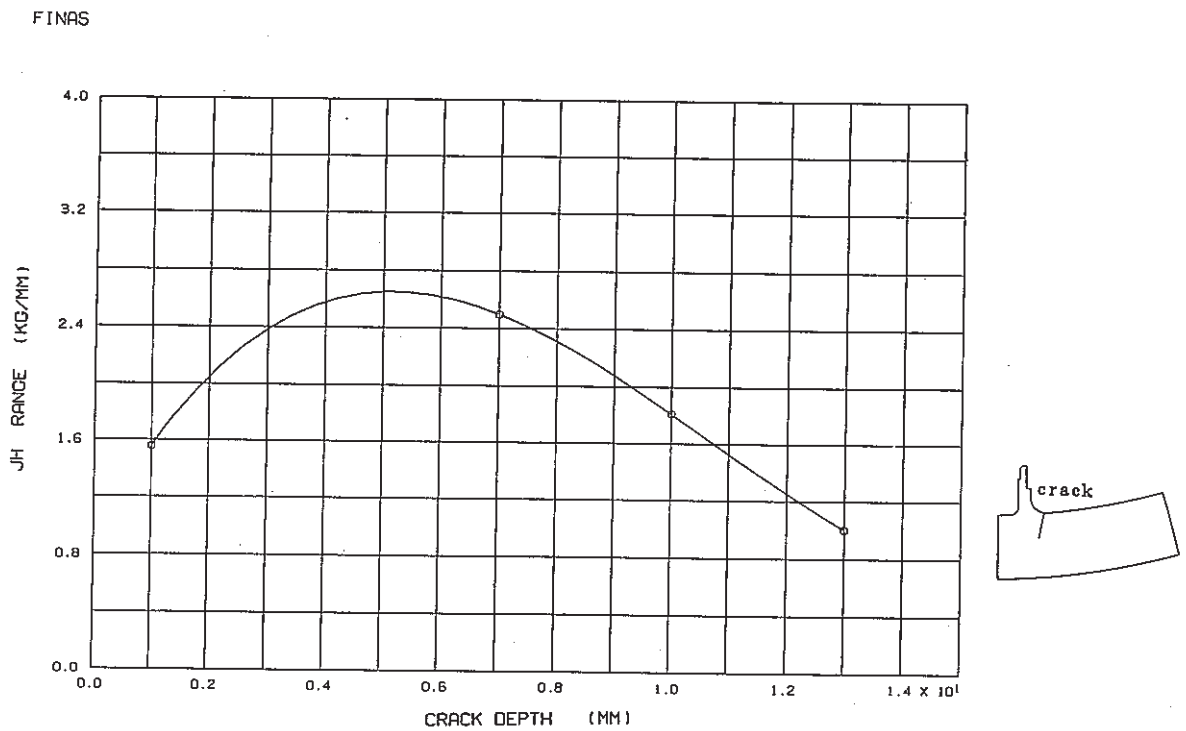


Fig. 3.2-5(4) Relation between \hat{J} -Integral Range and Crack Depth for Stud Bolt

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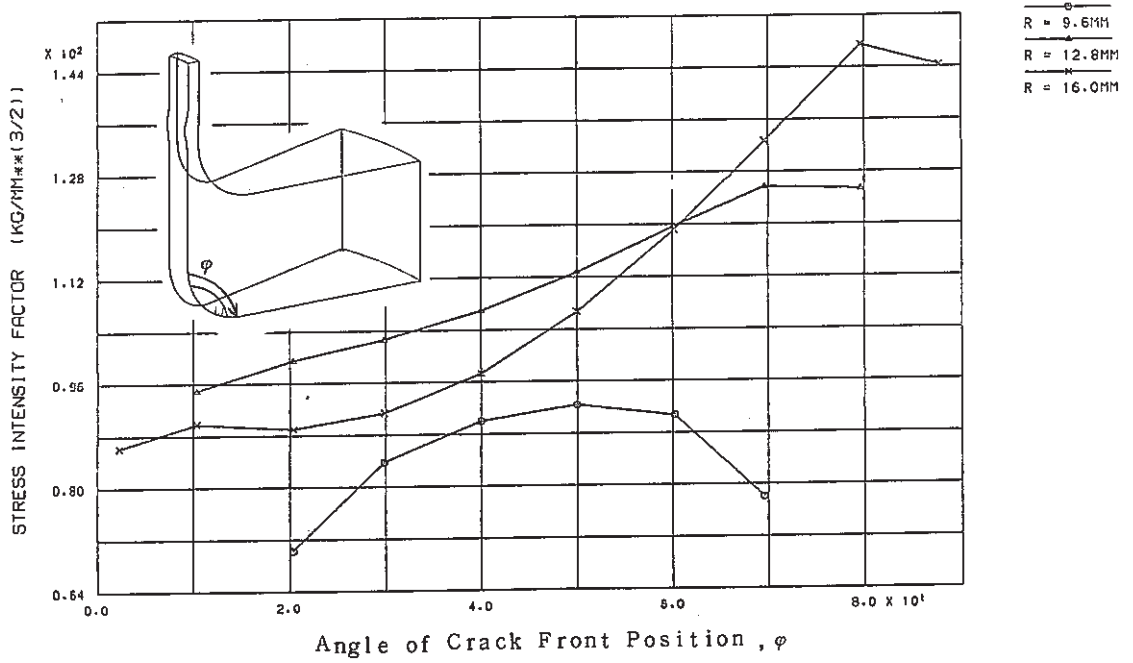


Fig. 3.2-6(1) K_I Distribution along Crack Front at Cold Shock for Instrumental Nozzle

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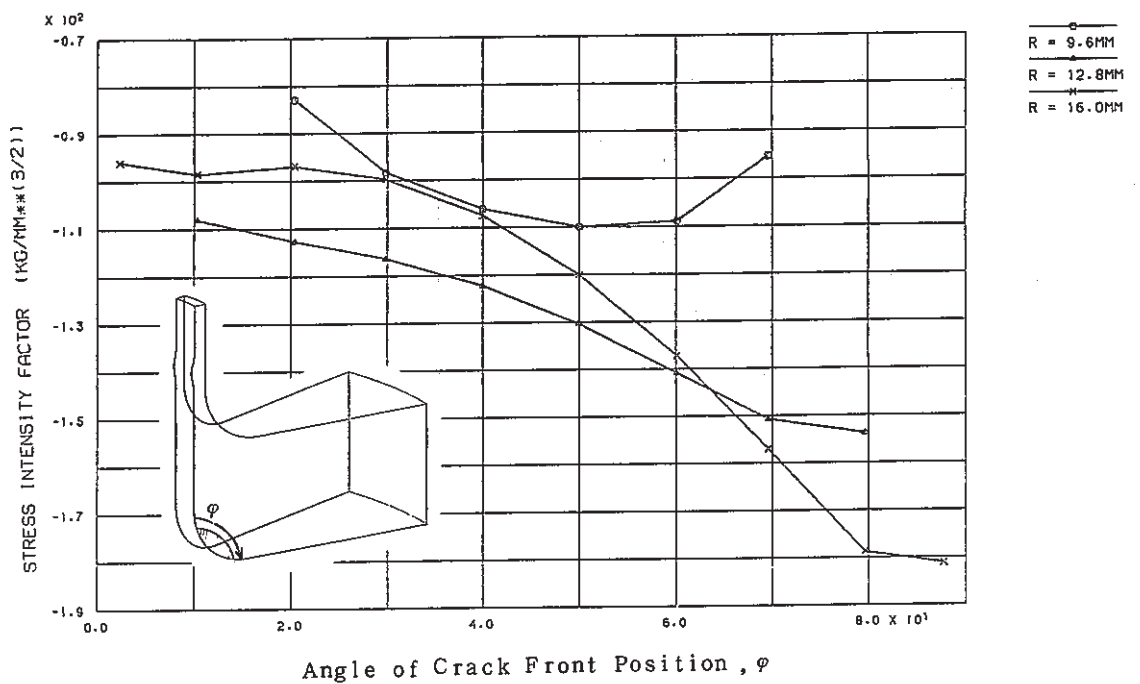


Fig. 3.2-6(2) K_I Distribution along Crack Front at Hot Shock for Instrumental Nozzle

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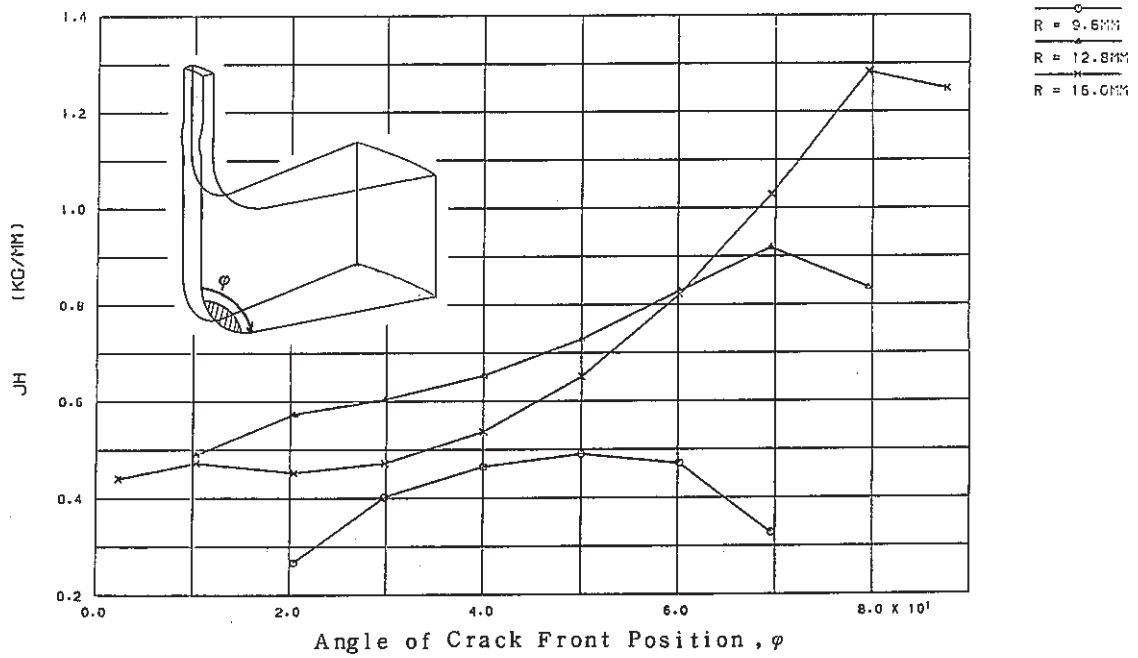


Fig. 3.2-6(3) \hat{J} -Integral Distribution along Crack Front at Cold Shock for Instrumental Nozzle

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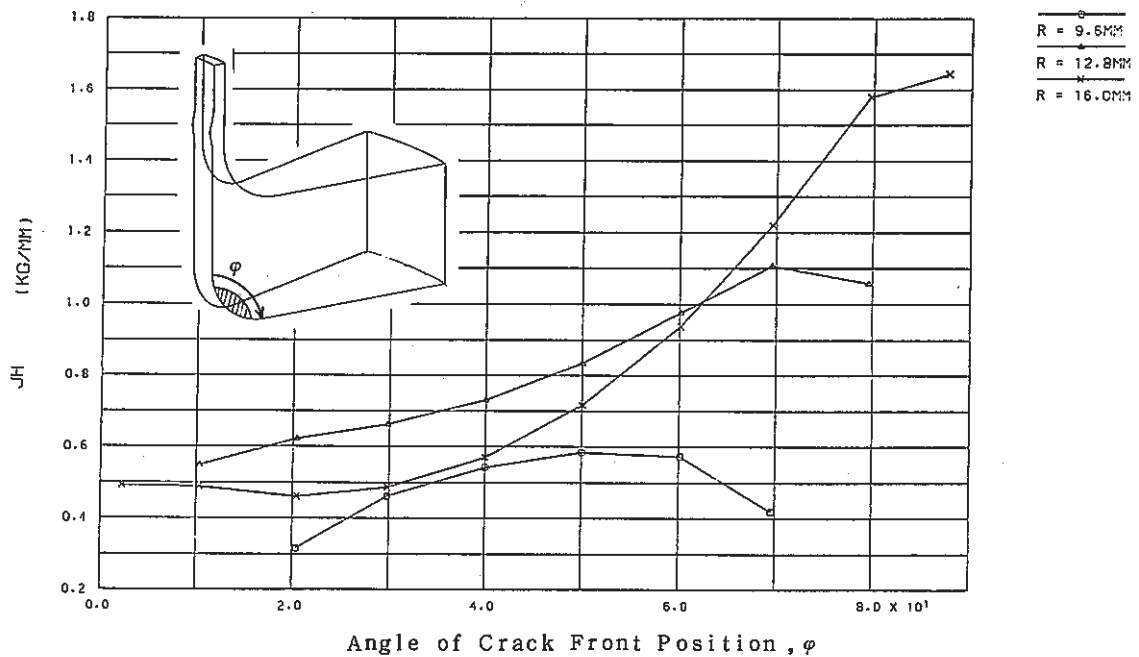


Fig. 3.2-6(4) \hat{J} -Integral Distribution along Crack Front at Hot Shock for Instrumental Nozzle

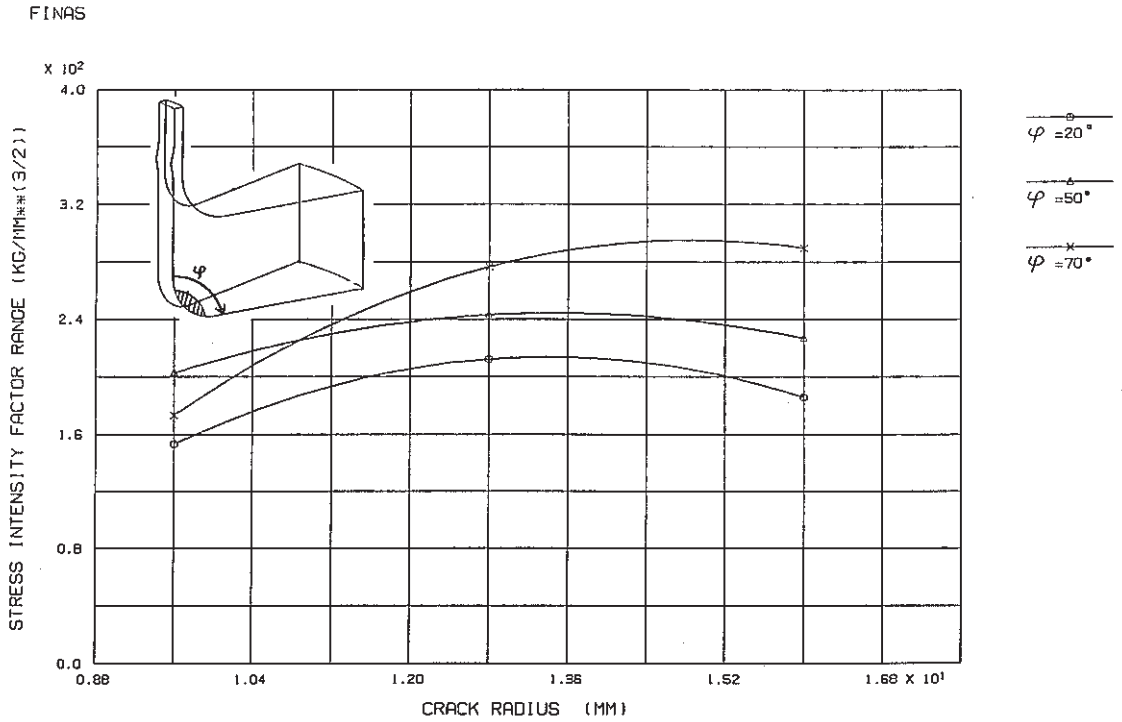


Fig. 3.2-6(5) Relation between Stress Intensity Factor Range and Crack Radius for Instrumental Nozzle

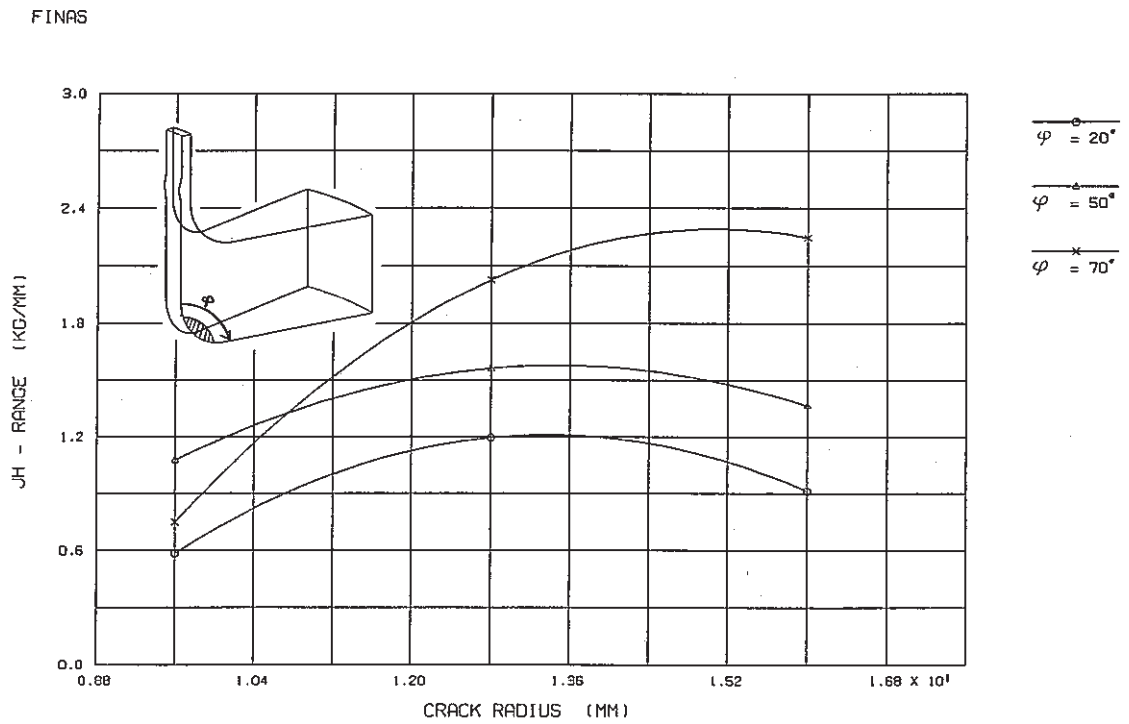


Fig. 3.2-6(6) Relation between \hat{J} -Integral Range and Crack Radius for Instrumental Nozzle

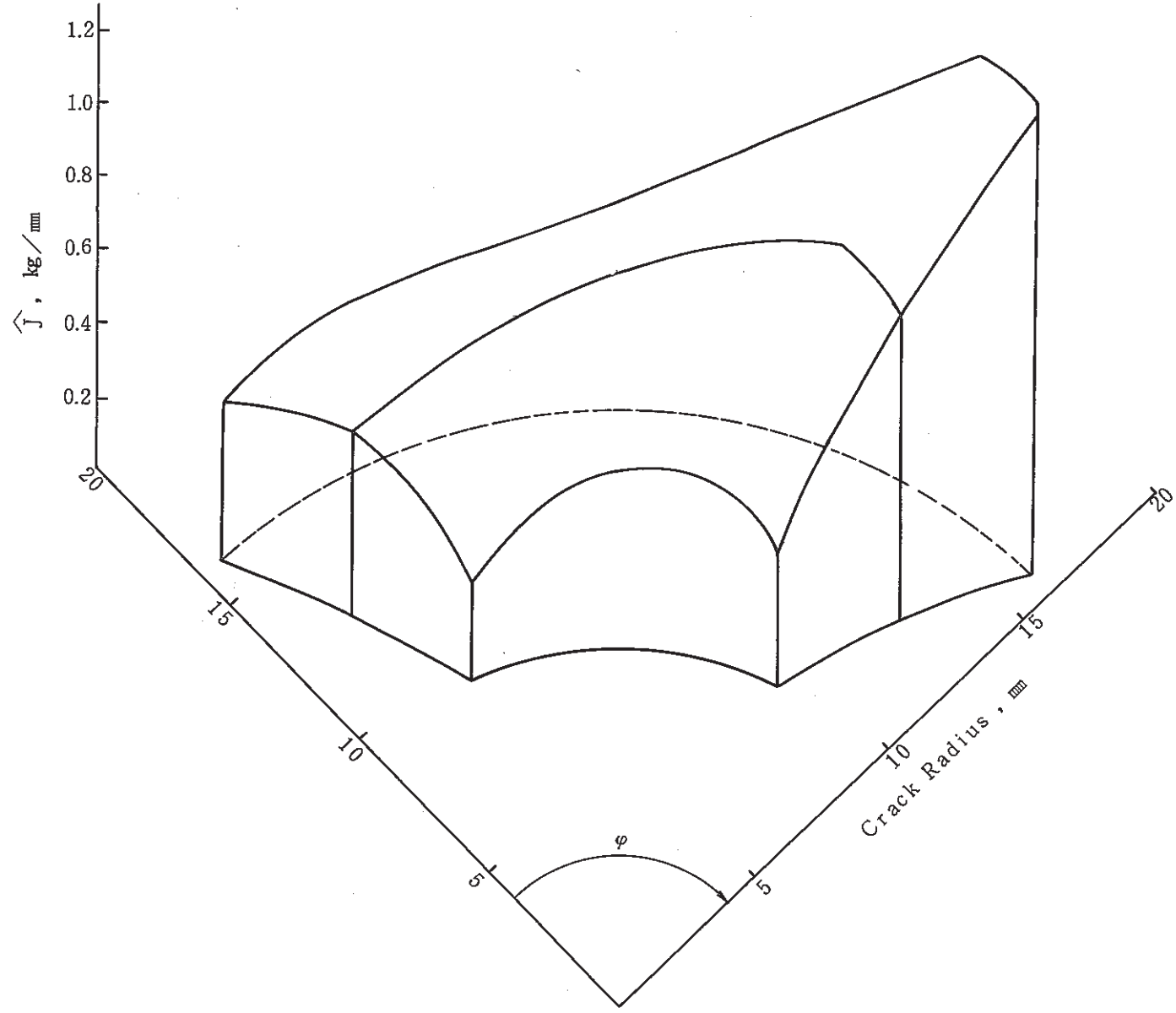


Fig. 3.2-6(7) \hat{J} -Integral at Cold Shock for Instrumental Nozzle

3.3 弾塑性解析に基づく破壊力学パラメータ解析

最終溶接部については、弾塑性解析を実施した。想定したき裂深さは1 mm、15 mm及び27 mmである。熱過渡荷重としてはコールドショック、ホットショック及びコールドショックの熱過渡荷重1.5サイクルを負荷した。弾塑性解析の詳細は附録Dに示す。また弾塑性解析結果より破壊力学パラメータを計算した。この詳細は附録Fに示す。

Fig. 3.3 - 1は、き裂深さごとの応力拡大係数 K_I の時間変化である。き裂深さが15 mmの場合が、この中で最大の履歴を示す。また、き裂深さが1 mmでは、1600 sec以降のホットショックにおいて、比較的大きな K_I (=約80 kg/mm^{3/2})が発生する。Fig. 3.3 - 2は、 \hat{J} 積分の時間変化である。この場合も、き裂深さ15 mmが最大の履歴を示す。しかしながらホットショックにおいて、 \hat{J} 積分は最大値を示した後、次のコールドショック開始までいずれのき裂も小さい値を示す。また、弾塑性解析においてORNL推奨の硬化則を用いているため、2回目のコールドショックの K_I 値及び \hat{J} 積分値が1回目のコールドショックのものより大きい。

Table 3.3 - 1に応力拡大係数範囲 ΔK_I と \hat{J} 積分範囲 $\Delta \hat{J}$ を示す。この結果より、き裂深さと $\Delta \hat{J}$ の関係を調べるとFig. 3.3 - 3, Fig. 3.3 - 4のようになる。き裂深さが約15 mmで K_I 値及び \hat{J} 値は最大を示しその後緩やかに減少している。

Fig. 3.3 - 5は、弾性解析及び弾塑性解析により計算した ΔK_I とき裂深さの関係である。弾塑性解析により計算した ΔK_I が、弾性解析により計算した ΔK_I を上回っている。き裂深さに対する ΔK_I の傾向は両者とも同じである。Fig. 3.3 - 6は、弾性解析及び弾塑性解析により計算した $\Delta \hat{J}$ とき裂深さの関係である。 $\Delta \hat{J}$ ではき裂1 mmを除いて、弾塑性解析により計算した $\Delta \hat{J}$ が弾性解析により計算した $\Delta \hat{J}$ を下回っているが、ほぼ同等である。また、弾塑性解析は、3つのき裂深さについて計算した $\Delta \hat{J}$ を近似した結果であり、弾性解析の傾向を考えると $\Delta \hat{J}$ のピークはき裂深さ10～15 mmであると思われる。

Fig. 3.3 - 7に ΔK_I が最大となるき裂深さは15 mmのモデルについての弾性解析により計算した K_I 値の時間変化を示す。弾塑性解析では、さらにコールドショック時が続いており、図中にこの2回目のコールドショック時の K_I 値を重ねてプロットした。応力拡大係数範囲 ΔK_I は、図中に示すようにコールド及びホットショック時における極値の差としたが、弾塑性解析では2回目のコールドショック時の最大の K_I 値とホットショック時の最小の K_I 値の差とした。この結果、弾塑性解析から計算した $\Delta K_{I,IN-ELASTIC}$ は、弾性解析から計算した $\Delta K_{I,ELASTIC}$ より大きい値となった。Fig. 3.3 - 8は同じく \hat{J} 値について示したものである。コールドショック時では、弾塑性解析から計算の \hat{J} 値が大きく、ホットショック時では弾性解析から計算の \hat{J} 値が大きい。この結果 $\Delta \hat{J}$ (= $J_{COLD,MAX} + \hat{J}_{HOT,MAX}$)は、Fig. 3.3 - 6に示すように弾塑性解析から計算の $\Delta \hat{J}_{INELASTIC}$ が、弾性解析から計算の $\Delta \hat{J}_{ELASTIC}$ より小さいか、ほぼ同等の値を示した。

Table 3.3.1 K_I and \hat{J} -Integral Range for Finally Welded Joint (In-Elastic Analysis)

Crack Depth (mm)	Stress Intensity Factor, $\text{kg}/\text{mm}^{3/2}$			\hat{J} -Integral, kg/mm		
	$K_{I, \text{HOT, max}}$	$K_{I, \text{COLD, max}}$	ΔK_I	$\hat{J}_{\text{HOT, max}}$	$\hat{J}_{\text{COLD, max}}$	$\Delta \hat{J}$
1	-9 4.2 (940sec)	1 9 0.0 (7351sec)	2 8 4.2	0.8 9 3 5 (990sec)	0.8 1 5 8 (7352sec)	1.7 0 9 3
15	-2 7 5.1 (1005sec)	2 0 6.9 (7352sec)	4 8 2.0	2.4 2 2 2 (1005sec)	2.5 6 4 5 (7352sec)	4.9 8 6 7
27	-2 4 0.1 (1020sec)	1 6 3.2 (7374sec)	4 0 3.3	1.7 3 9 1 (1020sec)	1.1 0 2 3 (7352sec)	2.8 4 1 4

FINAS

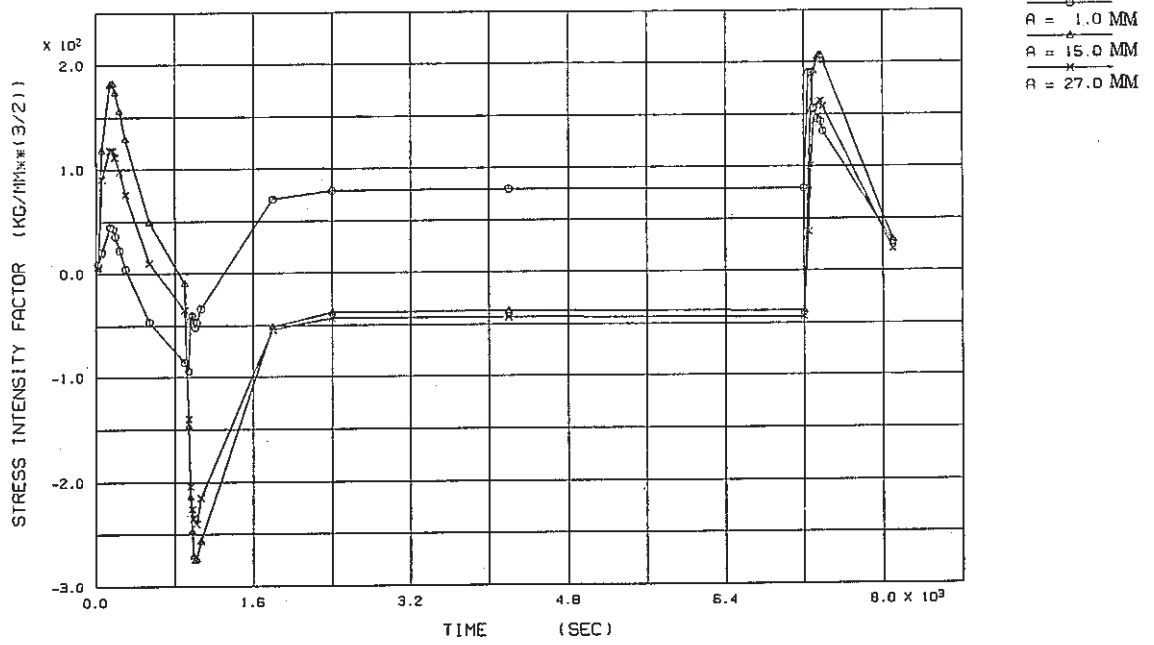


Fig. 3.3-1 History of Stress Intensity Factor for Finally Welded Joint (In-Elastic Analysis)

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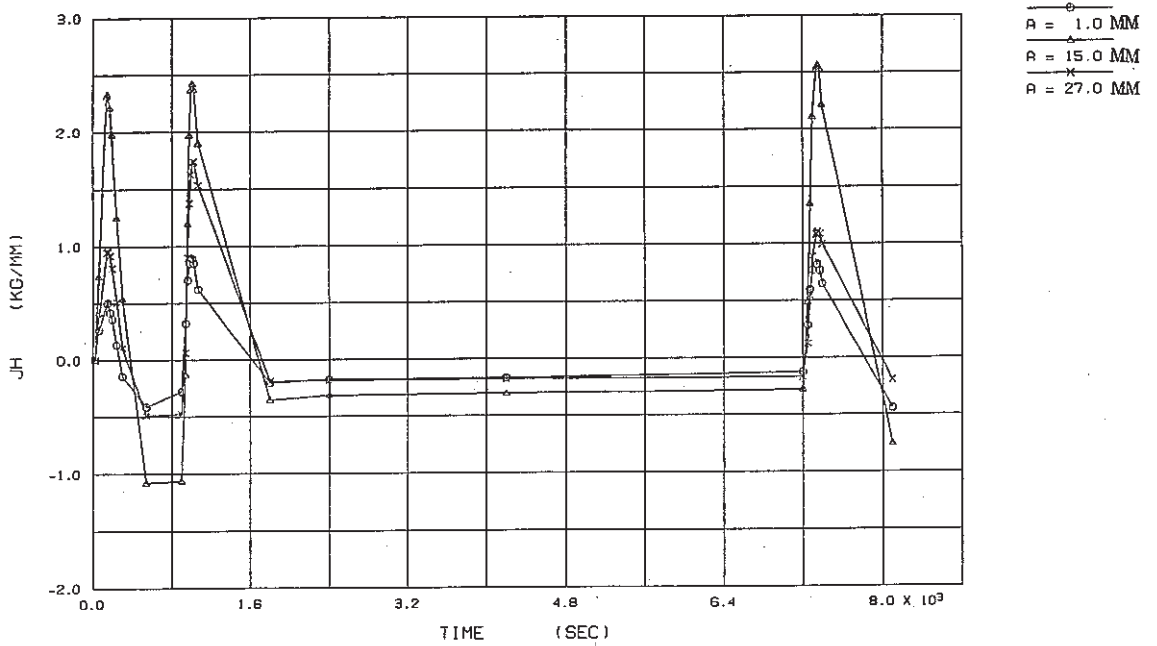


Fig. 3.3-2 History of \hat{J} -Integral for Finally Wlded Joint (In-Elastic Analysis)

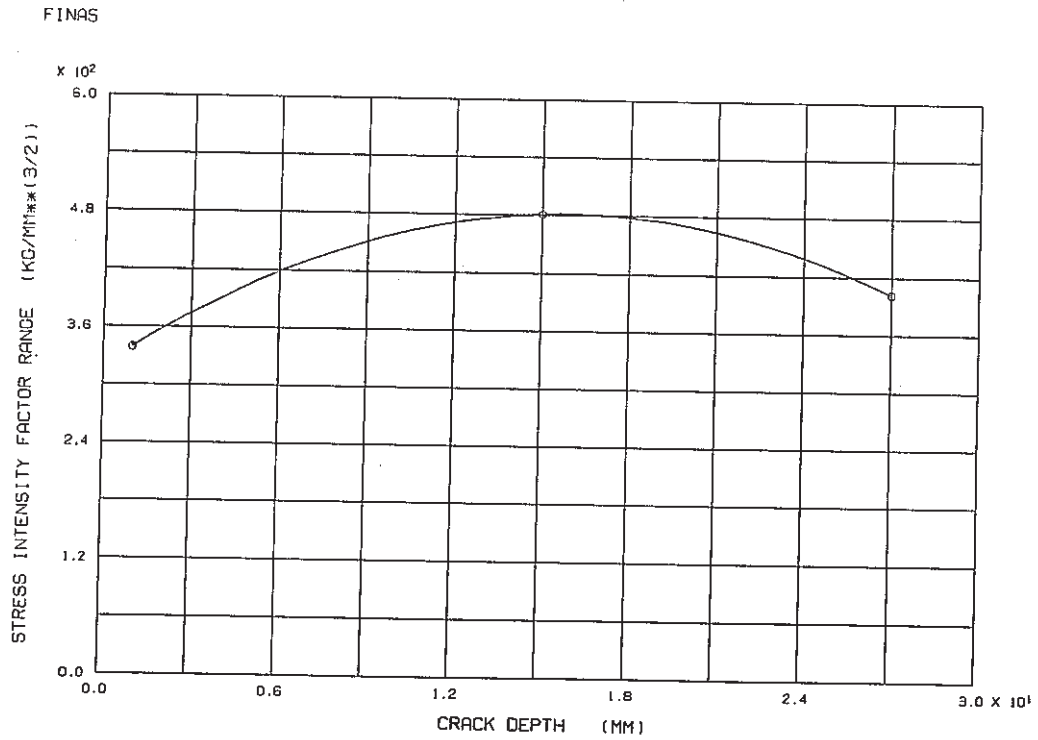


Fig. 3.3-3 Relation between Stress Intensity Factor Range and Crack Depth for Finally Welded Joint (In-Elastic Analysis)

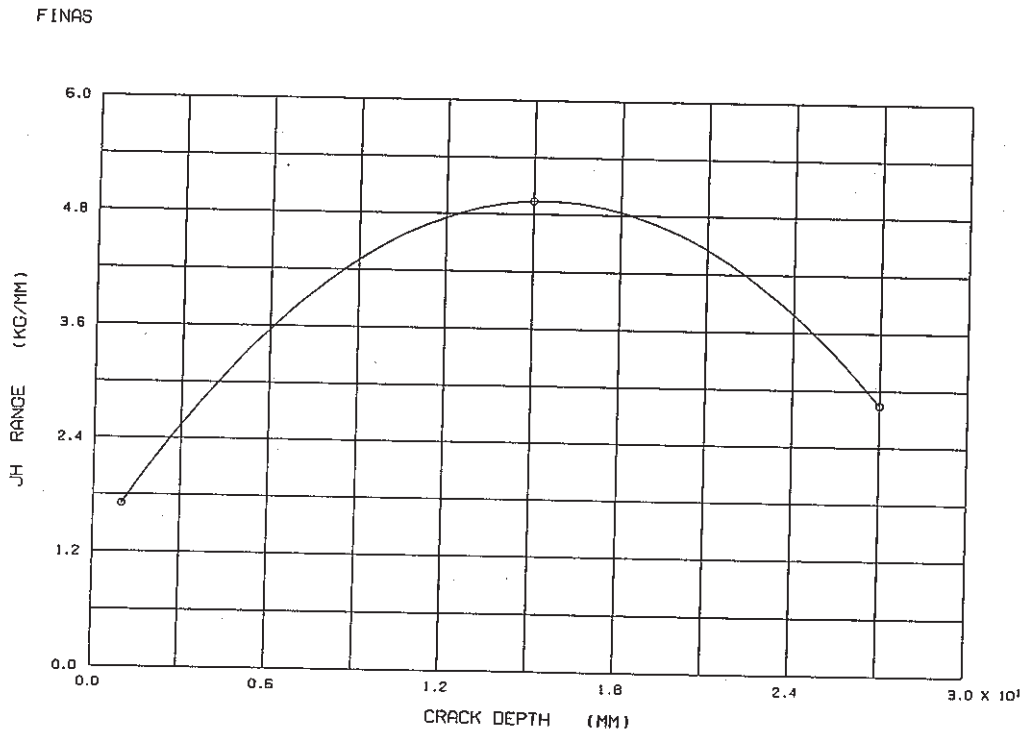


Fig. 3.3-4 Relation between \hat{J} -Integral Range and Crack Depth for Finally Welded Joint (In-Elastic Analysis)

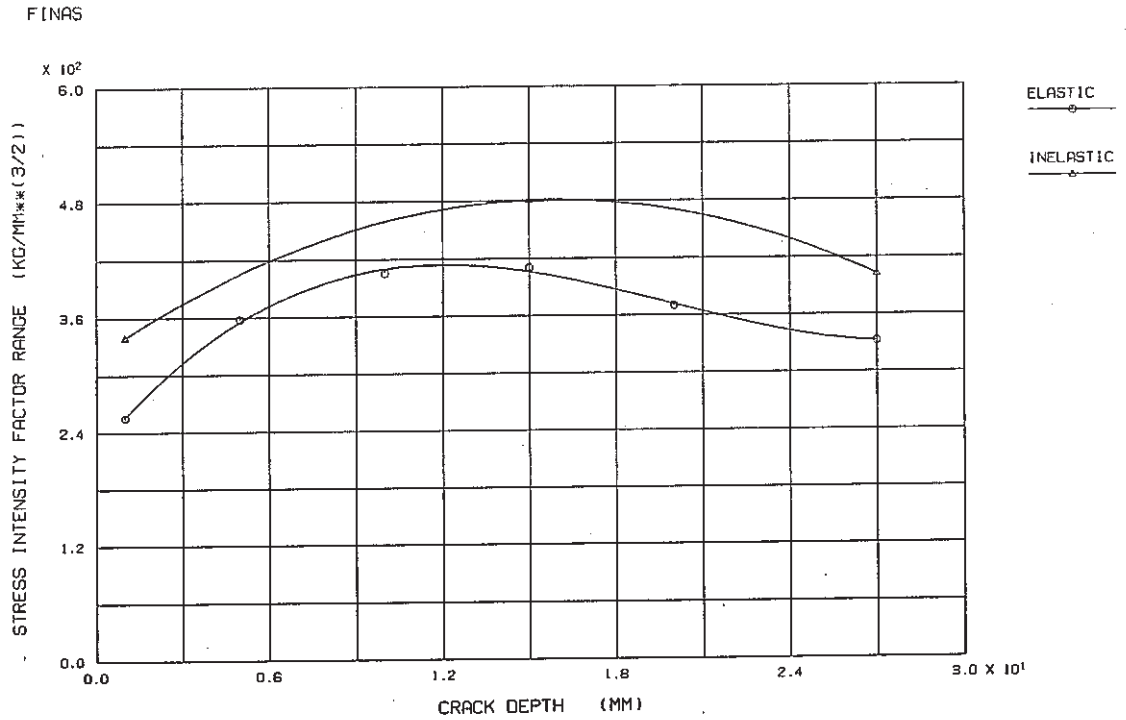


Fig. 3.3-5 Comparison of Stress Intensity Factor Range calculated from Elastic and In-Elastic Analysis for Finally Welded Joint

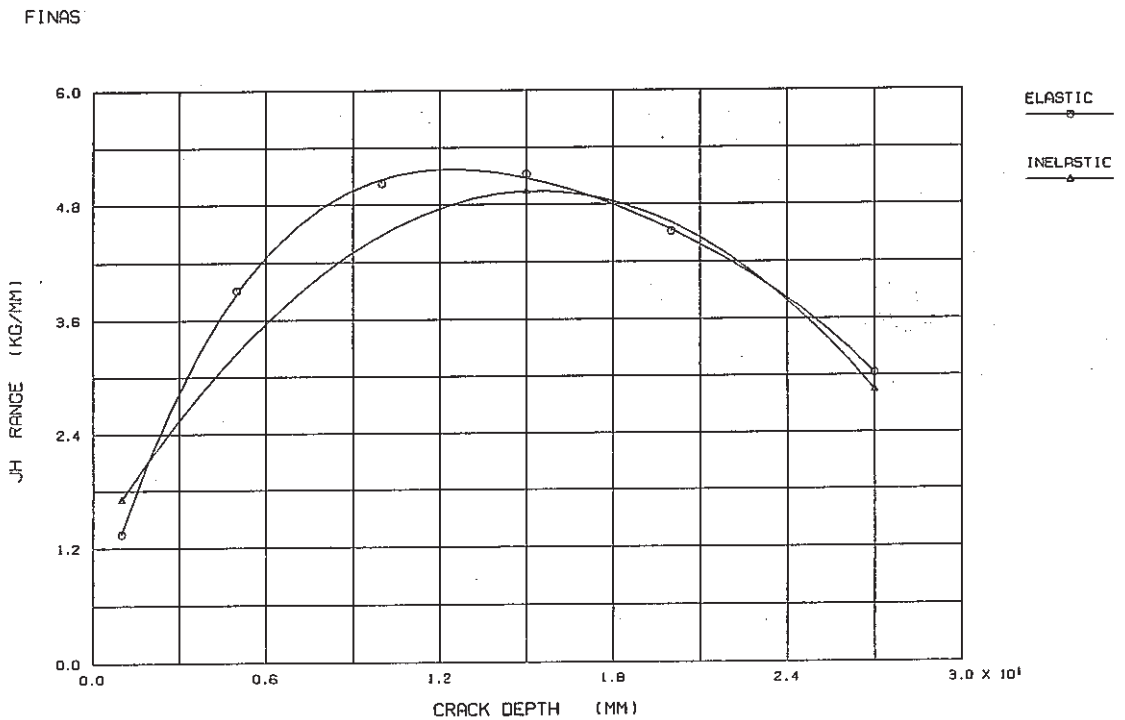


Fig. 3.3-6 Comparison of \hat{J} -Integral Range calculated from Elastic and In-Elastic Analysis for Finally Welded Joint

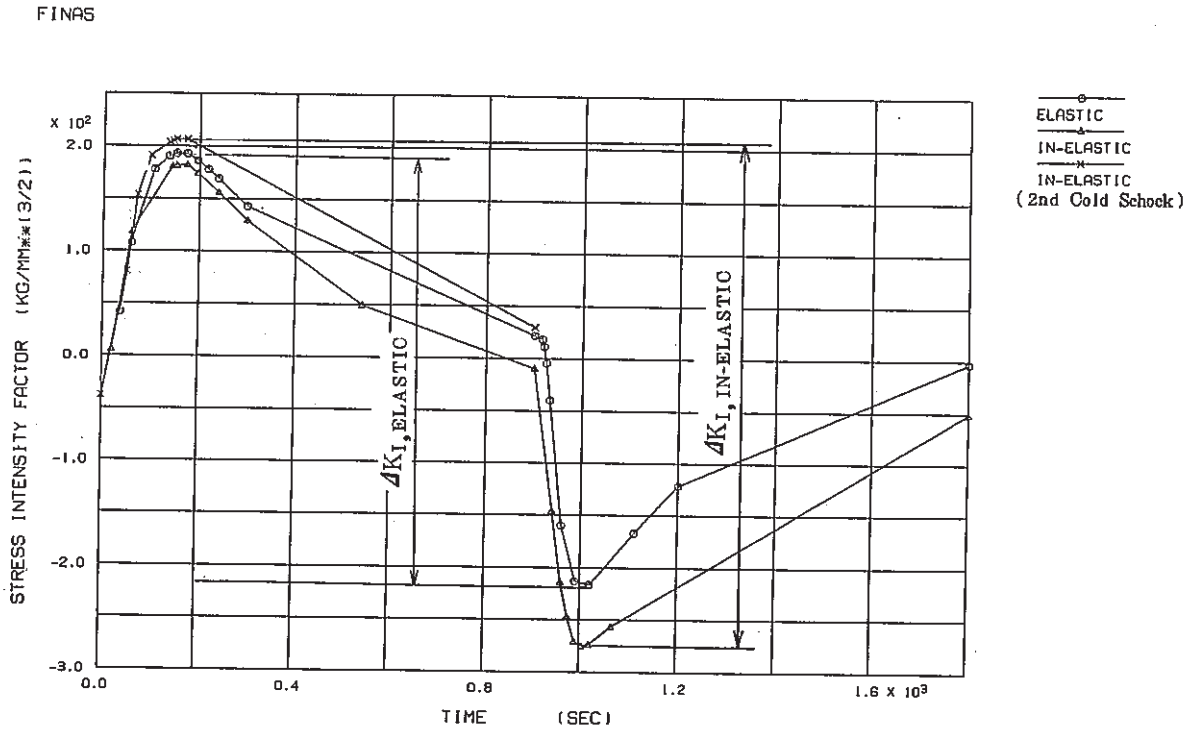


Fig. 3.3-7 Comparison of Stress Intensity Factor History calculated from Elastic and In-Elastic Analysis for Finally Welded Joint

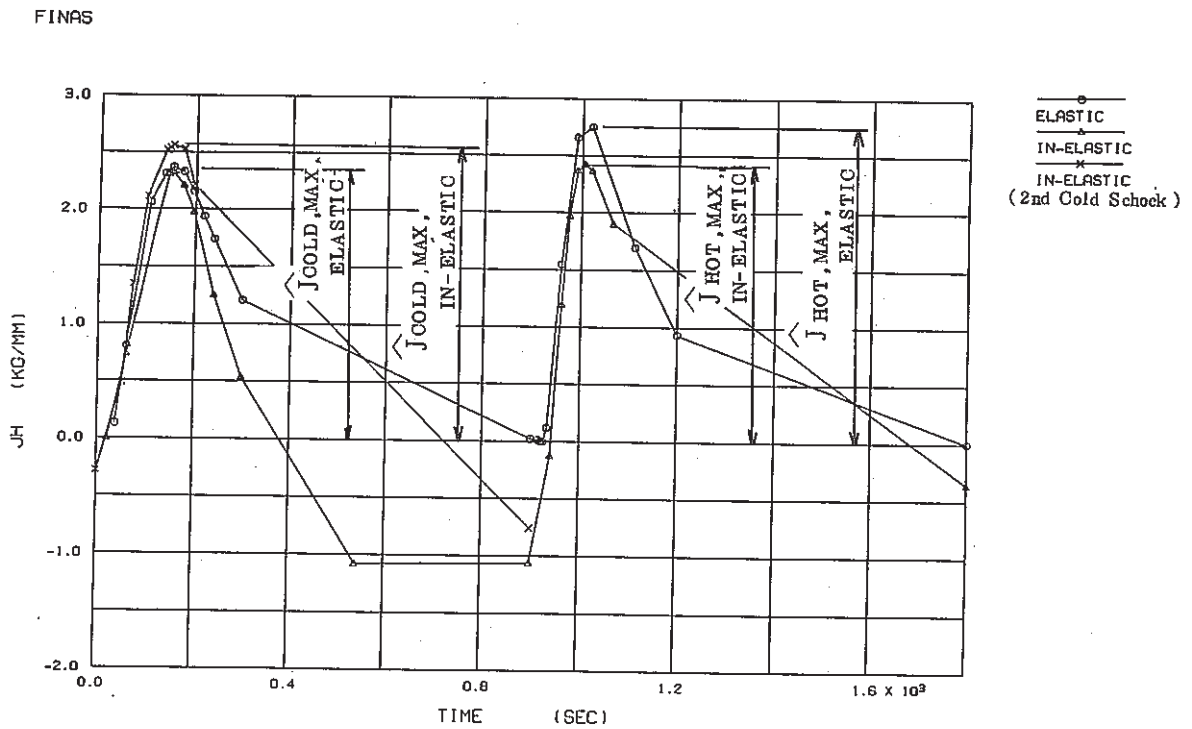


Fig. 3.3-8 Comparison of \hat{J} -Integral History calculated from Elastic and In-Elastic Analysis for Finally Welded Joint

4. き裂進展挙動

原子炉容器モデルに発生したき裂のうち12ヶ所について熱応力解析及び破壊力学パラメータ解析を実施し、き裂深さと ΔK_I 、 $\Delta \hat{J}$ の関係を求めた。この解析結果と材料試験結果(da/dn vs ΔK_I 、 $\Delta \hat{J}$)を比較することにより、想定したき裂の進展に要した繰返し回数 N_P を算出する。このき裂進展の評価手法をFig. 4-1に示す。

破面観察(第3報、熱過渡強度試験)によれば、ほとんどの破面が粒界割れを呈しており、またストライエーションが認められる場所は非常に少なくき裂進展速度は定かではなかった。さらに、各き裂の初生に要した繰返し数 N_C も定かでない。最終溶接部付近に取付のアカースティックエミッションによれば(第7報、UT及びAEによる探傷)、700~800サイクルでイベント数及びリングダウン数の増加がみられ、これ以降の熱過渡がき裂進展に関与していると思われる。このように、試験結果と解析結果の直接的比較はできないが、解析結果に基づいてき裂進展挙動の検討を行う。

4.1 破壊力学に基づくき裂進展速度の推定

熱過渡荷重が繰返し負荷される場合の供試体内表面及びき裂先端の弾塑性解析による応力履歴は、附録D(Fig.D-1)に記したようにFig. 4.1-1のようになる。このようにコールドショックの開始からホットショックの圧縮側最大応力が発生して、応力が正に戻るまでの期間が疲労き裂進展であり、その後継続するホットショックのうち定常的な応力が発生する期間ではクリープき裂の進展を考慮すれば良いと思われる。従って、熱過渡1サイクル当りのき裂進展量は次のように表わされる。

$$da/dN = (da/dN)_{fatigue} + \int_{t_1}^{t_2} (da/dt)_{creep} dt \quad \dots\dots\dots (4.1)$$

ここで、 $(da/dt)_{creep} \doteq \text{Const.}$ ($t_H = t_1 \sim t_2$)とすれば(4.1)式は次のように表わされる。

$$da/dN = (da/dN)_{fatigue} + (da/dt)_{creep} \cdot t_H \quad \dots\dots\dots (4.2)$$

この場合には、クリープ解析を実施してクリープき裂進展量 $(da/dt)_{creep}$ を求める必要がある。しかしながら本解析の最終溶接部における弾塑性解析及び破壊力学パラメータ解析結果より、クリープき裂が進展するような期間で $\hat{J} \simeq 0$ であった(Fig. 3.3-2)。また K_I については、き裂が浅い場合には比較的大きな K_I ($= 80 \text{ kg/mm}^{3/2}$)が発生したが、き裂が深い場合には K_I は負の値 ($= -40 \text{ kg/mm}^{3/2}$)を示した。き裂が深い場合の解析では、この応力場がき裂先端では引張であるが、き裂先端から離れるとすぐ圧縮の応力場になっていることに起因して、

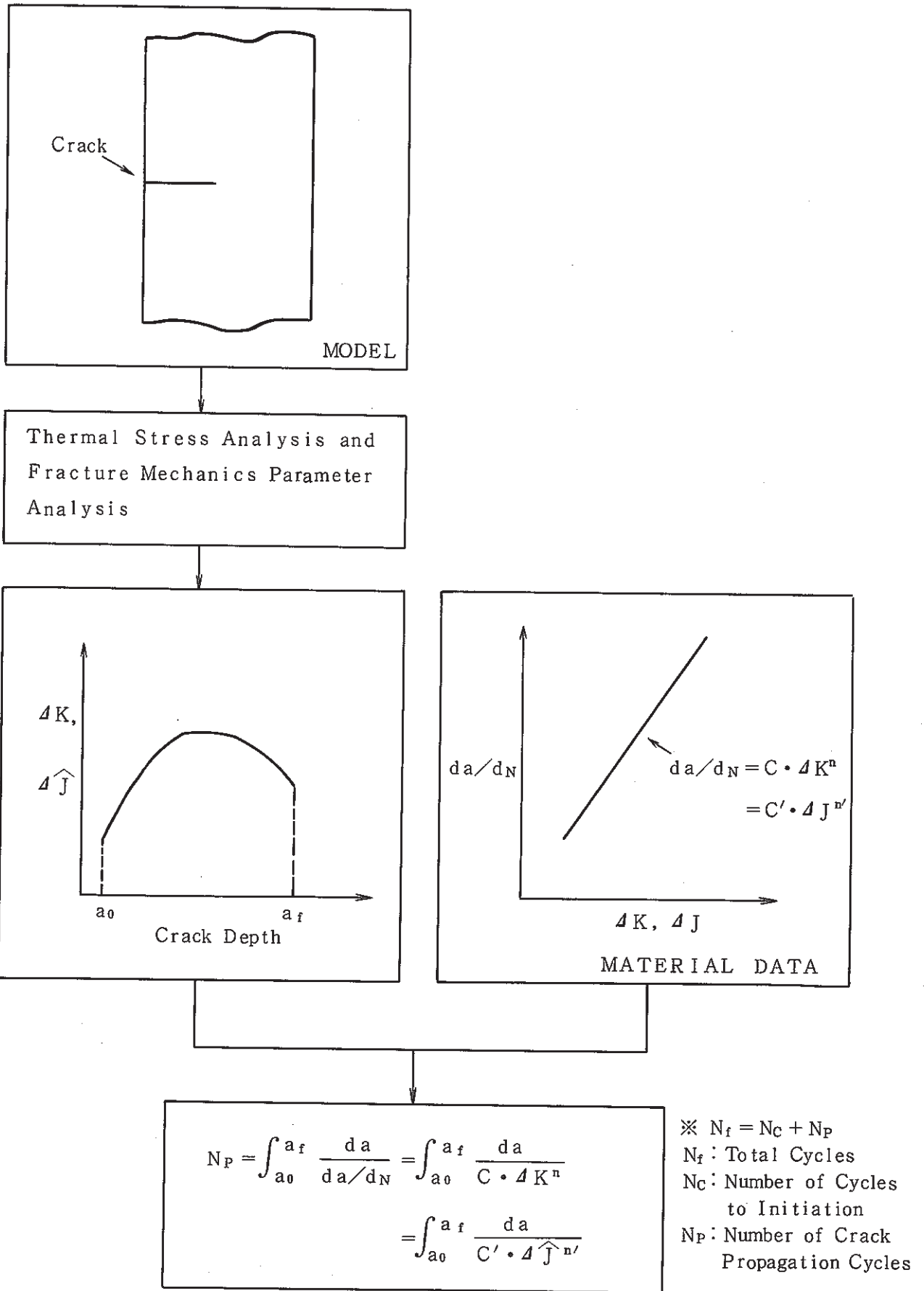


Fig. 4-1 Procedure of Crack Propagation Analysis

K_I のき裂への外挿がこの応力場を特徴づけられなかったと思われる（参照，附録D，Fig. D-14）。クリープき裂進展速度を特徴づけるパラメータとして J' 積分があるが，前述のようにこの期間ではき裂先端の応力場の強さを定めることは難しく，クリープき裂進展速度を決定することも難しい。これらのことより，き裂進展挙動を簡易的に特徴づけることとし，前述のように疲労き裂進展とクリープき裂進展を個々の問題とせず，ひずみ速度の遅い疲労き裂進展，さらには台形波のような波形を伴った疲労き裂進展という既にクリープを考慮した疲労き裂進展として検討した。この場合には，熱過渡1サイクル当りのき裂進展量は次のように表わされる。

$$da/d_N = (da/d_N)_{\text{fatigue+creep}} \dots\dots\dots (4.3)$$

き裂進展量を特徴づける関係は，高温構造安全技術研究組合（ISES）が動燃の委託を受けて実施した文献調査の結果⁴⁾として，593℃（1100F）における ΔK と da/d_N の関係を示している。この結果は Fig. 2.1-1 で既に示されている。荷重保持のあるき裂進展速度はばらつきが大きく，他の荷重あるいは変位保持のない標準材及び溶接継手等の結果よりもかなり速い進展速度となっている結果もある。高温では，小規模降伏が満足される ΔK 領域及び試験条件であれば， ΔK でき裂進展量を特徴づけられる。破壊力学パラメータ解析より求めた ΔK_I は 100～460 kg/mm^{3/2} であり材料試験結果の ΔK （50～250 kg/mm^{3/2}）を上回っているが，このき裂進展評価では適用範囲（ $\Delta K = 50 \sim 250 \text{ kg/mm}^{3/2}$ ）を超えて同図中の Paris 側で検討した。適用したき裂進展速度 da/d_N と応力拡大係数範囲 ΔK の関係は次式の通りである。

・標準材

$$da/d_N = 3.57 \times 10^{-8} (\Delta K)^{2.21} \dots\dots\dots (4.4)$$

・溶接継手

$$da/d_N = 6.57 \times 10^{-9} (\Delta K)^{2.56} \dots\dots\dots (4.5)$$

また， J 積分範囲 ΔJ とき裂進展速度 da/d_N の関係は荷重制御及び変位制御について Fig. 2.1-9，Fig. 2.1-11 及び Fig. 2.1-12 に示した。このうち後述のき裂進展評価で適用したのは，日本溶接協会原子力研究委員会が動燃の委託を受けて実施の試験結果（Fig. 2.1-10，Fig. 2.1-11）である。ここで適用した試験結果は最大荷重または最大変位で60分の保持時間を含んでおり，試験周期としてはここで解析した供試体が120分（高温ナトリウム循環時間105分）に対して短い，材料試験結果には供試体と同程度若しくはそれ以上のクリープの効果が含まれていると考えた。これらの試験結果を簡単に Paris 則で近似した。破壊力学パラメータ解析より求めた ΔJ は最大で約 7 kg/mm であり，ほぼこれらの材料試験結果の範囲にあると言える。適用したき裂進展速度 da/d_N と J 積分範囲 ΔJ の関係は次式の通りである。適用した線図を Fig. 4.1-2，Fig. 4.1-3 に示す。

• 荷重制御

$$\begin{aligned} da/d_N &= 1.513 \times 10^{-2} (\Delta J)^{2.098} \quad (\Delta J \leq 2.46 \text{ kg/mm}) \\ da/d_N &= 5.646 \times 10^{-3} (\Delta J)^{3.193} \quad (\Delta J > 2.46 \text{ kg/mm}) \end{aligned} \quad \dots\dots\dots (4.6)$$

• 変位制御

$$da/d_N = 5.370 \times 10^{-3} (\Delta J)^{1.106} \quad \dots\dots\dots (4.7)$$

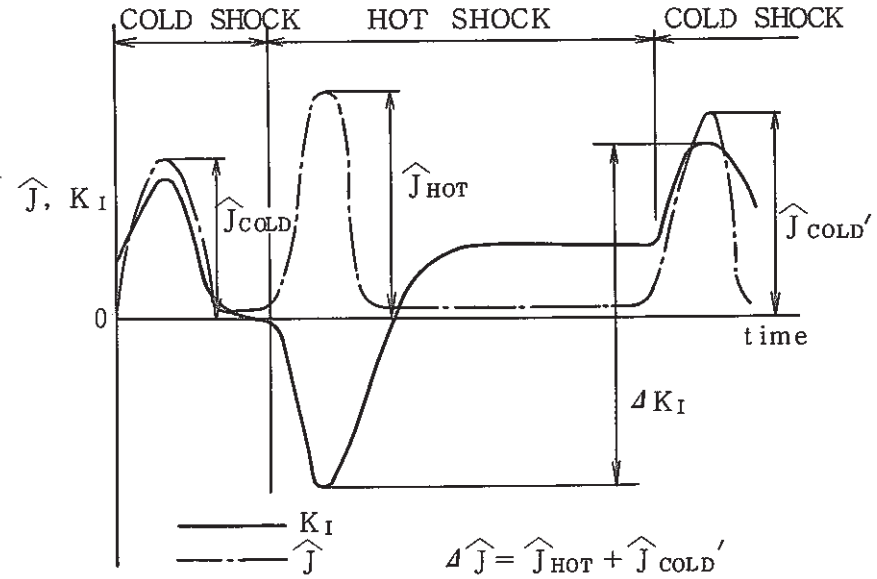
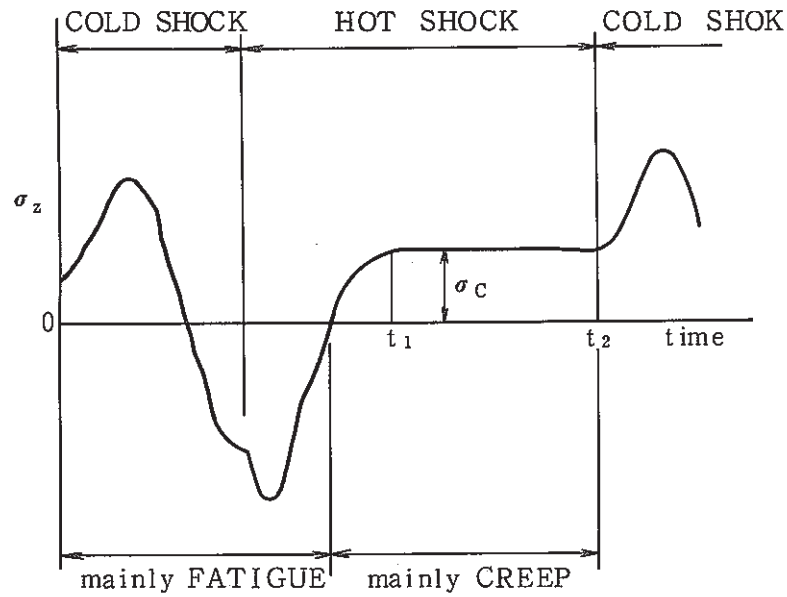


Fig. 4.1-1 Typical Thermal Stress History and \hat{J} , K_I History (In-Elastic Analysis)

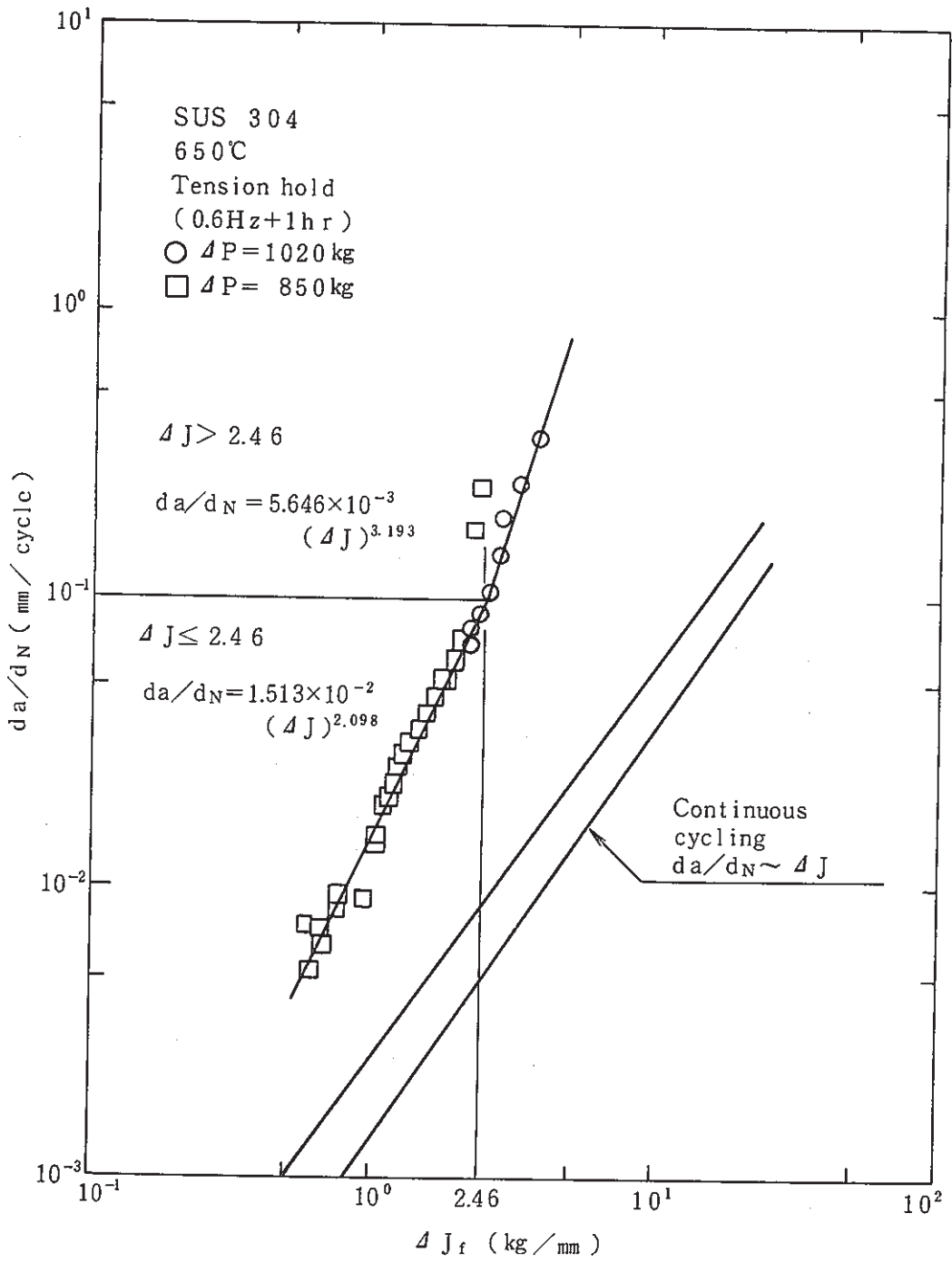
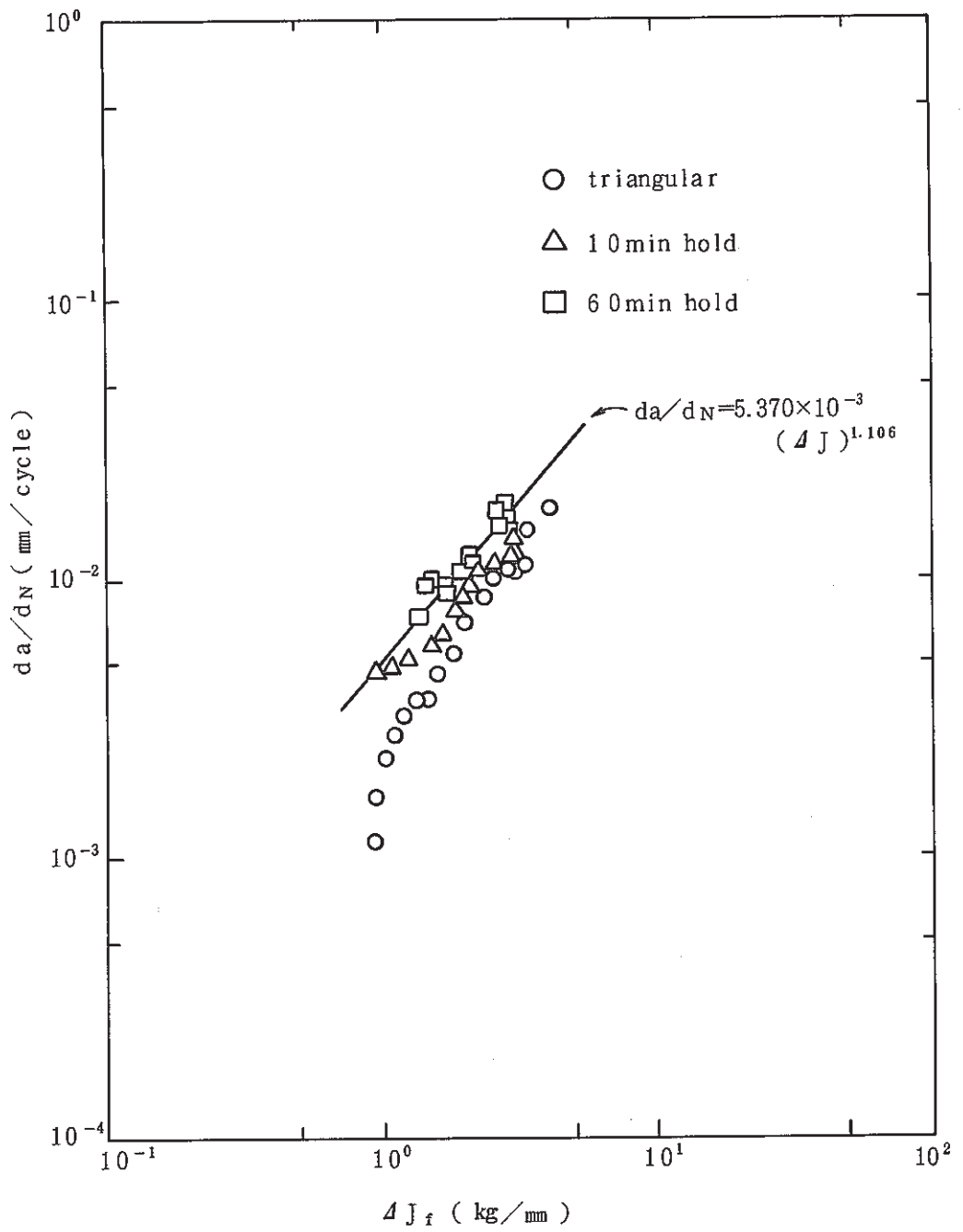


Fig. 4.1-2 Relation between da/dN and ΔJ_f (Load Controlled)



4.2 き裂進展量の計算

Fig. 4-1に示すように、各き裂のき裂深さと ΔK 、 $\Delta \hat{J}$ の関係と材料試験から得られるき裂進展速度と ΔK 、 $\Delta \hat{J}$ の関係を用いてき裂進展に要した繰返し数 N_P を計算する。あるき裂深さ a_0 から最終き裂深さ a_f に達するまでに要する繰返し数 N_P は、次のように表わされる。

$$N_P = \int_{a_0}^{a_f} \frac{da}{da/dN} = \int_{a_0}^{a_f} \frac{da}{C \cdot \Delta K^n} \dots\dots\dots (4.8)$$

または

$$N_P = \int_{a_0}^{a_f} \frac{da}{C' \cdot \Delta \hat{J}^{n'}} \dots\dots\dots (4.9)$$

ここで初期き裂深さ a_0 として軸対称モデルでは $a_0 = 1 \text{ mm}$ 、3次元モデルでは $a_0 = 9.6 \text{ mm}$ (最深部でき裂深さ約 1.6 mm)を採用し、各き裂の最終き裂深さ a_f に達するまでに要した繰返し数 N_P を算出した。

Table 4.2-1に軸対称モデルについて算出した繰返し数 N_P を、Table 4.2-2に3次元モデルについて算出した繰返し数 N_P を示す。き裂進展速度は式(4.4)~(4.7)を適用した。応力拡大係数 ΔK を用いて算出した N_P は、入口ノズルやシンニング部(a_2 き裂)では1002回を下回ったが、他のき裂については試験回数の1002回を上回る結果となった。また、コニカル・下部鏡溶接部のき裂については非常に多くの繰返し数を要する結果となった。 ΔK についてはクリープの効果を考慮すればき裂進展に要した繰返し数はさらに少なくなると考えられる。

軸対称モデルのき裂について、 \hat{J} 積分範囲 $\Delta \hat{J}$ を用いて計算した N_P をFig. 4.2-1にまとめた。図中には、アコースティックエミッション(AE)によるイベント数及びリングダウンカウント数の増加し始めた試験繰返し数の範囲を示す。このAEは最終溶接部付近を対象としており、炉容器モデルの全てを包括しているとは言えないが、き裂進展のある基準として採用する。この結果、き裂進展速度則として、クリープの効果をも含んだ荷重制御の材料試験結果とAEの結果は良い対応が得られた。変位制御の材料試験結果から得られた繰返し数 N_P は、AE信号の増加する繰返し数よりも以前からき裂の進展が始まっていることを示しており、また試験繰返し数1002回を上回ることもあり試験結果と一致しなかった。コニカル胴・下部鏡溶接部については、荷重制御の材料試験結果でも、多くの繰返し数 $N_P (> 1002)$ を要した。この箇所では、入口ノズルや最終溶接部のような熱過渡による応力の他に、スカート部の温度追従性が悪いため熱過渡荷重応答が緩かになり、ホットショック時に高応力が維持されたためクリープき裂進展が材料試験結果から予測されるものよりもさらに加速されたと思われる。

計装ノズルコーナーに発生したき裂についても、荷重制御の材料試験結果を用いて評価した場合に妥当な N_P が得られている。また K_I 、 \hat{J} 値の分布からもわかるように容器側で優先的にき裂が進展する結果となっており、試験結果と一致している。

Table 4.2-1 Number of Crack Propagation Cycles for Axisymmetric Models

MODEL	Number of Crack Propagation : Cycles from a_0 to a_f (N_p)					
	Crack Depth a_f , mm	Stress Intensity Factor Range, ΔK		\hat{J} Range, $\Delta \hat{J}$		
		Base Metal	Weld Joints	Load Controlled	Disp. Controlled	
Finally Welded Joint	27.0	1601 (1062)*	1112 (690)*	74 (83)*	1051 (1113)*	
Inlet Nozzle a_1 crack	4.0	688	—	171	516	
	a_2 crack	5.3	798	660	183	597
	a_3 crack	4.0	829	733	149	467
Thinning a_1 crack	9.4	1644	1380	383	1192	
	a_2 crack	15.0	791	—	63	564
Conical-Bottom Head	32.0	5552	4653	1016	2984	
Stud Bolt	13.0	1463	1133	214	1073	

* Calculated based on In-Elastic Analysis

Table 4.2-2 Number of Crack Propagation Cycles for Instrumental Nozzle

φ	Number of Crack Propagation : Cycles from a_0 to a_f (N_p)		
	Stress Intensity Factor Range ΔK	\hat{J} Range, $\Delta \hat{J}$	
		Load Controlled	Disp. Controlled
20°	1331	430	1176
50°	1051	201	800
70°	887	161	670

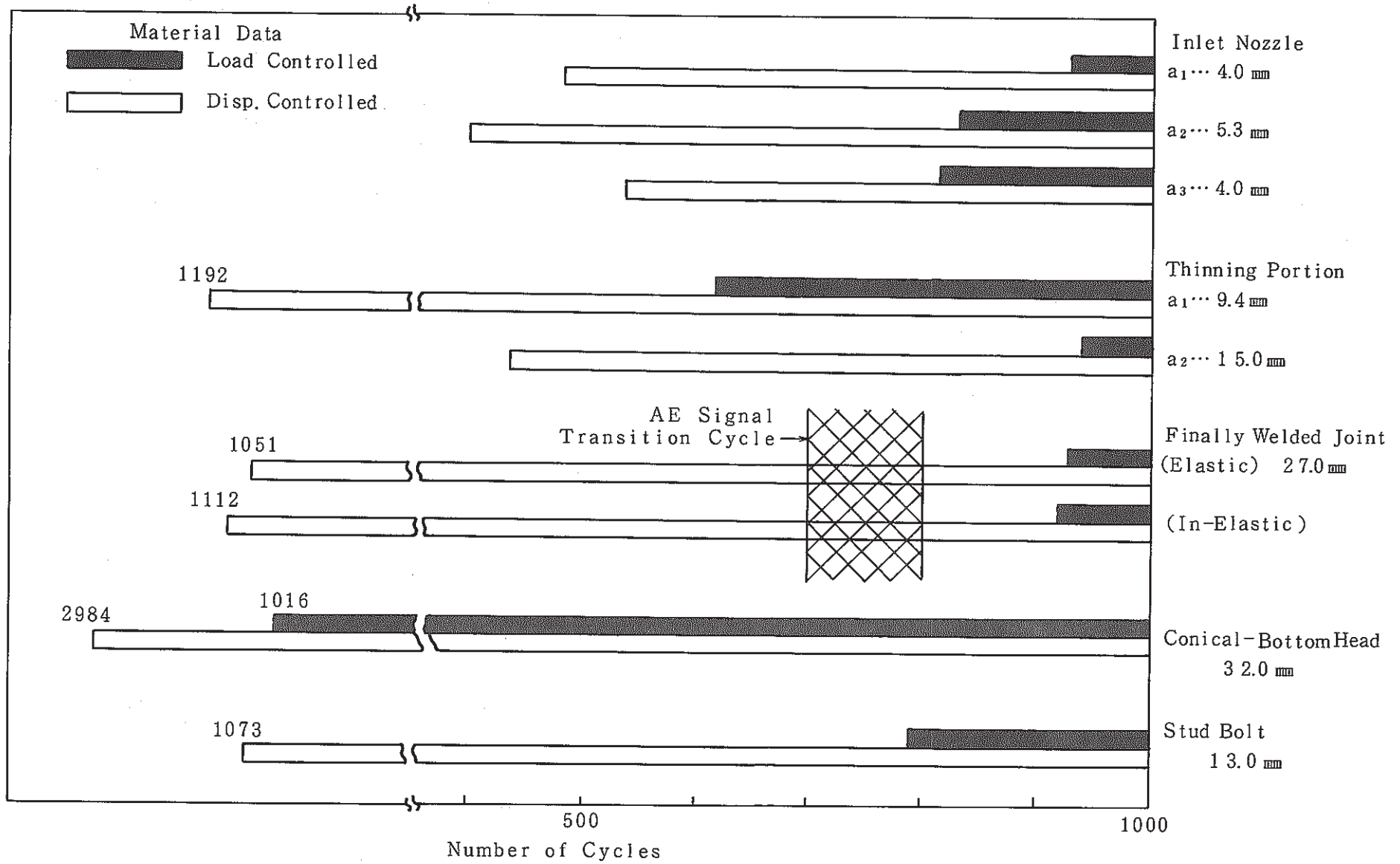


Fig. 4.2-1 Number of Crack Propagation Cycles calculated from ΔJ

4.3 熱過渡荷重を受ける構造物のき裂進展挙動と今後の課題

き裂の進展に要する繰返し数は、荷重制御の材料試験結果を用いることによりうまく整理できそうである。ここでき裂の深さ方向の ΔK_I 、 $\Delta \hat{J}$ の関係を調べるとFig. 4.3-1, Fig. 4.3-2のようになる。これらのき裂はいずれもあるき裂深さで ΔK_I 及び $\Delta \hat{J}$ が最大値を示している。板厚に対して比較的浅いき裂深さで ΔK_I 及び $\Delta \hat{J}$ が最大値を示すのは、入口ノズル a_2 き裂、シンニング部 a_1 き裂、最終溶接部及びスタッドボルトのき裂である。これらはいずれも円筒の平滑部あるいはき裂近傍が構造不連続による応力を受けない部位である。しかしながら、シンニング部 a_2 き裂やコナル・下部鏡溶接部に発生したき裂では、 ΔK_I 及び $\Delta \hat{J}$ の最大値は板厚内の相対的に深い位置に発生し、試験終了時の最終き裂深さ（シンニング部 a_2 き裂 ≈ 15 mm, コナル・下部鏡溶接部き裂 $= 32$ mm）においても ΔK_I 及び $\Delta \hat{J}$ の値はその最大値に近い値を保っている。シンニング部では板厚が25 mm \sim 40 mmと変化することによる曲げの応力を受けて深いき裂で ΔK_I 及び $\Delta \hat{J}$ の最大値が発生し、コナル・下部鏡溶接部でも温度追従の悪いスカート部の影響により深いき裂で ΔK_I 及び $\Delta \hat{J}$ の最大値が発生する。

一般に熱過渡荷重では、き裂が進展するとともにある深さで ΔK_I 、 $\Delta \hat{J}$ の最大値があり、その後緩かに減少しき裂は停止する傾向であるが、構造不連続近傍に発生したき裂では ΔK_I 及び $\Delta \hat{J}$ の最大値が板厚の半分を超える場合があり、き裂の停止もかなりき裂が進展した後に起こると思われる。この点は、構造物の健全性を知る上で重要である。

本研究を進める上で気づいた問題点及び今後の課題について以下に列挙する。

- ① 熱過渡荷重負荷によるき裂進展速度は破面観察結果から得られなかった。このため解析で得られた応力拡大係数範囲 ΔK 及びJ積分範囲 $\Delta \hat{J}$ とき裂進展速度を直接的に関連づけることができなかった。またき裂初生に要する熱過渡サイクル数が明確でないため、解析から求めたき裂進展に要する熱過渡サイクル数は、試験サイクル数あるいはAE信号の増加するサイクル数との比較に止まった。
- ② き裂進展挙動は、温度一定の材料試験結果を用いて評価した。またクリープき裂進展は特別の破壊力学パラメータを用いず、クリープき裂を含む形の材料試験結果を用いて簡易的に評価した。破面がほとんど粒界割れを呈していたことにより、クリープき裂進展はクリープ解析も含んでその挙動を検討する必要がある。
- ③ 破壊力学パラメータとして ΔK 及び $\Delta \hat{J}$ を選びき裂進展速度と対応させたが、き裂の開閉口を考慮せず用いた。き裂の閉口では、解析上接触問題を考慮できないのでき裂面やき裂先端部で応力やひずみ場の特異性に影響があると思われる。
- ④ 熱過渡荷重では板厚方向に応力分布が生じ、浅いき裂では、き裂先端近傍の応力場が、き裂が存在することにより発生した特異応力場ではなく内表面からの熱過渡によりこの応力場が乱される。また深いき裂ではき裂先端近傍で応力の反転（コールドショックではき裂先端で引張応力だが、外表面に近づくほど圧縮応力となる）が生じるので径路積分により求まる \hat{J} 積分の範囲について議論する必要がある。

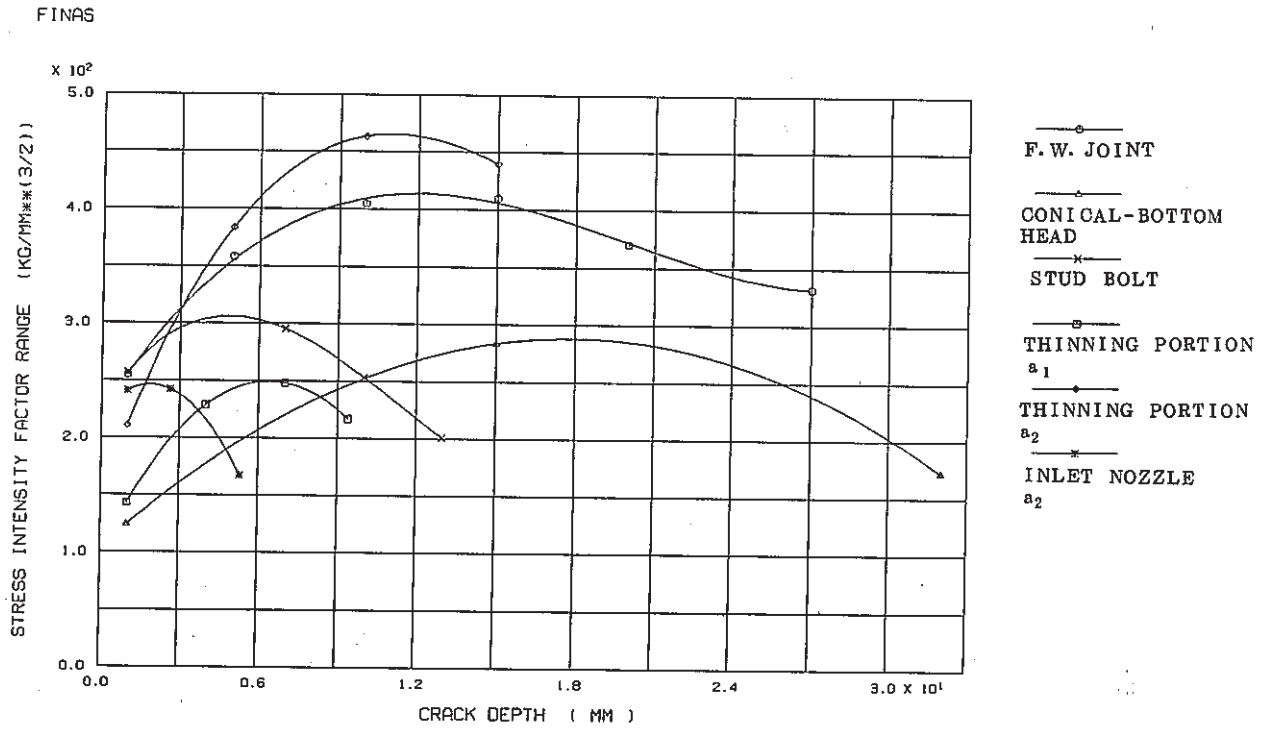


Fig. 4.3-1 Relation between Stress Intensity Factor Range and Crack Depth

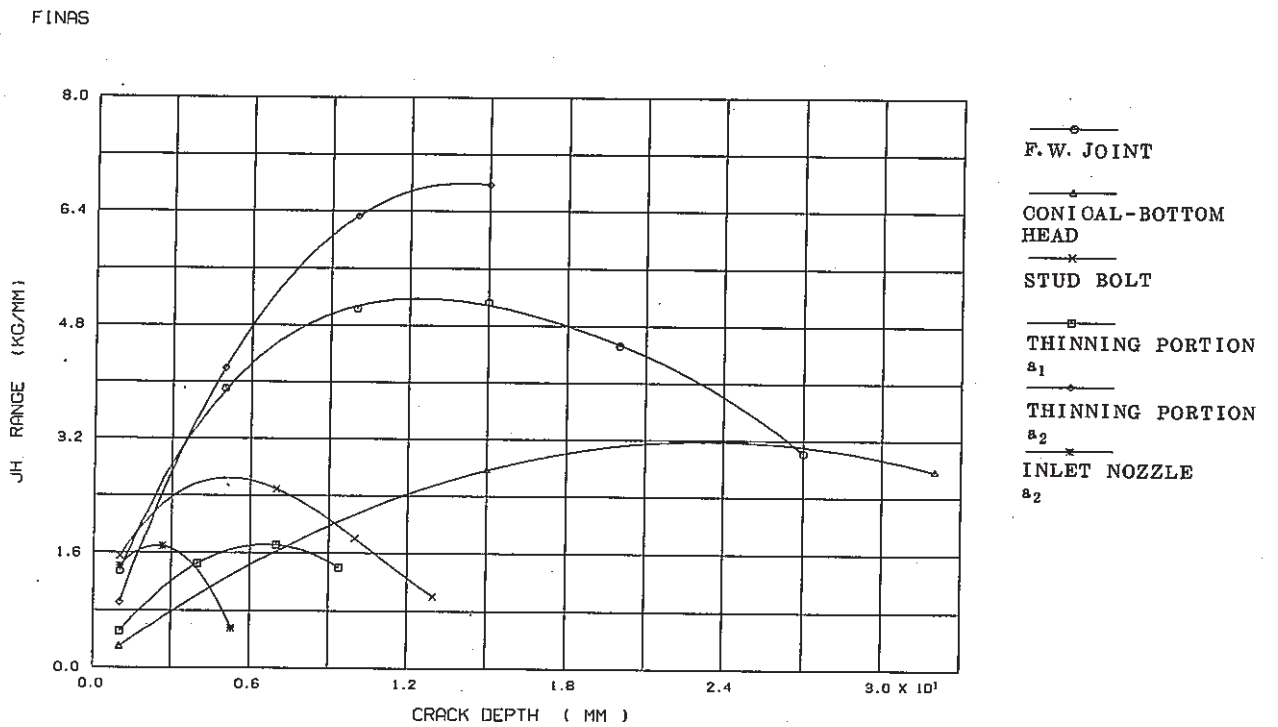


Fig. 4.3-2 Relation between \hat{J} -Integral Range and Crack Depth

5. ま と め

軸対称及び3次元問題において破壊力学パラメータを算出するプログラムCANISを用いて、「原子炉容器モデル」に発生する代表的なき裂について一連の応力解析，破壊力学パラメータ解析及びき裂の評価を実施した。この結果以下のことがわかった。

- (1) 熱応力場のJ積分は径路に依存するが， \hat{J} 積分は径路に依存せず独立であり，熱応力を受ける構造物の健全性には \hat{J} 積分が有効である。
- (2) 最終溶接部について実施の弾性解析及び弾塑性解析から算出した破壊力学パラメータは， \hat{J} 積分範囲 $\Delta \hat{J}$ についてはほぼ同等である。
- (3) 応力拡大係数範囲 ΔK_I 及び \hat{J} 積分範囲 $\Delta \hat{J}$ は一般に最初き裂深さとともに増加しあるき裂深さで最大を示し，その後緩かに減少する。構造不連続部による曲げ等の影響を受ける場合には， ΔK_I 及び $\Delta \hat{J}$ の最大値が，深いき裂位置で発生する。
- (4) 熱過渡荷重下の破壊力学パラメータとき裂進展速度の関係は，クリープの効果を十分に含んだ荷重制御型の材料試験結果が最も良い対応を示す。

6. 謝 辞

本研究を行うにあたり破壊力学パラメータの計算プログラムはセンチュリ・リサーチ・センタ(株)構造技術部にて作成された。同部吉田氏はじめ関係各位に感謝します。

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附録 A 軸対称問題における破壊力学パラメータ

附録A 軸対称問題における破壊力学パラメータ

構造物の健全性評価にあたって、線形破壊力学さらには非線形破壊力学が適用されている。ここでは、軸対称問題に対する破壊力学パラメータの式を示す。本附録では、円筒内面の円周上に一様なき裂を有する軸対称モデルの破壊力学パラメータ解析を示し、破壊力学パラメータとしては、応力拡大係数K、J積分、 \hat{J} 積分及びJ'積分についてその式を示す。

A.1 応力拡大係数K

有限要素法により応力拡大係数Kを計算する方法として、直接法とエネルギー法が挙げられる。直接法は、き裂先端近傍の応力及び変位から応力拡大係数Kを定義する方法であり、エネルギー法は、面積分（J、 \hat{J} 積分）から求める方法である。

(a) 直接法

き裂先端の応力場は、き裂の変形モードにより以下の式で示される。

(1) モードI（開口型変形）

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \begin{Bmatrix} 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \\ 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \\ \sin \frac{\theta}{2} \cos \frac{3\theta}{2} \end{Bmatrix} \dots\dots\dots (A-1)$$

$$\sigma_{33} = \nu (\sigma_{11} + \sigma_{22}) : \text{平面ひずみ}$$

(2) モードII（面内せん断形）

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \frac{K_{II}}{\sqrt{2\pi r}} \begin{Bmatrix} -\sin \frac{\theta}{2} \left(2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right) \\ \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \\ \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \end{Bmatrix} \dots\dots\dots (A-2)$$

$$\sigma_{33} = \nu (\sigma_{11} + \sigma_{22}) : \text{平面ひずみ}$$

(3) モードⅢ (面外せん断変形)

$$\begin{Bmatrix} \sigma_{13} \\ \sigma_{23} \end{Bmatrix} = \frac{K_{III}}{\sqrt{2\pi r}} \begin{Bmatrix} -\sin \frac{\theta}{2} \\ \cos \frac{\theta}{2} \end{Bmatrix} \dots\dots\dots (A-3)$$

このようにき裂先端の応力場は $1/\sqrt{r}$ の特異性をもっており、各変形モードにより異なる分布を示している。 K_I 、 K_{II} 及び K_{III} は応力の特異性の強さを示しており応力拡大係数と呼ばれる。このように応力に基づく K_I は、

$$K_I = \sigma_r \sqrt{2\pi r} / f(\theta) \dots\dots\dots (A-4)$$

で表わされ、 r がゼロにおける値を外挿することによりき裂先端の K_I を得ることができる。 K_{II} 及び K_{III} についても同じようにして求めることができる。なお、軸対称問題ではモードⅠ及びモードⅡの変形について求まる。

(b) エネルギー法

後述の J 、 \hat{J} 積分値より、材料が線形弾性体であると仮定すると K と J あるいは \hat{J} には次のような対応関係が存在する。モードⅠについて

$$\left. \begin{aligned} J &= \frac{1-\nu^2}{E} K_I^2 && \text{(平面ひずみ)} \\ J &= \frac{K_I^2}{E} && \text{(平面応力)} \end{aligned} \right\} \dots\dots\dots (A-5)$$

が得られる。

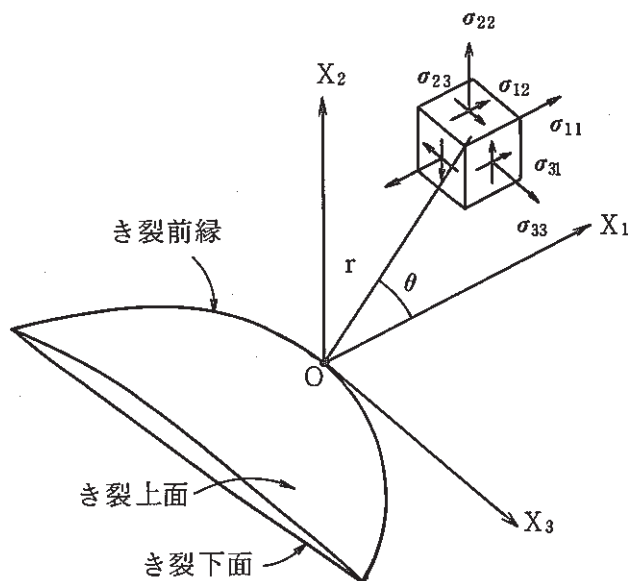
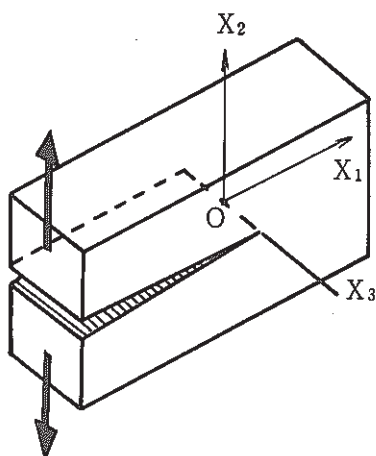
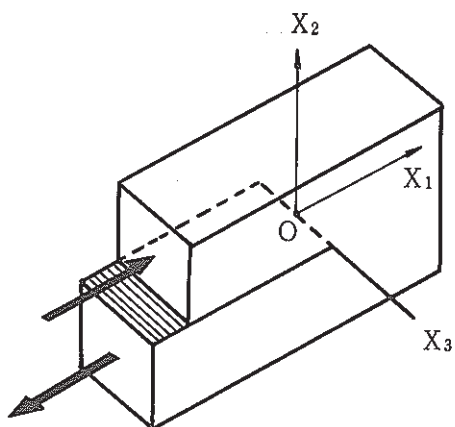


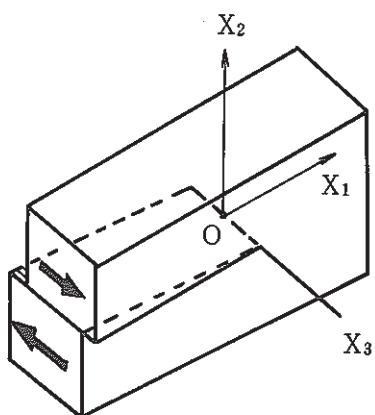
Fig. A.1-1 Stress Components in a Plane Normal to Crack Front



(a) 開口形 (モード I)



(b) 面内せん断 (モード II)



(c) 面外せん断形 (モード III)

Fig. A.1-2 Basic Deformation Mode of Crack

A.2 J 積分

軸対称問題に対する J 積分は、3次元問題に対する J 積分式より導かれる。そこで、Fig.A.2-1 に示すように、き裂前縁と点 O' 及び点 O'' で交わる任意の閉曲面 S を考え、次の面積積分を考える。^{A-1)}

$$J(3) = \lim_{\epsilon \rightarrow 0} \frac{1}{2\epsilon} \iint_{S+S_0} \left(W n_i - T_i \frac{\partial u_i}{\partial X_1} \right) ds \quad \dots\dots\dots (A-6)$$

ただし、OO'=OO''=εである。n_i は S または S₀ の面要素の外向き単位法線の X_i 方向成分である。式(A-6)は積分曲面 S に依存せず、Fig. A.2-2 に示すように輪かくが曲線 Γ で表される X₃ 軸に垂直な板の表面を考え、この板の厚さ 2ε を 0 に近づけると、式(A-6)は次式のようにになる。

$$J(3) = \int_{\Gamma} \left(W dx_2 - T_i \frac{\partial u_i}{\partial X_i} d\Gamma \right) - \iint_A \frac{\partial}{\partial X_3} \left(\sigma_{13} \frac{\partial u_1}{\partial X_1} \right) dA \quad \dots\dots\dots (A-7)$$

式(A-7)を軸対称問題に適用すると次式が得られる。

$$J_r = \int_{\Gamma} \left(W n_r - \sigma_r n_r \frac{\partial u_r}{\partial r} - \tau_{rz} n_z \frac{\partial u_z}{\partial r} - \tau_{rz} n_z \frac{\partial u_r}{\partial r} - \sigma_z n_z \frac{\partial u_z}{\partial r} \right) r d\Gamma - \iint_A \left(W - \sigma_{\theta} \frac{u_r}{r} \right) dA \quad \dots\dots\dots (A-8)$$

ここで式(A-8)は単位ラジアン当りの値であり、n_r dΓ=dz, n_z dΓ=dr, dA=drdzとすれば次のようになる。^{A-4)}

$$J_r = \int \left(W - \sigma_r \frac{\partial u_r}{\partial r} - \tau_{rz} \frac{\partial u_z}{\partial r} \right) r dz - \int \left(\tau_{rz} \frac{\partial u_r}{\partial r} + \sigma_z \frac{\partial u_z}{\partial r} \right) r dr - \iint \left(W - \sigma_{\theta} \frac{u_r}{r} \right) dr dz \quad \dots\dots\dots (A-9)$$

A.3 Ĵ 積分

本解析では、3次元問題における Ĵ 積分のうち、物体力、慣性力の項を無視して熱ひずみ及び塑性ひずみの項を考慮しており、Ĵ 積分は次のようになる。^{A-2) A-3)}

$$\hat{J}_r = \int_{\Gamma} \left(-T_i \frac{\partial u_i}{\partial X_1} d\Gamma \right) + \iint_A \left\{ \sigma_{1j} \frac{\partial \epsilon_{1j}}{\partial X_1} - \frac{\partial}{\partial X_3} \left(\sigma_{13} \frac{\partial u_1}{\partial X_1} \right) \right\} dA \quad \dots\dots\dots (A-10)$$

軸対称問題に適用すると次式のようなになる。

$$\begin{aligned} \hat{J}_r = & \int_{\Gamma} \left(-\sigma_r n_r \frac{\partial u_r}{\partial r} - \tau_{rz} n_r \frac{\partial u_z}{\partial r} - \tau_{rz} n_z \frac{\partial u_r}{\partial r} - \sigma_z n_z \frac{\partial u_z}{\partial r} \right) r d\Gamma \\ & + \int_A \sigma_\theta \frac{u_r}{r} dA \\ & + \iint \left(\sigma_r \frac{\partial \epsilon_r}{\partial r} + \sigma_z \frac{\partial \epsilon_z}{\partial r} + \sigma_\theta \frac{\partial \epsilon_\theta}{\partial r} + \tau_{rz} \frac{\partial \gamma_{rz}}{\partial r} \right) r dA \quad \dots\dots (A-11) \end{aligned}$$

さらに $n_r d\Gamma = dz$, $n_z d\Gamma = dr$, $dA = dr dz$ より次式のようなになる。

$$\begin{aligned} \hat{J}_r = & \int \left(\sigma_r \frac{\partial u_r}{\partial r} + \tau_{rz} \frac{\partial u_z}{\partial r} \right) r dz - \int \left(\tau_{rz} \frac{\partial u_r}{\partial r} + \sigma_z \frac{\partial u_z}{\partial r} \right) r dr \\ & + \int_A \sigma_\theta \frac{u_r}{r} dr dz \\ & + \iint \left(\sigma_r \frac{\partial \epsilon_r}{\partial r} + \sigma_z \frac{\partial \epsilon_z}{\partial r} + \sigma_\theta \frac{\partial \epsilon_\theta}{\partial r} + \tau_{rz} \frac{\partial \gamma_{rz}}{\partial r} \right) r dr dz \quad \dots\dots (A-12) \end{aligned}$$

A.4 J' 積分

J'積分はクリープ条件下のき裂進展問題へJ積分を拡張する目的で用いられ、J積分の定義式において ϵ_{ij} を $\dot{\epsilon}_{ij}$ で、 u_i を \dot{u}_i で置換えた式で与えられる。J'積分は3次元問題の場合に次のように表わされる。

$$J'_r = \int_{\Gamma} \left(W' dx_2 - T_i \frac{\partial \dot{u}_i}{\partial X_1} d\Gamma \right) - \iint_A \frac{\partial}{\partial X_3} \left(\sigma_{i3} \frac{\partial \dot{u}_i}{\partial X_1} \right) dA \quad \dots\dots (A-13)$$

式(A-13)を軸対称問題に適用すると次式が得られる。

$$\begin{aligned} J'_r = & \int \left(W' - \sigma_r \frac{\partial \dot{u}_r}{\partial r} - \tau_{rz} \frac{\partial \dot{u}_z}{\partial r} \right) r dz - \int \left(\tau_{rz} \frac{\partial \dot{u}_r}{\partial r} + \sigma_z \frac{\partial \dot{u}_z}{\partial r} \right) r dr \\ & - \iint \left(W' - \sigma_\theta \frac{\dot{u}_r}{r} \right) dr dz \quad \dots\dots (A-14) \end{aligned}$$

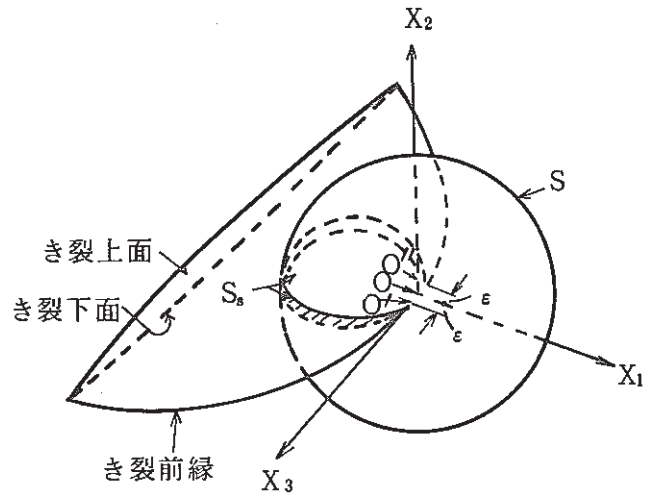


Fig. A.2-1 Three-Dimensional Crack in Elastic-Plastic Solid

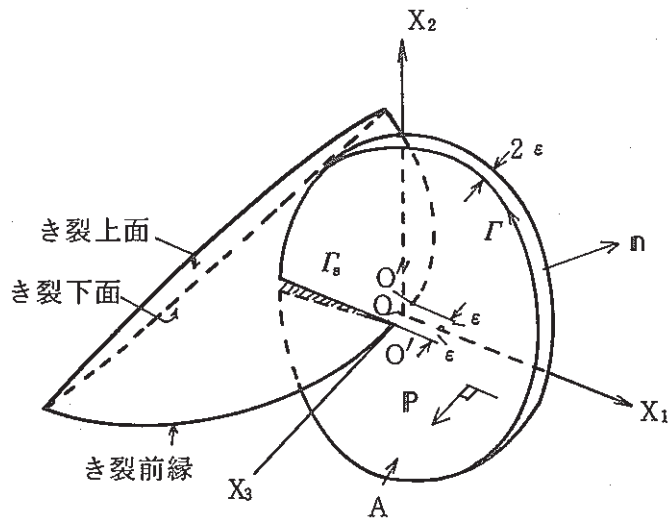


Fig. A.2-2 Surface for the Integration of Three-Dimensional J Integral

A.5 検証例題

軸対称問題としてFig. A.5-1に示すような埋没円き裂を有する無限体について解析を実施した。弾性解析の問題として、引張荷重を負荷した場合を設定し、熱弾性解析の問題として一様に冷却した場合を設定した。この問題は渡辺らの^{A-5)}論文に記載されているものである。

Fig. A.5-1に示すような埋没円き裂を有する無限体について、 K_I 値及び \hat{J} 値の解析を行った。有限要素モデルは対称性を利用してFig. A.5-2のようにモデル化し、8節点軸対称要素QAX8を用いてFig. A.5-3のようにメッシュ分割した。材料データとして次の値を用いた。

弾性係数	$E=1.85 \times 10^5 \text{ N/mm}^2$
ポアソン比	$\nu=0.3$
熱膨張係数	$\alpha=1.2 \times 10^{-5} \text{ 1/}^\circ\text{C}$

(1) 弾性解析

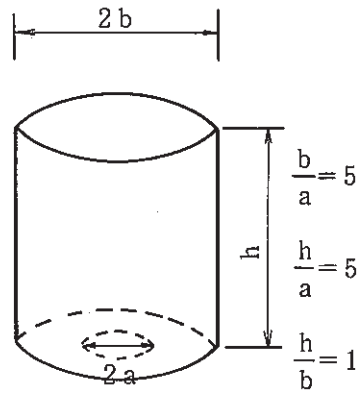
遠方で一様な引張応力 $\sigma_0 = 10 \text{ N/mm}^2$ を受けた場合の K_I 値及び J 値を求める。理論解は $K_I = 2\sigma_0\sqrt{a/\pi} = 35.682$ である。Table A.5-1に理論解との比較を示す。Fig. A.5-4は K_I 値を計算するために用いた積分点位置である。またFig. A.5-5は J 値を計算する積分経路である。 K_I 及び J 積分の計算値は工業的に満足できる程度で理論解と一致している。

Table A.5-1 A Comparison of Different Methods of Stress Intensity Factor for Unfinite Body containing a Penny Shaped Crack

	理論解	計算値	誤差 (%)
K_I (直接法)	35.682	35.929	0.69
K_I (エネルギー法)		34.873	2.27
J	0.00626	0.00598	4.49

(2) 熱弾性解析

解析モデルは、Fig. A.5-1の無限体の上下面で上下方向の変位を固定し、温度を 0°C から -60°C まで一様に冷却した状態を仮定する。温度が -60°C の時の \hat{J} 値は 1.053 N/mm であり渡辺らの解^{A-5)}($=1.055 \text{ N/mm}$)と良く一致した。



$a = 10 \text{ mm}$
 $b = 50 \text{ mm}$
 $h = 50 \text{ mm}$

Fig. A.5-1 Unfinite Body containing a Penny Shaped Crack

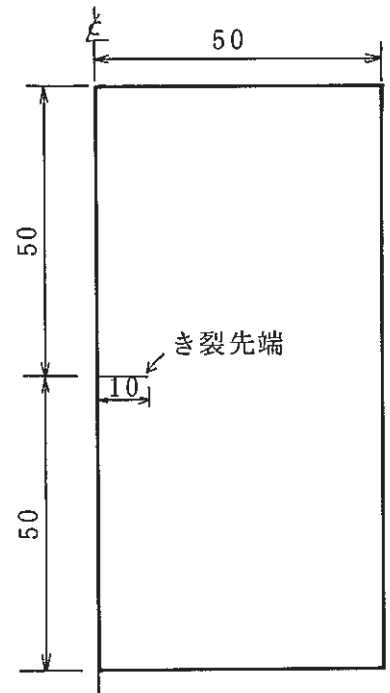


Fig. A.5-2 Geometry of Analytical Model

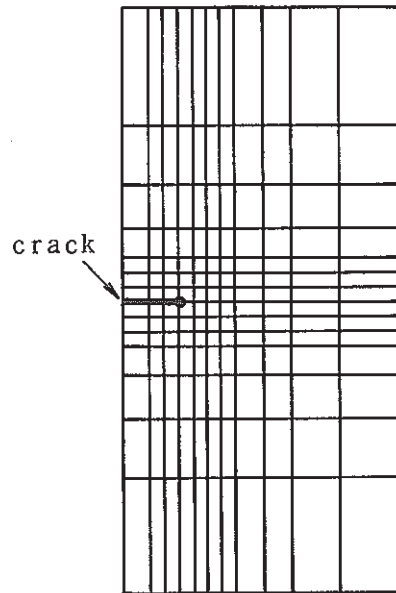


Fig. A.5-3 Finite Element Model

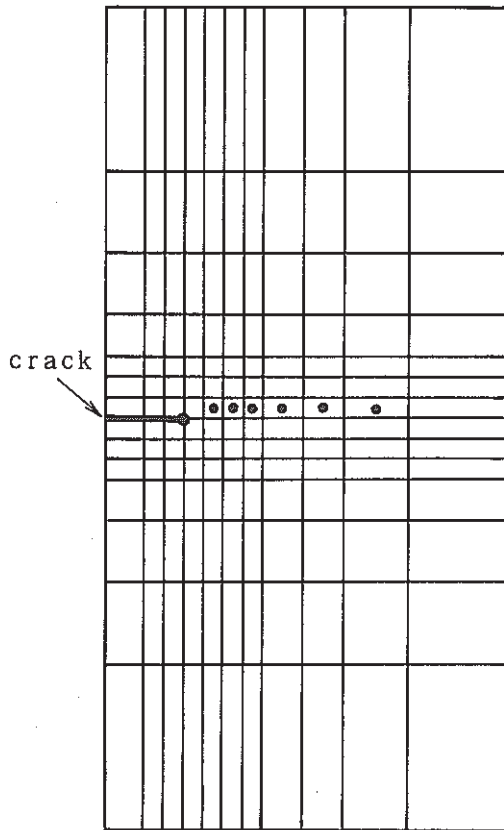


Fig. A.5-4 Integral Points for K Evaluation

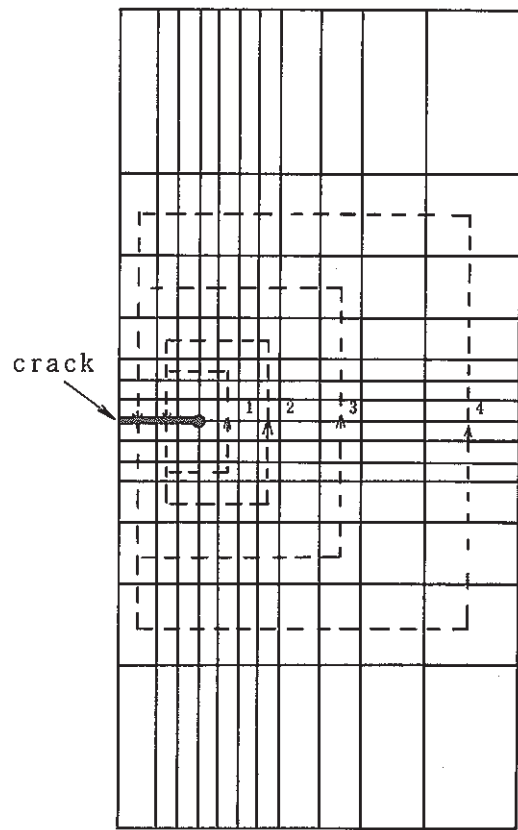


Fig. A.5-4 Paths for J-Integral Evaluation

A.6 解析結果例

軸対称問題における破壊力学パラメータの解析結果例を以下に示す。解析モデルは、Fig. A.6-1に示すき裂深さ15mmの最終溶接部である。Fig. A.6-2に直接法により応力拡大係数を計算するために用いた積分点位置を示す。これらの積分点位置で計算した応力場の強さをき裂先端部に外挿することにより応力拡大係数 K_I 、 K_{II} を求めることができる。Fig. A.6-3は、J積分等で用いた積分径路である。

Table A.6-1にコールドショックにおいて応力が最大となる時点(152 sec)での弾性解析に基づく K_I と K_{II} の計算結果を示す。モードIの変形については軸方向応力 σ_z が、またモードIIの変形についてはせん断応力 τ_{RZ} が主であるので、これらの成分より求めた応力拡大係数を代表値とした。一般に K_{II} は K_I と比較して小さく、き裂はモードIの変形により進展したと思われる。Fig. A.6-4及びFig. A.6-5にき裂先端に外挿した K_I 及び K_{II} を示す。本解析では、Fig. A.6-2に示す積分点位置で計算した K_I 及び K_{II} をそれぞれ最小2乗法を用いて2次曲線でき裂先端に外挿している。 K_I は各成分ごとの誤差は小さいが、 K_{II} では誤差が大きい。 K_{II} では軸方向応力 σ_z 及び周方向応力 σ_θ からの外挿はFig. A.6-5にもみられるように非常に大きな値からの外挿となっているため誤差が大きくなったものと思われる。

Table A.6-2及びTable A.6-3は弾性解析に基づいたJ積分及び \hat{J} 積分の径路積分結果であり、平面応力または平面ひずみを仮定してJまたは \hat{J} 積分から求めた K_I も示している。また、Fig. A.6-6及びFig. A.6-7には、J積分及び \hat{J} 積分の径路依存性を示す。同図に示すようにJ積分は径路に依存するので破壊力学のパラメータとして用いることはできないが、 \hat{J} 積分では、径路に対して独立性がみられ、熱過渡荷重のように熱ひずみが存在する場合には \hat{J} 積分が有効である。また \hat{J} 積分より求めた K_I 値と直接法に求めた K_I 値は、ほぼ一致している。

Table A.6-4は非弾性解析に基づいた K_I 及び K_{II} の計算結果を示す。またFig. A.6-8、Fig. A.6-9には K_I 及び K_{II} の外挿を示す。Table A.6-5及びTable A.6-6にJ積分及び \hat{J} 積分の径路積分結果を示す。 \hat{J} 積分から変換した K_I 値は、軸方向応力 σ_z より求めた K_I 値に近い値となっており、き裂先端で小規模降伏条件が満たされていると思われる。Fig. A.6-10及びFig. A.6-11にJ積分及び \hat{J} 積分の径路依存性を示すが、弾性解析に基づく結果と同様、J積分は径路に依存し \hat{J} 積分は径路に依存しない。

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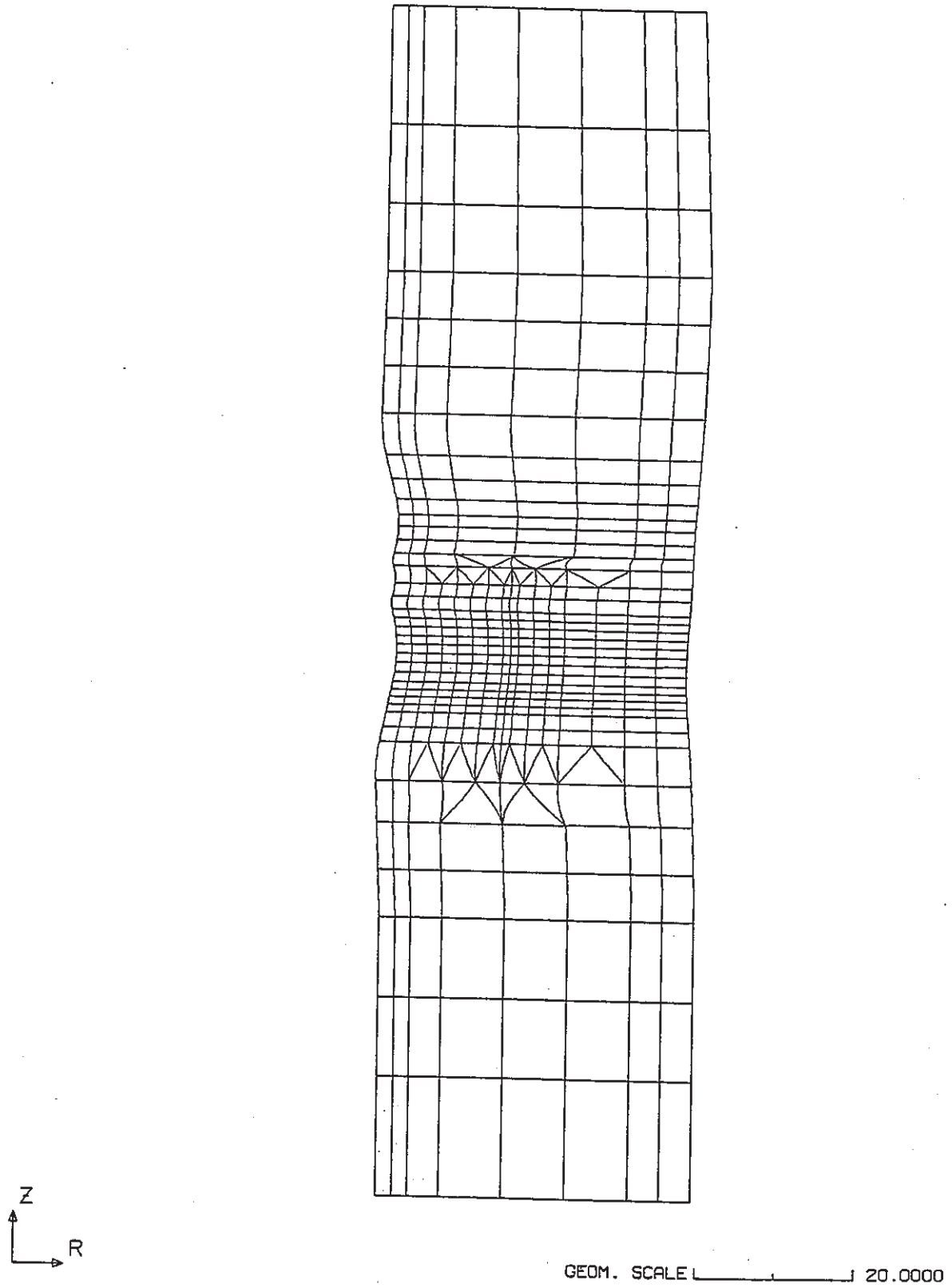


Fig. A.6-1 Finite Element Model for Finally Welded Joint

FINAS

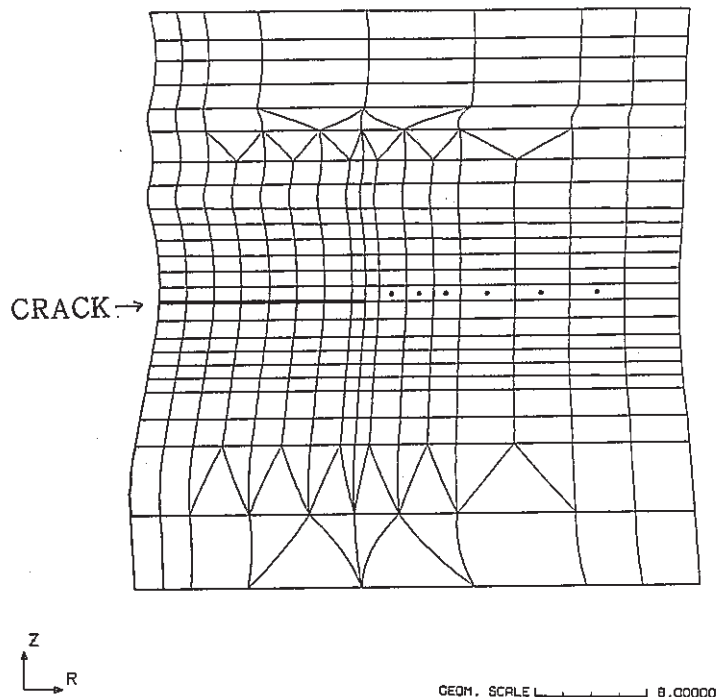


Fig. A.6-2 Mesh Breakdown for the Finite Element Analysis and Integral Points for K Evaluation

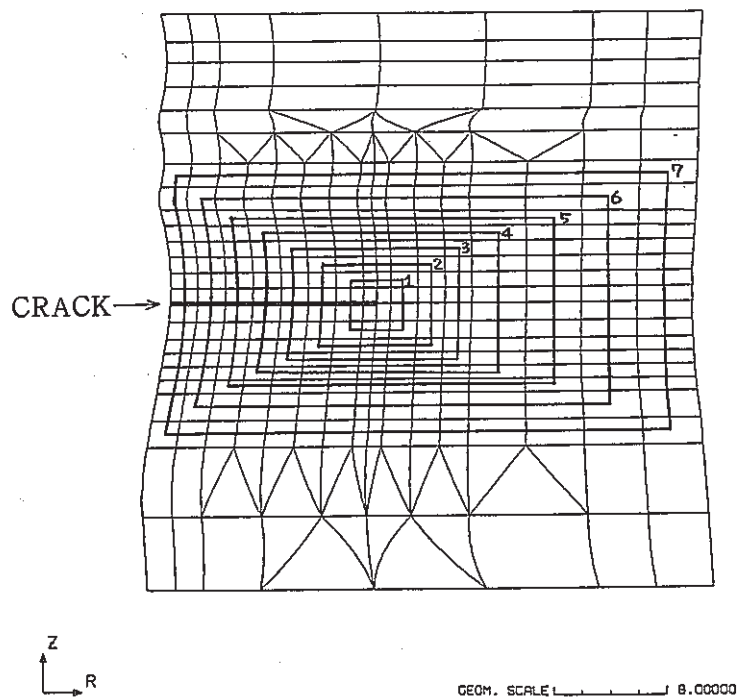


Fig. A.6-3 Mesh Breakdown for the Finite Element Analysis and Paths for J-Integral Evaluation

Table A.6-1 Stress Intensity Factor K_I and K_{II} calculated by CANIS (Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
 FRACTURE MECHANICS PARAMETERS

STEP ----- 5
 TIME ----- 152.000
 CRACK TIP TEMP. --- 476.437
 OPENING DISP. ----- 0.66790E-01 (FROM CRACK TIP 2.9211)

*** K-VALUE (K-1) ***

POINT	RADIUS	PHI	SIG-R	SIG-Z	SIG-TH	TAU-RZ
1	2.047	0.272	191.32	151.13	142.73	172.43
2	3.957	0.140	171.97	107.67	83.798	188.64
3	5.892	0.094	151.82	60.285	18.985	188.82
4	8.803	0.063	118.52	-14.050	-83.470	159.50
5	12.692	0.043	72.594	-120.16	-222.21	140.98
6	16.583	0.033	29.150	-244.59	-360.25	125.08
EXTERP.			213.65	193.17	211.33	182.35

*** K-VALUE (K-2) ***

POINT	RADIUS	PHI	SIG-R	SIG-Z	SIG-TH	TAU-RZ
1	2.047	0.272	-454.05	1278.5	-1041.6	22.707
2	3.957	0.140	-814.36	1600.7	-1198.2	13.062
3	5.892	0.094	-1076.8	1309.3	-405.17	8.8088
4	8.803	0.063	-1259.4	-451.97	2664.2	4.9874
5	12.692	0.043	-1113.0	-5551.0	10227.	3.0603
6	16.583	0.033	-583.97	-14738.	21659.	2.0793
EXTERP.			35.047	-407.11	167.11	28.678

Table A.6-2 J-Integral calculated by CANIS
(Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
FRACTURE MECHANICS PARAMETERS

STEP ---- 5
TIME ---- 152.000

*** J-VALUE ***

PASS	J	K(P.STRS)	K(P.STRN)
1	1.8836	175.95	184.45
2	1.8377	173.79	182.19
3	1.8378	173.80	182.20
4	1.9520	179.12	187.77
5	2.1748	189.06	198.20
6	2.5079	203.02	212.83
7	2.9231	219.19	229.78
AVE.	2.1596	188.40	197.50

Table A.6-3 \hat{J} -Integral calculated by CANIS
(Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
FRACTURE MECHANICS PARAMETERS

STEP ---- 5
TIME ---- 152.000

*** JH-VALUE ***

PASS	JH	K(P.STRS)	K(P.STRN)
1	2.3321	195.78	205.24
2	2.3748	197.56	207.11
3	2.3732	197.50	207.04
4	2.3726	197.47	207.01
5	2.3731	197.49	207.04
6	2.3936	198.34	207.93
7	2.3600	196.95	206.47
AVE.	2.3685	197.30	206.84

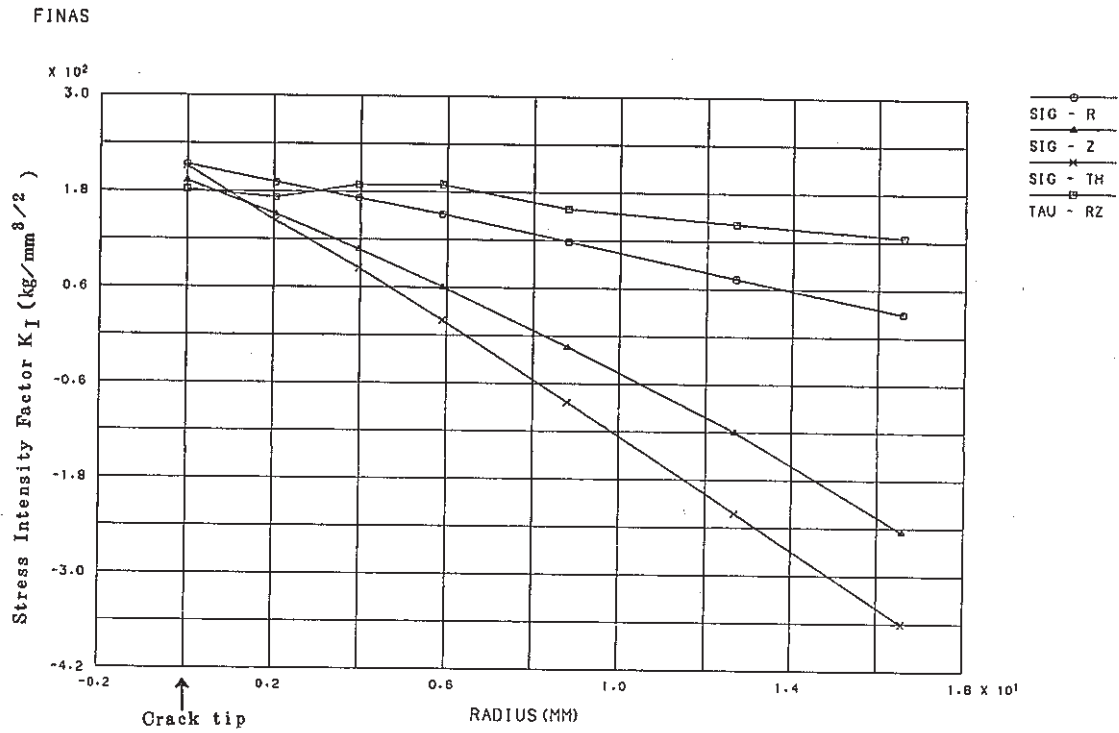


Fig. A.6-4 Extrapolation of K_I Value to Crack Tip (Elastic Analysis)

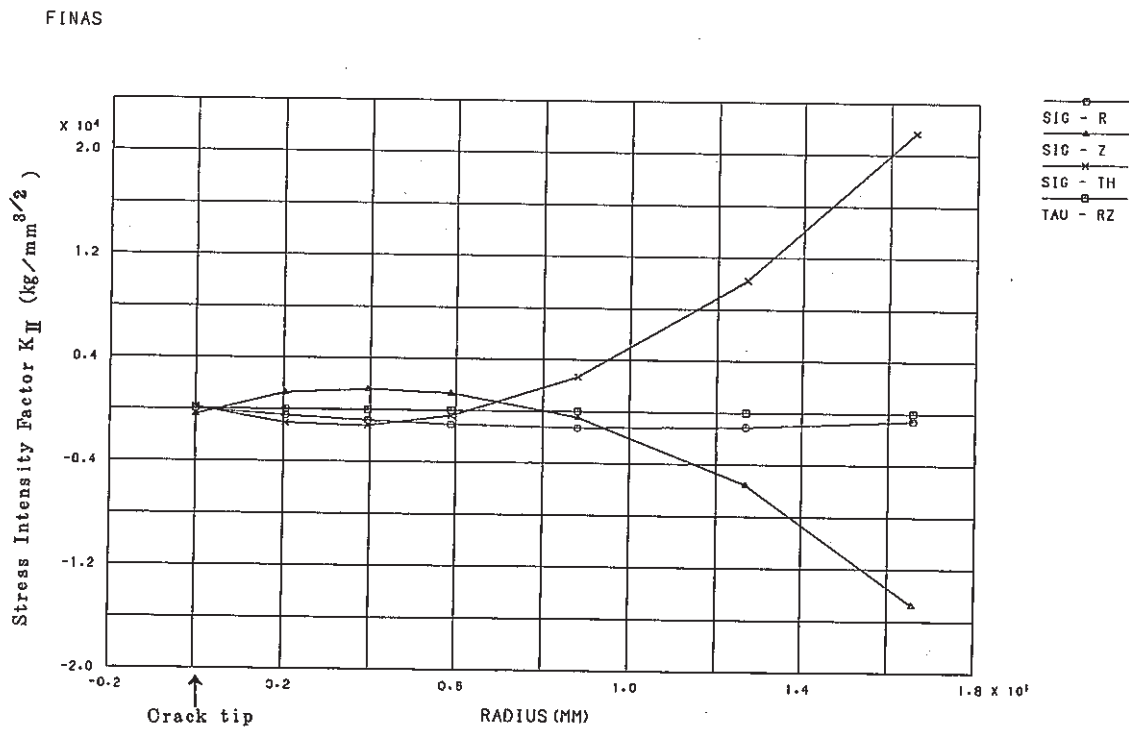


Fig. A.6-5 Extrapolation of K_{II} Value to Crack Tip (Elastic Analysis)

FINAS

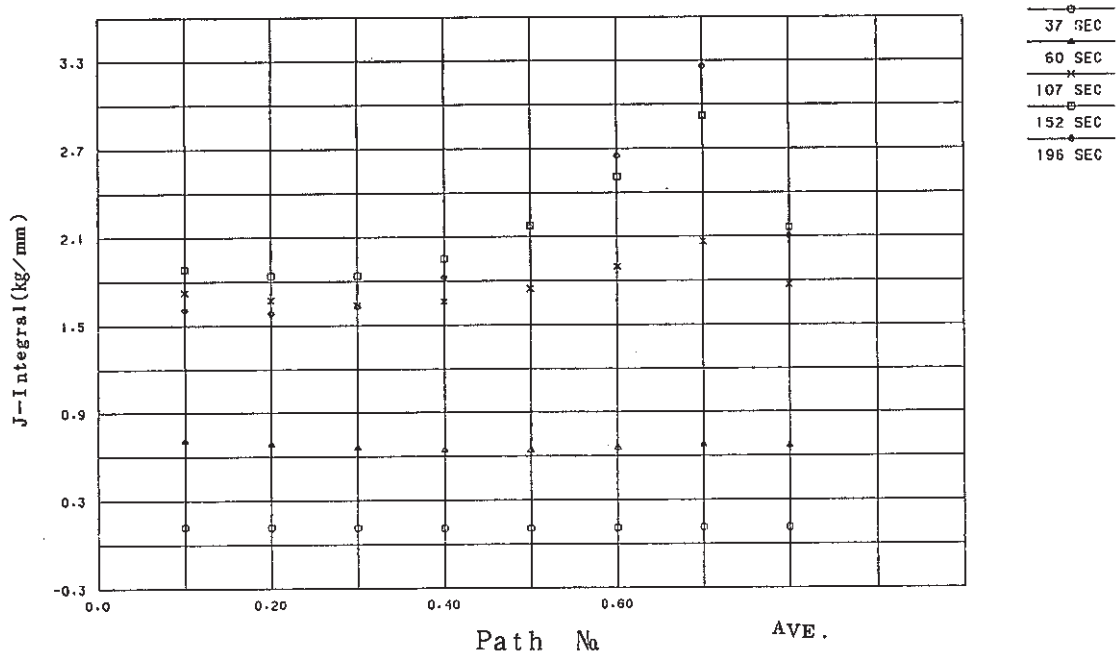


Fig. A.6-6 \hat{J} -Integral of Each Path (Elastic Analysis)

FINAS

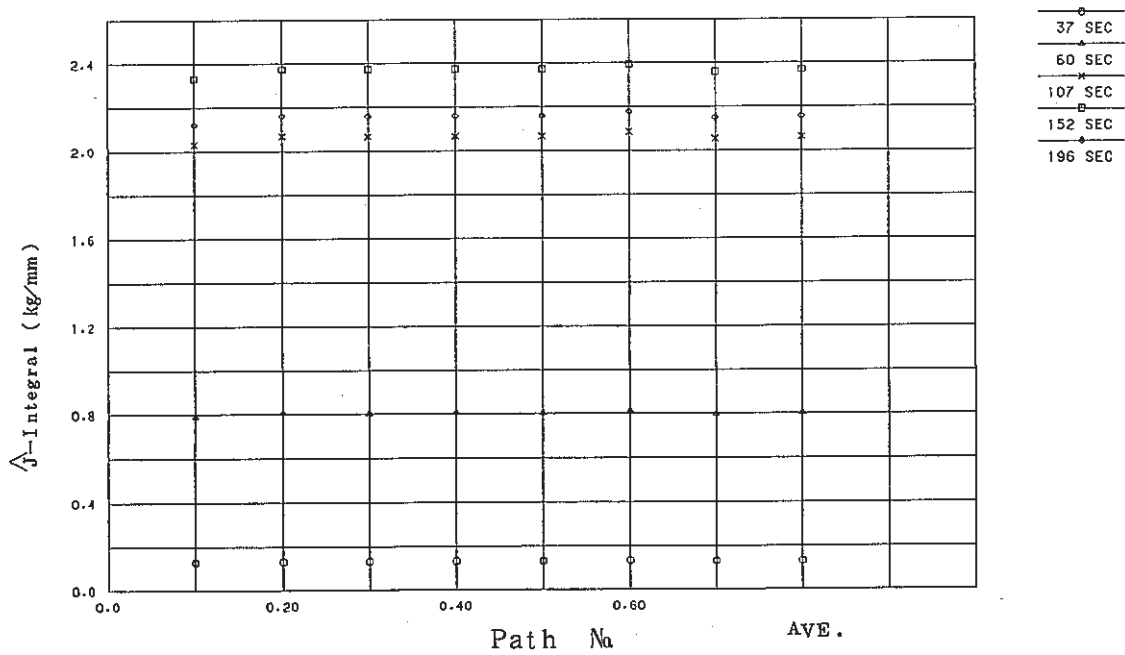


Fig. A.6-7 \hat{J} -Integral of Each Path (Elastic Analysis)

Table A.6-4 Stress Intensity Factor K_I and K_{II} calculated by CANIS
(In-Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
 FRACTURE MECHANICS PARAMETERS
 STEP ----- 26
 TIME ----- 152.000
 CRACK TIP TEMP. --- 476.435
 OPENING DISP. ----- 0.93821E-01 (FROM CRACK TIP 2.9211)

*** K-VALUE (K-1) ***

POINT	RADIUS	PHI	SIG-R	SIG-Z	SIG-TH	TAU-RZ
1	2.046	0.272	94.542	114.42	109.92	82.427
2	3.957	0.140	99.562	114.53	70.991	124.45
3	5.891	0.094	89.305	76.756	3.8981	139.83
4	8.803	0.063	61.879	-21.735	-83.299	38.138
5	12.691	0.043	22.391	-117.19	-135.80	6.9924
6	16.582	0.033	0.52907	-171.22	-177.12	2.5455
EXTERP.			110.98	181.51	195.32	124.95

*** K-VALUE (K-2) ***

POINT	RADIUS	PHI	SIG-R	SIG-Z	SIG-TH	TAU-RZ
1	2.046	0.272	-224.26	967.59	-801.79	10.859
2	3.957	0.140	-471.39	1702.4	-1014.9	8.6186
3	5.891	0.094	-633.37	1666.9	-83.181	6.5239
4	8.803	0.063	-657.43	-699.15	2658.5	1.1926
5	12.691	0.043	-343.25	-5413.1	6249.1	0.15181
6	16.582	0.033	-10.598	-10316.	10648.	0.42319E-01
EXTERP.			15.666	872.22	-1628.0	15.507

Table A.6-5 J-Integral calculated by CANIS
(In-Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
 FRACTURE MECHANICS PARAMETERS

STEP ----- 26
 TIME ----- 152.000
 CRACK TIP TEMP. --- 476.435
 OPENING DISP. ----- 0.93821E-01 (FROM CRACK TIP 2.9211)

*** J-VALUE ***

PASS	J	K(P.STRS)	K(P.STRN)
1	1.5150	157.80	165.42
2	1.4283	153.22	160.62
3	1.4652	155.18	162.68
4	1.6056	162.44	170.30
5	1.6974	167.03	175.10
6	1.7369	168.96	177.13
7	1.7049	167.40	175.49
AVE.	1.5933	161.83	169.65

Table A.6-6 \hat{J} -Integral calculated by CANIS
(In-Elastic Analysis)

MODEL-2 THERMAL STRESS (CRACK = 15 MM)
 FRACTURE MECHANICS PARAMETERS

STEP ----- 26
 TIME ----- 152.000
 CRACK TIP TEMP. --- 476.435
 OPENING DISP. ----- 0.93821E-01 (FROM CRACK TIP 2.9211)

*** JH-VALUE ***

PASS	JH	K(P.STRS)	K(P.STRN)
1	2.2658	192.97	202.30
2	2.3234	195.42	204.86
3	2.3365	195.96	205.43
4	2.3414	196.17	205.65
5	2.3408	196.14	205.62
6	2.3626	197.06	206.58
7	2.3404	196.13	205.60
AVE.	2.3301	195.70	205.15

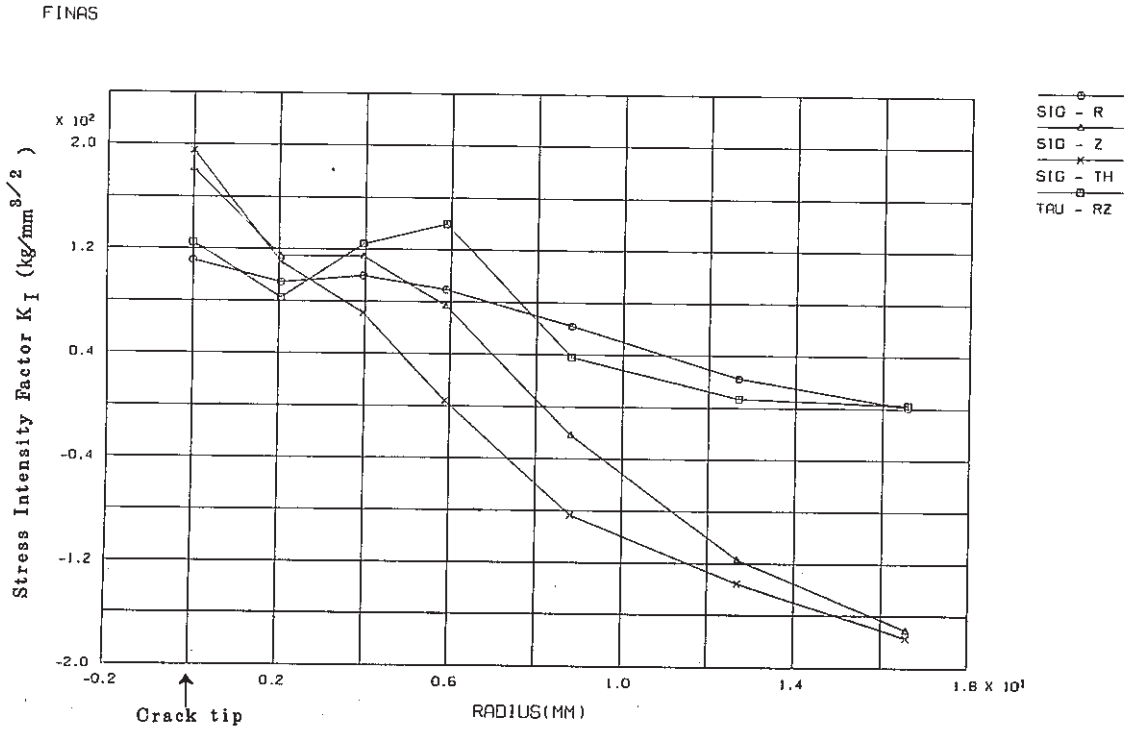


Fig. A.6-8 Extrapolation of K_I Value to Crack Tip (In-Elastic Analysis)

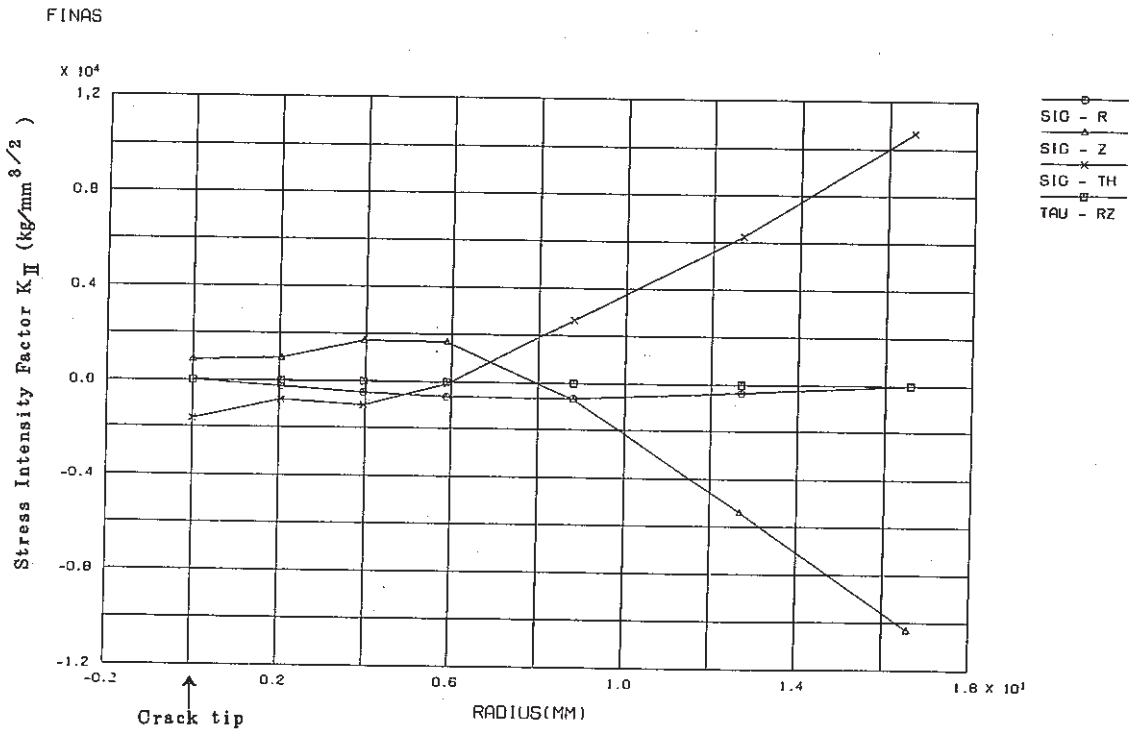


Fig. A.6-9 Extrapolation of K_{II} Value to Crack Tip (In-Elastic Analysis)

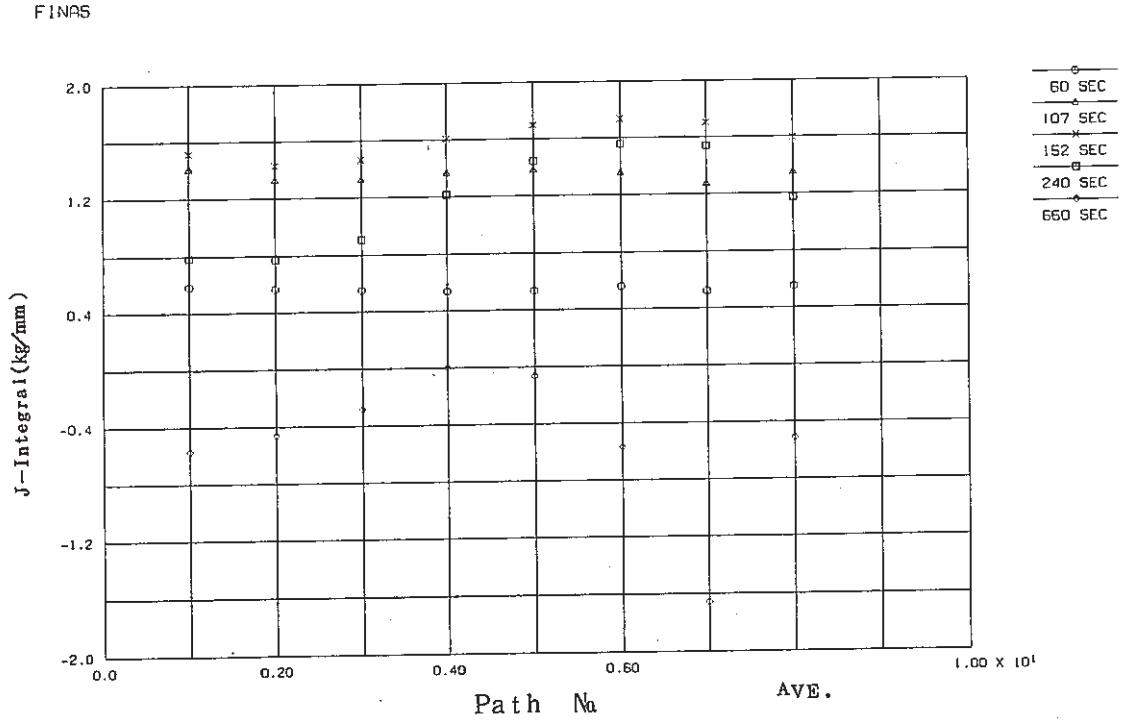


Fig. A.6-10 J-Integral of Each Path (In-Elastic Analysis)

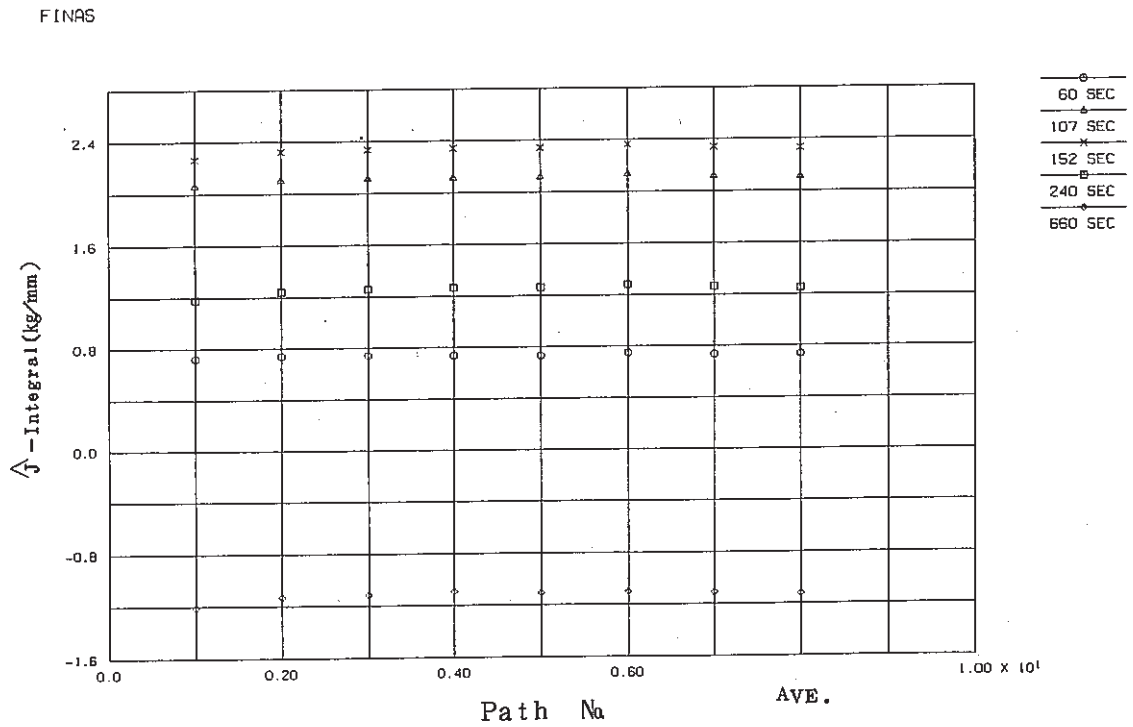


Fig. A.6-11 \hat{J} -Integral of Each Path (In-Elastic Analysis)

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機械の研究, 第33巻, 第1号(1981)
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附録B 3次元問題における破壊力学パラメータ

附録B 3次元問題における破壊力学パラメータ

3次元き裂問題における破壊力学パラメータとして、応力拡大係数 K 、 J 積分及び \hat{J} 積分について示す。

応力拡大係数については、附録Aに示したように、き裂前縁の任意の座標系 $X_1 X_2 X_3$ における応力成分より、各変形モードについて K_I 、 K_{II} 及び K_{III} 値を求める。き裂前縁の応力場を表す式は既に式(A-1)~(A-3)で示した。

J 積分については、Fig. A.2-2に示すき裂前縁の任意の点における基準座標系 XYZ 各方向の J 積分値(J_x, J_y, J_z)を次式で表わす。

$$J_k = \int_{\Gamma} \left(W_{n_k} - T_1 \frac{\partial u_1}{\partial X_k} \right) d\Gamma + \int_{A} \left\{ \frac{\partial W}{\partial P} P_k - \frac{\partial}{\partial P} \left(\sigma_{1j} P_j \frac{\partial u_1}{\partial X_k} \right) \right\} dA \dots\dots\dots (B-1)$$

($K=X, Y, Z$)

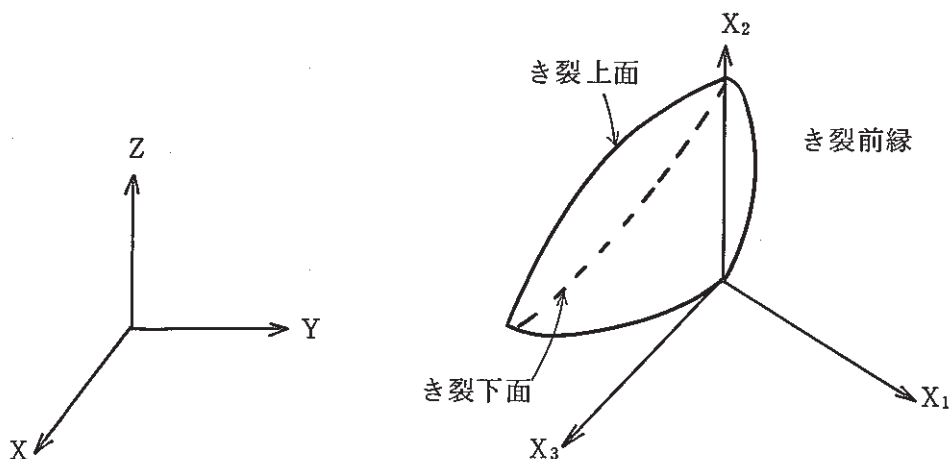


Fig. B-1 Coordinate Systems in 3D Cracking

J 値は(J_x, J_y, J_z)により次式で表わされる。

$$J = J_x \cos \theta_0 + J_y \cos \varphi_0 + J_z \cos \phi_0 \dots\dots\dots (B-2)$$

ここで、 $\theta_0, \varphi_0, \phi_0$ は、き裂進展方向の X_1 軸と基準座標系 XYZ 軸とのなす角である。

\hat{J} 積分についても、き裂前縁の任意の点における基準座標系 XYZ 各方向の \hat{J} 積分値 ($\hat{J}_x, \hat{J}_y, \hat{J}_z$) を次式で表わす。

$$\hat{J}_k = \int_{\Gamma} \left(-T_1 \frac{\partial u_1}{\partial X_k} \right) d\Gamma + \iint_A \left\{ \sigma_{ij} \frac{\partial \varepsilon_{ij}}{\partial X_k} - \frac{\partial}{\partial P} \left(\sigma_{ij} P_j \frac{\partial u_1}{\partial X_k} \right) \right\} dA \quad \dots\dots\dots (B-3)$$

(K=X, Y, Z)

また同様に \hat{J} 値は ($\hat{J}_x, \hat{J}_y, \hat{J}_z$) により次式で表わされる。

$$\hat{J} = \hat{J}_x \cos \theta_0 + \hat{J}_y \cos \varphi_0 + \hat{J}_z \cos \phi_0 \quad \dots\dots\dots (B-4)$$

(1) 検証問題

3次元問題として Fig. B-2 に示すような埋没円き裂を有する無限体について解析を実施した。有限要素モデルは 1/8 モデルである。使用要素は 20 節点六面体要素 HEX 20 である。解析は引張荷重を負荷する場合の弾性解析であり、材料データとして次の値を仮定した。

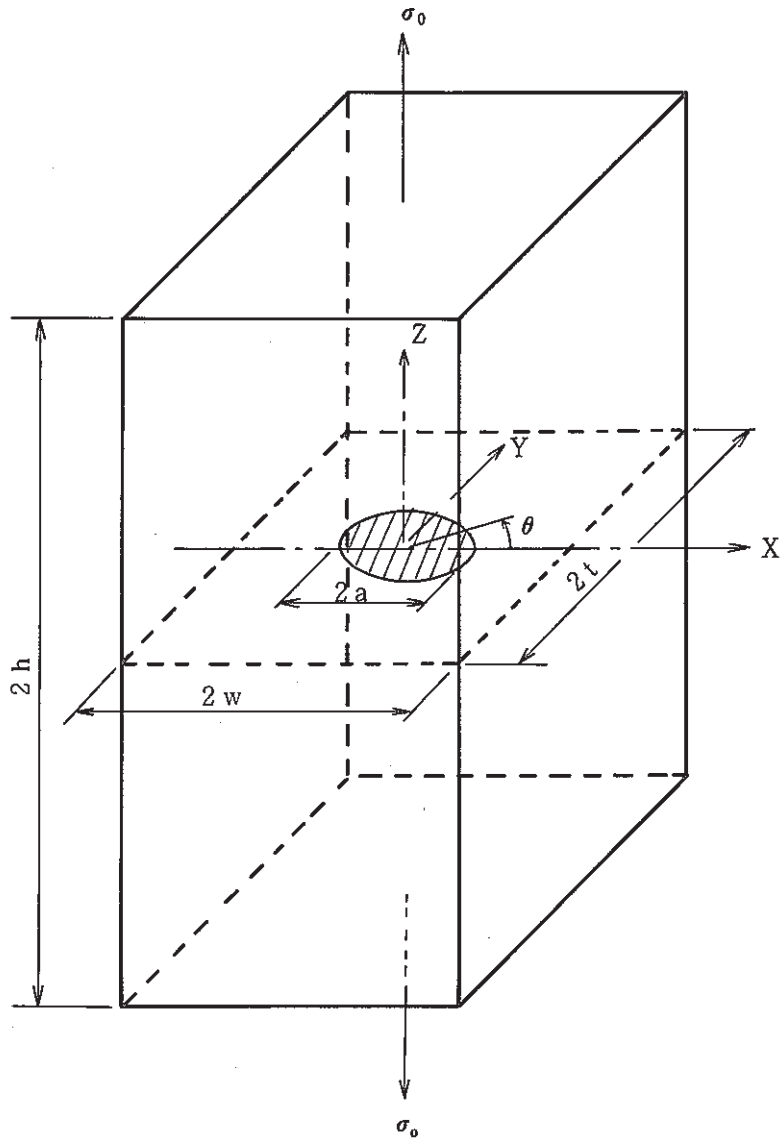
弾性係数 $E = 2.1 \times 10^4 \text{ kg/mm}^2$

ポアソン比 $\nu = 0.3$

引張荷重として $\sigma_0 = 100 \text{ kg/mm}^2$ を負荷した。この時の K 値、 J 値及び \hat{J} 値を Fig. B-3 に示すポジション A~G において求めた。また、図中に K_I 値を計算するための積分点位置を示す。 K_I 値はこれらの値よりき裂先端に外挿した。Fig. B-4 は、 J 値を計算する積分径路である。Table B-1 に理論解 ($K_I = 2 \sigma_0 \sqrt{a/\pi}$) との比較を示す。ここで、 J 値及び \hat{J} 値は平面ひずみ場として K に換算した値を示す。解析結果は工学的に満足できる程度で理論解と一致している。

Table B-1 A Comparison of Different Methods of Stress Intensity Factor for Unfinite Body containing a Penny Shaped Crack

ポジション θ (度)	理論解 K_I	σ_y より求めた		J 値より求めた		\hat{J} 値より求めた	
		K_I	誤差 (%)	K	誤差 (%)	K	誤差 (%)
A 3.75	504.63	464.37	-8.0	499.54	-1.0	513.11	1.7
B 11.25	504.63	464.70	-7.9	499.67	-1.0	513.23	1.7
C 22.50	504.63	465.66	-7.7	499.75	-1.0	513.57	1.8
D 37.50	504.63	468.68	-7.1	499.71	-1.0	513.52	1.8
E 52.50	504.63	468.67	-7.1	499.74	-1.0	513.55	1.8
F 67.50	504.63	465.68	-7.7	499.79	-1.0	513.60	1.8
G 82.50	504.63	464.48	-8.0	499.87	-0.9	513.65	1.8



$$a/t = 0.2$$

$$a/w = 0.2$$

$$h/t = 1.0$$

$$a = 20 \text{ mm}$$

$$w = 100 \text{ mm}$$

$$t = 100 \text{ mm}$$

$$h = 100 \text{ mm}$$

$$\sigma_0 = 100 \text{ kg/mm}^2$$

Fig. B-2 Unfinite Body containing a Penny Shaped Crack

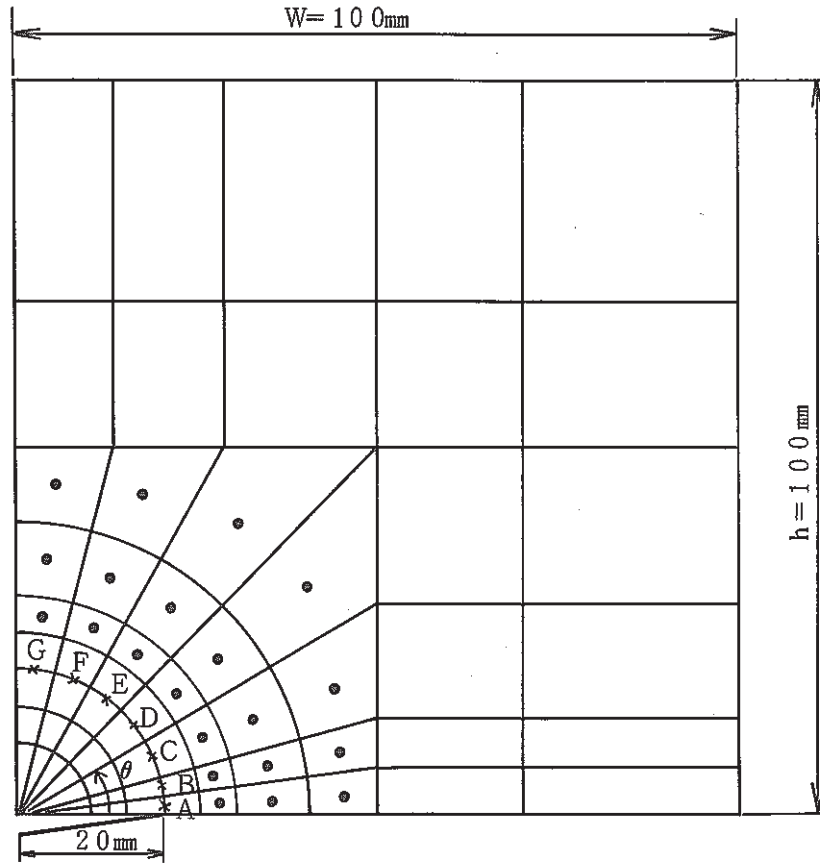


Fig. B-3 Finite Element Model and Integral Points for K Evaluation

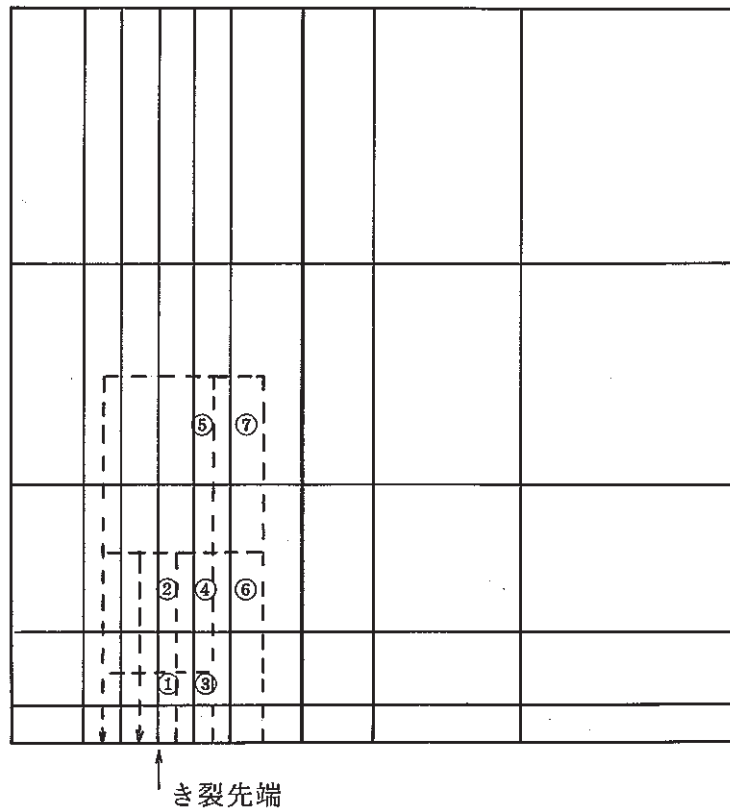


Fig. B-4 Paths for J-Integral Evaluation

(2) 解析結果例

3次元問題における破壊力学パラメータの解析結果例を以下に示す。解析モデルはFig. B-5に示す計装ノズル部である。Fig. B-6は直接法により応力拡大係数を計算するために用いた積分点位置である。これらの積分点位置で計算した応力場の強さをき裂先端に外挿することにより K_I 、 K_{II} 及び K_{III} 値を求めることができる。Fig. B-7は \int 積分で用いた積分径路である。ここでは、 $\varphi=50^\circ$ における応力拡大係数及び \int 積分を示す。

Table B-2に応力拡大係数 K_I 、 K_{II} 及び K_{III} の計算結果を示す。ここで示すのはコードショックにおいて応力が最大となる時(150 sec)の $\varphi=50^\circ$ 方向の計算結果である。Fig. B-8~Fig. B-10は、き裂先端に外挿した K_I 、 K_{II} 及び K_{III} 値である。このように開口型のモードI変形が他の変形より主である。

Table B-3に \int 積分の径路積分結果を示す。 $\varphi=50^\circ$ 方向の基準座標系で示される \hat{J}_X 、 \hat{J}_Y 、 \hat{J}_Z の和として \int 積分値を得る。またこのようにして得られた \int 積分値を K_I に変換した値も示すが、(平面ひずみを仮定すると $K_I=95.6\text{kg}/\text{mm}^{3/2}$)直接法により得られた K_I 値(σ_y より求めた K_I 、 $K_I=92.4\text{kg}/\text{mm}^{3/2}$)とほぼ同じ値を示した。また、Fig. B-11にみられるように \int 積分は径路に独立である。

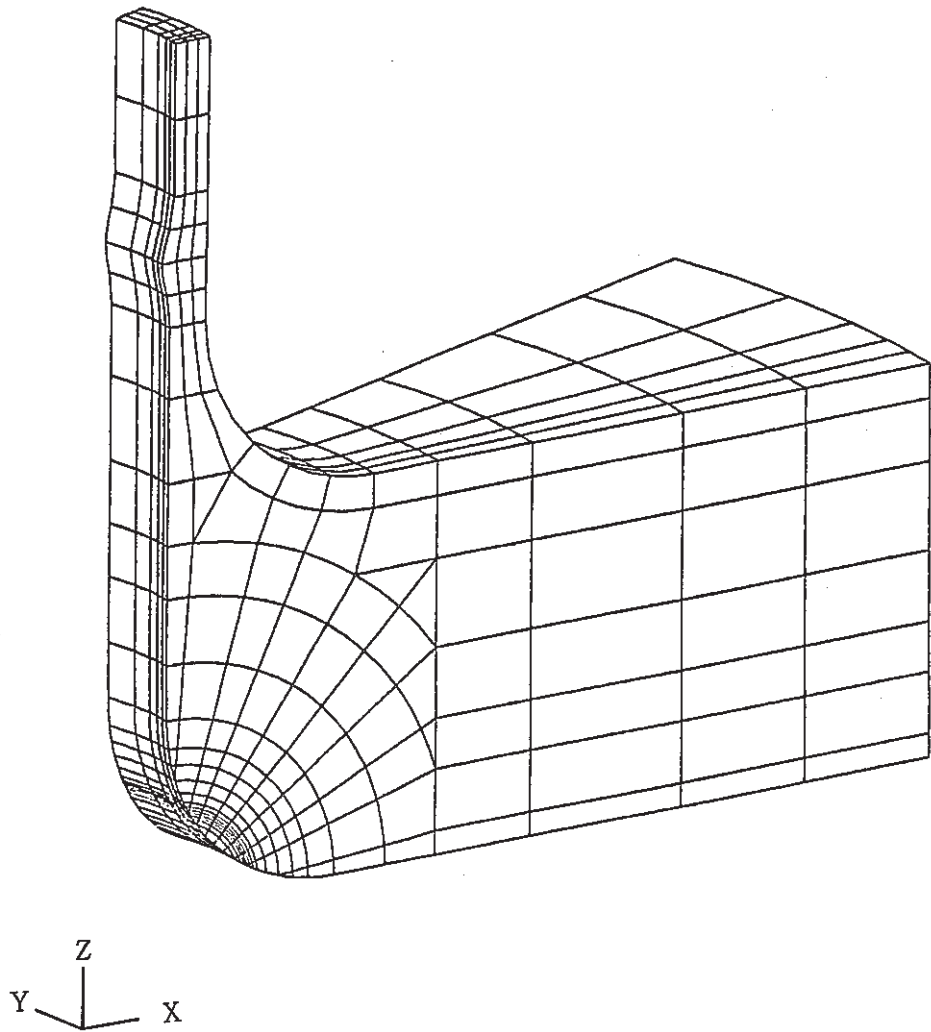


Fig. B-5 Finite Element Model for Instrumental Nozzle

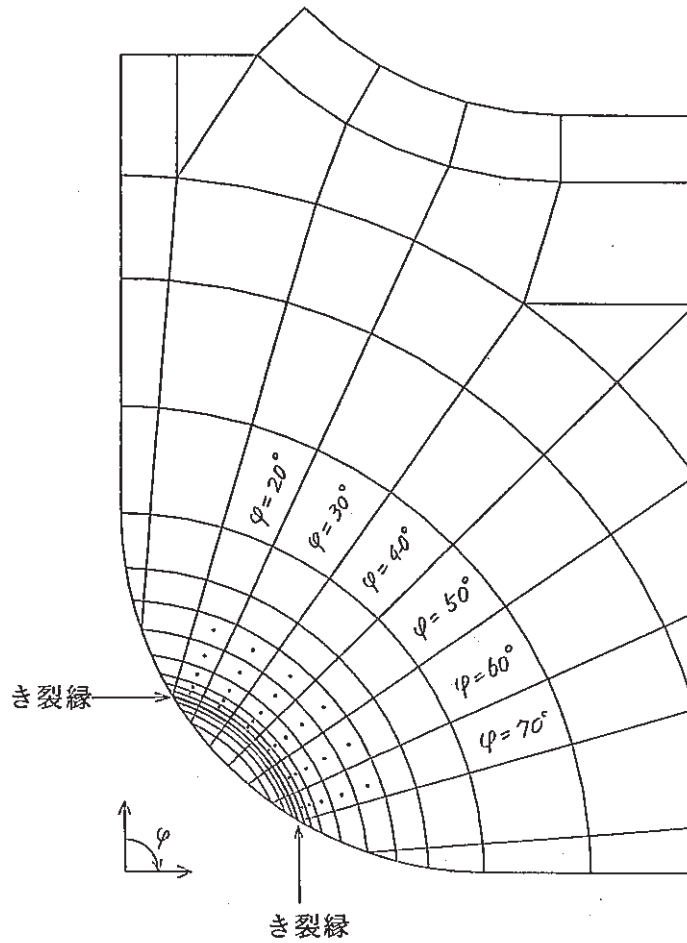


Fig. B-6 Mesh Breakdown for the Finite Element Analysis and Integral Points for K Evaluation

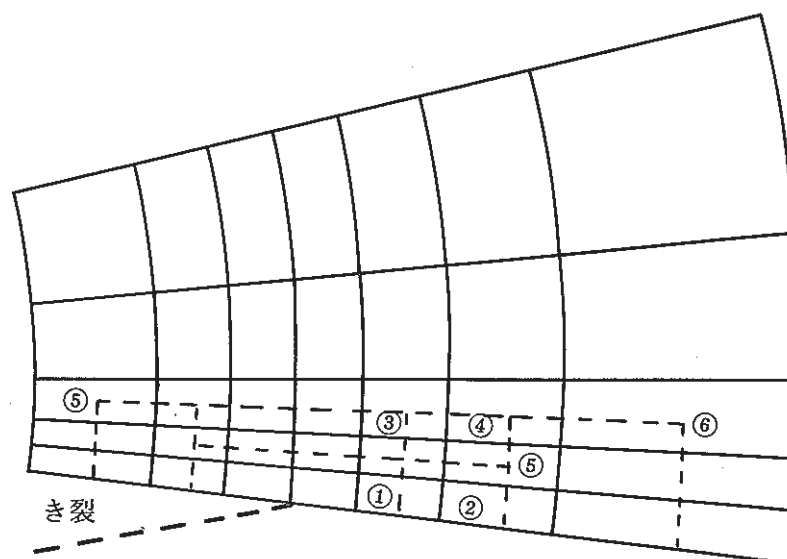


Fig. B-7 Paths for \hat{J} -Integral Evaluation

Table B-2 Stress Intensity Factor K_I , K_{II} and K_{III} calculated by CANIS

MODEL-6-1 (R = 9.6 MM) PARAMETER OF FRACTURE MECHANICS

POSITION - D, THETA = 50.000, DEPTH = 9.600

FRACTURE MECHANICS PARAMETERS

STEP ----- 2
 TIME ----- 150.000
 CRACK TIP TEMP. --- 414.807
 OPENING DISP. ----- 0.11407E-01 (FROM CRACK TIP 0.55002)
 CRACK DIRECTION --- (X) 40.000 (Y) 90.000 (Z) 50.000

*** K-VALUE (K-1) ***

POINT	RADIUS	PHI	SIG-X	SIG-Y	SIG-Z	TAU-XY	TAU-YZ	TAU-ZX
1	0.421	0.315	59.754	102.12	74.781	83.757		
2	0.786	0.168	55.725	110.57	66.484	98.564		
3	1.456	0.092	52.037	122.31	52.540	72.820		
4	2.553	0.054	50.873	138.57	38.861	29.339		
5	3.952	0.036	51.596	149.18	27.100	11.598		
EXTERP.			62.452	92.384	84.521	108.09		

*** K-VALUE (K-2) ***

POINT	RADIUS	PHI	SIG-X	SIG-Y	SIG-Z	TAU-XY	TAU-YZ	TAU-ZX
1	0.421	0.315	-121.18	782.81	-470.30	12.611		
2	0.786	0.168	-218.24	1387.6	-788.53	8.1905		
3	1.456	0.092	-376.12	2705.0	-1142.5	3.3346		
4	2.553	0.054	-631.34	5193.8	-1448.2	0.78616		
5	3.952	0.036	-962.36	8372.1	-1517.0	0.20706		
EXTERP.			-23.245	-53.381	-178.98	16.122		

*** K-VALUE (K-3) ***

POINT	RADIUS	PHI	SIG-X	SIG-Y	SIG-Z	TAU-XY	TAU-YZ	TAU-ZX
1	0.421	0.315					10.070	-41.763
2	0.786	0.168					6.9826	-65.558
3	1.456	0.092					3.0115	-20.056
4	2.553	0.054					0.88870	215.19
5	3.952	0.036					0.41282	665.85
EXTERP.							12.938	-39.535

Table B-3 \hat{J} -Integral calculated by CANIS

MODEL-G-1 (R - 9.6 MM) PARAMETER OF FRACTURE MECHANICS

POSITION - D, THETA = 50.000, DEPTH = 9.600

FRACTURE MECHANICS PARAMETERS

STEP ----- 2
 TIME ----- 150.000
 CRACK TIP TEMP. --- 414.807
 OPENING DISP. ----- 0.11407E-01 (FROM CRACK TIP 0.55002)
 CRACK DIRECTION --- (X) 40.000 (Y) 90.000 (Z) 50.000

*** JH-VALUE ***

PASS	JH	JH(X)	JH(Y)	JH(Z)	K(P.STRS)	K(P.STRN)
1	0.49637	0.37670	-.81933E-01	0.32329	91.788	96.106
2	0.49836	0.37723	-.47379E-01	0.32575	91.972	96.298
3	0.49688	0.37626	-.81109E-01	0.32460	91.835	96.155
4	0.49738	0.37524	-.47428E-01	0.32660	91.881	96.203
5	0.47958	0.36060	-.44035E-01	0.31634	90.222	94.465
6	0.47709	0.35712	0.30948E-01	0.31662	89.988	94.220
AVE.	0.49095	0.37053	-.45156E-01	0.32220	91.285	95.579

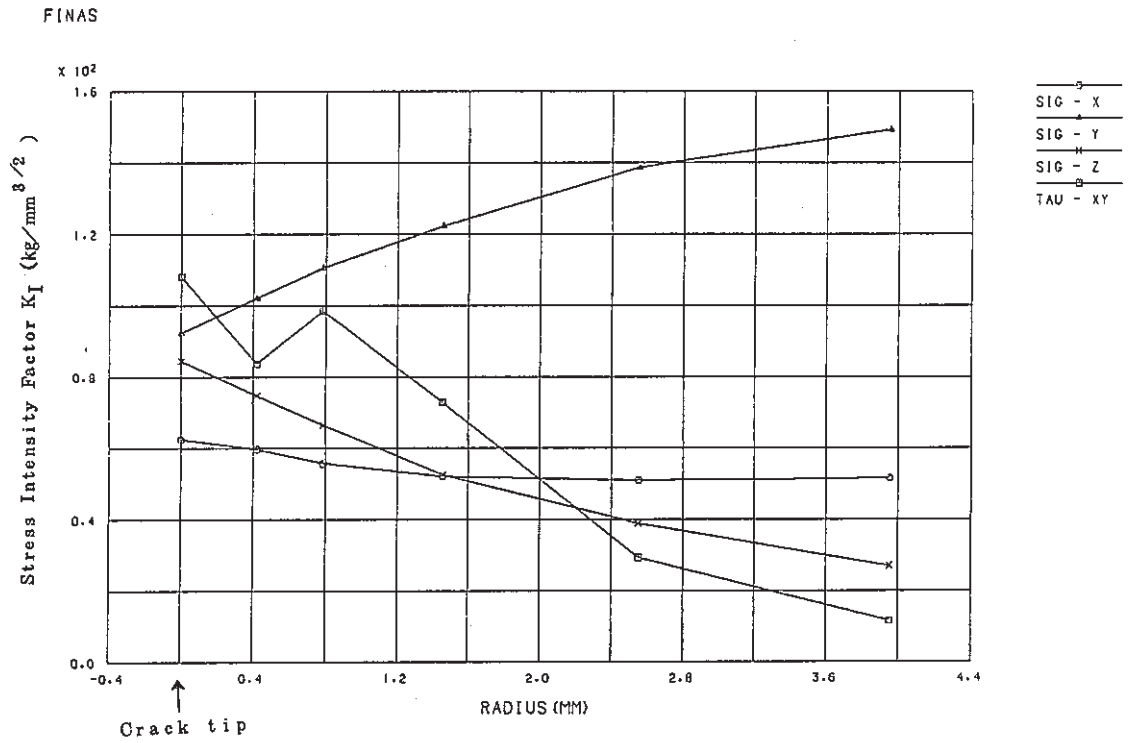


Fig. B-8 Extrapolation of K_I Value to Crack Tip ($\psi=50^\circ$)

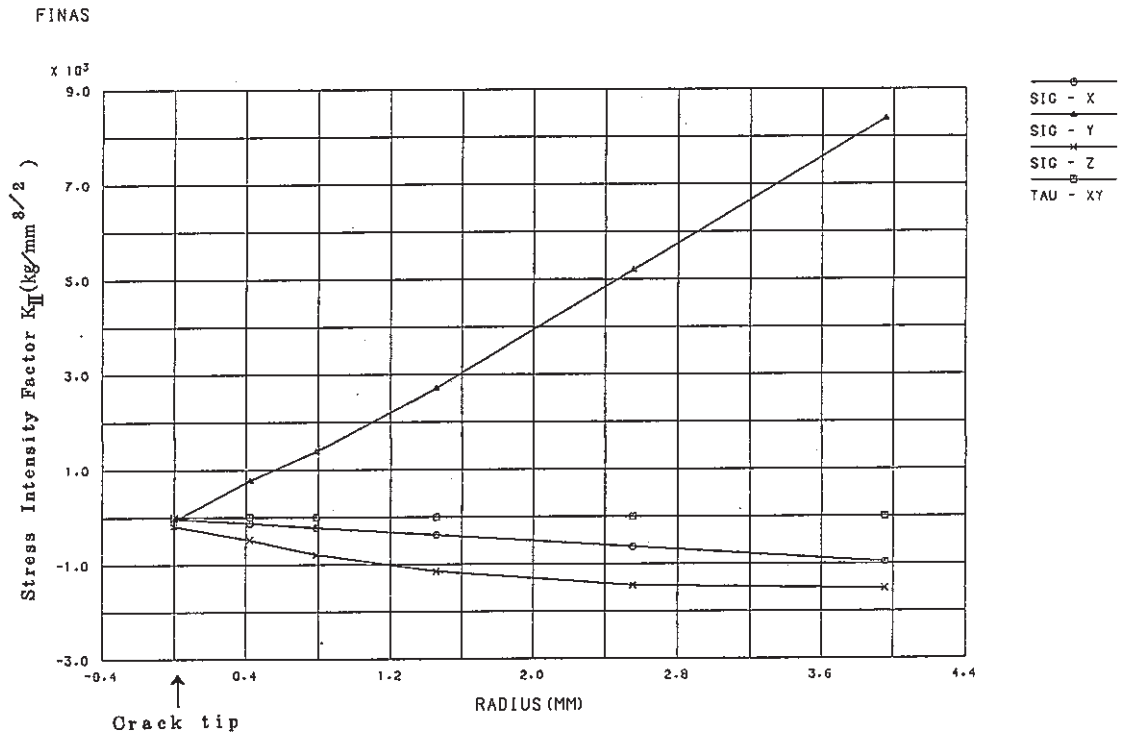


Fig. B-9 Extrapolation of K_{II} Value to Crack Tip ($\psi=50^\circ$)

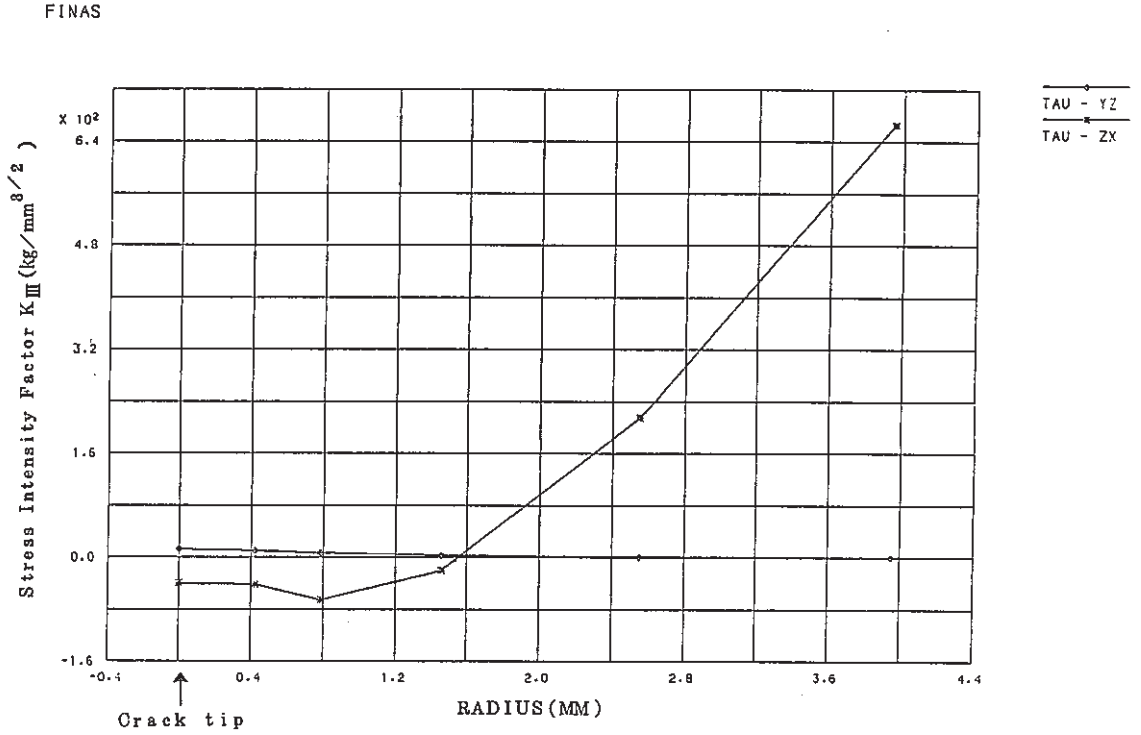


Fig. B-10 Extrapolation of K_{III} Value to Crack Tip ($\psi=50^\circ$)

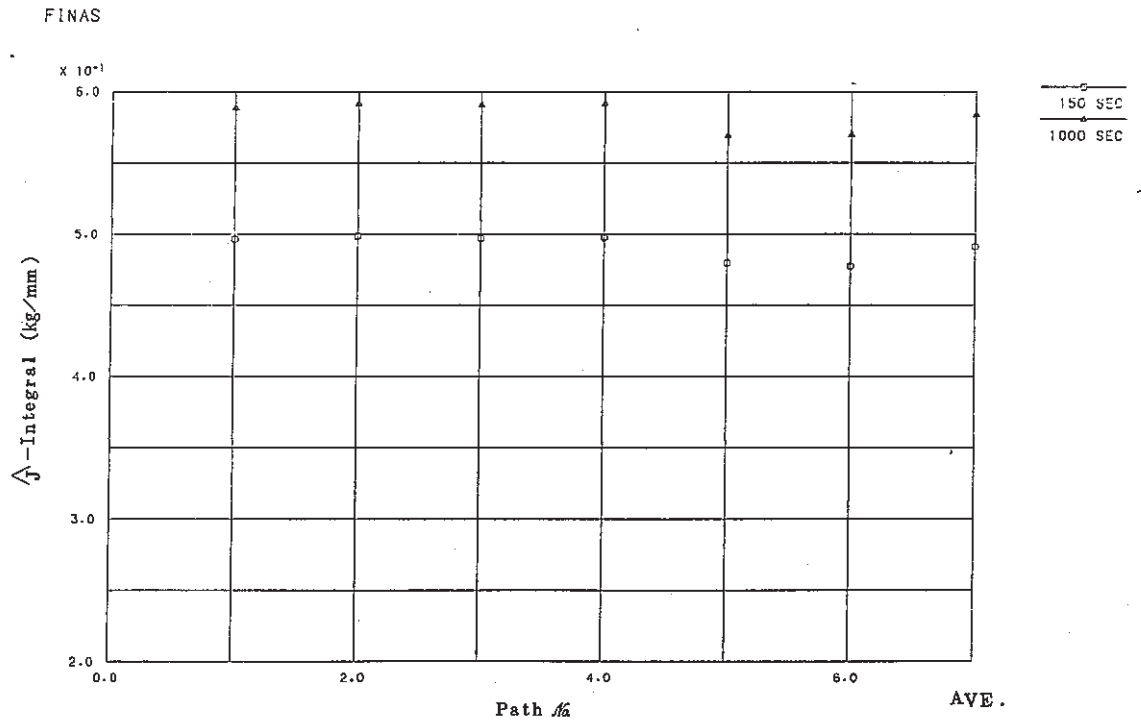


Fig. B-11 \hat{J} -Integral of Each Pass ($\psi=50^\circ$)

附録 C 弾性応力解析結果

附録C 弾性応力解析結果

き裂を考慮した解析モデルを用いて実施した熱過渡に対する応力解析結果を示す。熱過渡はコールドショック(250°C×0.25 hrs)+ホットショック(600°C×1.75 hrs)であるが、本解析では、第5報「伝熱・応力解析と強度評価」の熱伝導解析結果を利用して弾性応力解析を実施した。計装ノズル部については3次元モデルその他は軸対称モデルである。

C.1. 最終溶接部

き裂深さ1, 5, 10, 15, 20, 及び27mmの6ケースについて弾性応力解析を実施した。全モデルとも境界条件はFig. 3.1-1に示すように下端をZ軸方向固定及び上端のZ軸方向を一定とした。全てのモデルについて、き裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻におけるき裂面及び内外表面に沿った応力分布、及び応力コンター図を示す。

最終溶接部ではき裂先端近傍の応力時刻歴(Fig. C.1.1)にみられるように、コールドショック時の最大応力は約152 sec, またホットショック時の最大応力は約1020 secで顕著に表われている。き裂面の応力分布はFig.C.1.4にみられるようにき裂先端近傍で降伏応力をはるかに超える大きな値を示す。この領域はある限られた狭い範囲について発生しており、き裂先端近傍で $1/\sqrt{r}$ に比例する特異応力場が支配的となっている。この特異応力場を特徴づけるパラメータとして応力拡大係数Kが導入されている。内表面に沿った応力分布(Fig.C.1.2, Fig.C.1.6)は、き裂深さが深くなってもあまり変化しないが、き裂の近傍でのみ軸方向応力及び周方向応力が減少し、特に軸方向応力の減少が顕著である。外表面に沿った応力分布(Fig.C.1.3, Fig.C.1.7)は、き裂が深くなるにしたがってき裂線上の外表面で応力の極値が顕著になる。

C.2. 入口ノズル

き裂深さ(a_1, a_2, a_3)=(1, 1, 1), (2, 2.65, 2), (4, 5.3, 4)の3ケースについて弾性応力解析を実施した。全モデルとも境界条件はFig. 3.1-3に示すように入口側の上端のZ軸方向変位を固定とし、短管部下端及び上部鏡端を自由とした。全モデルについて、 a_1, a_2, a_3 き裂のき裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻における a_1, a_2, a_3 き裂面及び内外表面に沿った応力分布、及び応力コンター図を示す。

コールドショック時の最大応力は内表面側の a_1, a_2 き裂では、12 secとかなり早いですが、 a_3 き裂では90~120 secと遅れている。またホットショックにおいても前者が910 secに対し後者は960~1020 secとなっている。また、 a_1, a_2 き裂では、応力の最大値が短い期間

で発生しているのに対し a_3 き裂では最大値は顕著でなく、応力履歴も緩やかである。内表面に沿った応力分布 (Fig. C.2.4, Fig. C.2.11) は厚肉部の a_1 き裂付近では周方向が優勢であり、この付近で発生した軸方向主体の亀甲状き裂と対応している。またき裂深さが深くなっても応力成分の大小関係はあまり変化しない。

C.3. シンニング部

き裂深さ $(a_1, a_2) = (1, 1), (4, 5), (7, 10), (9.4, 15)$ の4ケースについて弾性応力解析を実施した。全モデルとも境界条件は Fig. 3.1-5 に示すように上部胴下端の Z 軸方向変位を固定とし、上部鏡端を自由とした。全モデルについて、 a_1, a_2 き裂のき裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻における a_1, a_2 き裂面及び内外表面に沿った応力分布、さらに応力コンター図を示す。

コールド及びホットショック時の最大応力は、それぞれ約 138 sec, 960~975 sec である。内表面に沿った応力分布 (Fig. C.3.3, Fig. C.3.8) にみられるように、 a_2 き裂付近では、き裂が浅い場合には軸方向応力が優勢である。外表面に沿った応力分布 (Fig. C.3.4, Fig. C.3.9) では、 a_1 及び a_2 き裂とも応力の極値を示すが、 a_2 き裂の極値の方が a_1 き裂のそれよりかなり大きい。これは a_2 き裂の外表面に全周にわたる PT 欠陥指示があったのに対して a_1 き裂の外表面には欠陥指示のなかったこと¹⁾ に対応する。また、本解析では2つのき裂を想定したが、軸方向応力のコンター (Fig. C.3.7, Fig. C.3.12) からわかるように互いに影響を及ぼしていない。

C.4. コニカル・下部鏡部

き裂深さ 1, 15. 及び 32mm の3ケースについて弾性応力解析を実施した。全モデルとも境界条件は Fig. 3.1-7 に示すように下部胴上端の Z 軸方向変位を一定、スカート下端の Z 軸方向変位を固定及び下部鏡端を自由とした。全てのモデルについて、き裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻におけるき裂面及び内外表面に沿った応力分布、及び応力コンター図を示す。

Fig. C.4.1 にみられるようにき裂先端近傍の応力履歴は緩かな挙動を示している。コールドショックにおける最大応力は 90~120 sec, ホットショックにおける最大応力は 990~1020 sec である。また、最大相当応力はホットショック時がコールドショック時のそれをかなり上回っている。

C.5. 出口ノズル

き裂深さ $(a_1, a_2, a_3) = (1.45, 1.55, 0.7), (2.9, 3.1, 1.4)$ の2ケースについて弾性応力解析を実施した。全モデルとも境界条件は Fig. 3.1-9 に示すように出口側下端の Z 軸方向変位を固定、下部鏡端では回転を拘束し、さらに出口ノズルサーマルスリーブ上端の変位を自

由とした。全モデルについて、 a_1 , a_2 , a_3 き裂のき裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻におけるき裂面及び内外面に沿った応力分布、及び応力コンター図を示す。

外表面側で発生する a_2 , a_3 き裂は、Fig. C.5.2, Fig. C.5.3 にみられるように発生応力は他と比較してかなり小さい。コールドショック時のピークは、 a_1 , a_3 き裂で60 sec前後、 a_2 き裂で約10 secであり、ホットショック時のピークは950~1000 secである。

C.6. スタッドボルト部

き裂深さ1, 7, 10及び13mmの4ケースについて弾性応力解析を実施した。全モデルとも境界条件はFig. 3.1-11に示すように胴部の切断面については回転を拘束し、胴部のもうひとつの一端においてZ軸方向変位を固定した。全モデルについてき裂先端近傍の応力時刻歴、コールド及びホットショック時のき裂先端近傍の応力が最大となる時刻におけるき裂面及び内外表面に沿った応力分布、さらに応力コンター図を示す。

コールドショック時の最大応力は150 secであり、ホットショック時の最大応力は1000 secである。Fig. C.6.1に示すように最大応力を示す時点での応力履歴は緩かである。またスタッドボルトでは、このようなき裂を想定するとFig. C.6.7にみられるようにき裂の外側でr方向応力が緩和されて θ 方向応力が主となる場合がある。このようなことは、このき裂より放射状のき裂が発生したと良く対応する。(附録G参照)

C.7. 計装ノズル部

き裂形状はき裂前縁が円弧状の3次元き裂であり、その半径rは9.6, 12.8, 16.0 mmである(Fig. 3.1-14)。これら3ケースのき裂について弾性応力解析を実施した。全モデルとも境界条件はFig. 3.1-13に示すように、①面ABCDEFGF及び面HIJKにおける節点の周方向(θ 方向)変位を拘束、②辺EIにおける節点の軸方向(Z方向)を拘束、③面EFJIにおける節点の半径方向(X方向)変位を一様変位とした。全モデルについて、コールド及びホットショック時のき裂前縁近傍の応力が最大となる時刻におけるき裂前縁に沿った応力分布、き裂前縁近傍で相当応力が最大となる角度における応力分布、及び周方向応力コンター図を示す。

Fig. C.7.1にみられるようにき裂前縁での応力は周方向応力が主体である。想定き裂 $r=9.6$ mmでは $\varphi=50^\circ$ 付近で最大を示す。しかしながらき裂が進展すると $\varphi=90^\circ$ に近づくにつれて相当応力が大きくなっている。これは熱過渡が容器側($\varphi=90^\circ$)で厳しくノズル側($\varphi=0^\circ$)で緩かなためである。

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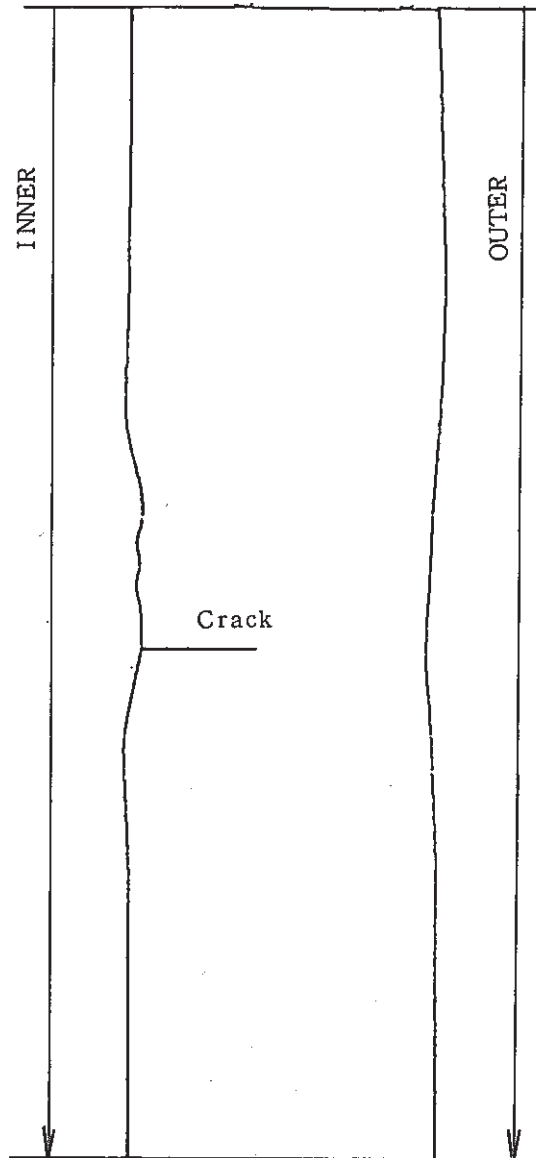


Fig. C.1-1 Evaluation Lines for Surface Stress Distribution of Finally Welded Portion

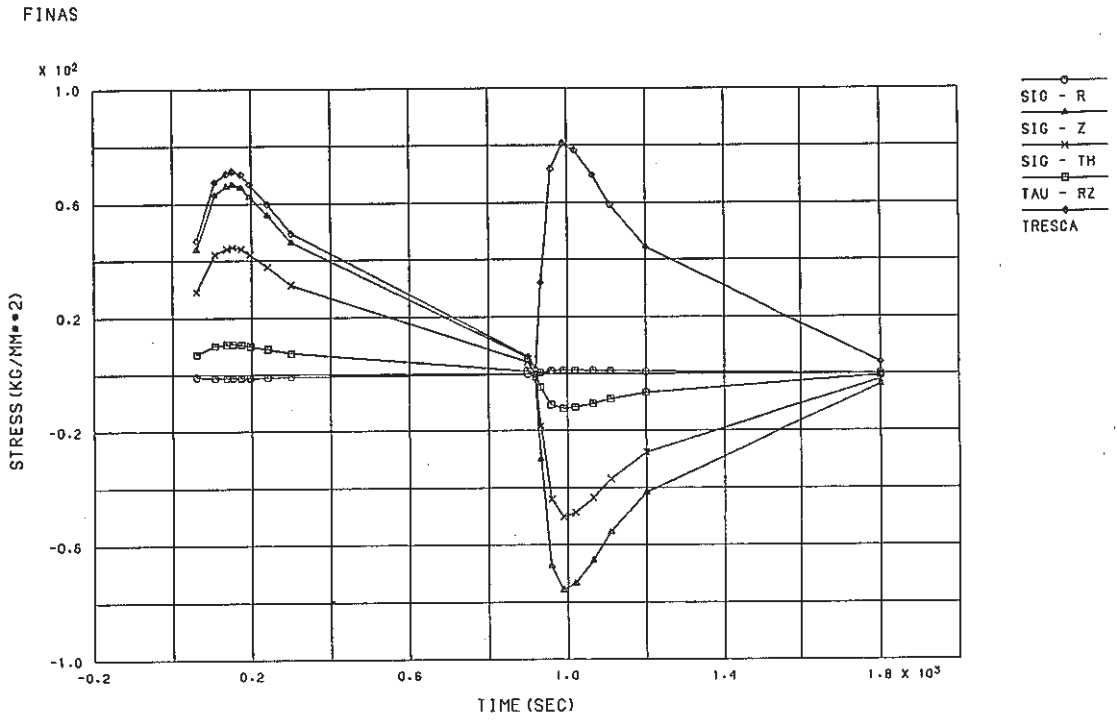


Fig. C.1.1-1 Stress History ahead of Crack Tip of Finally Welded Portion (crack depth a=1 mm)

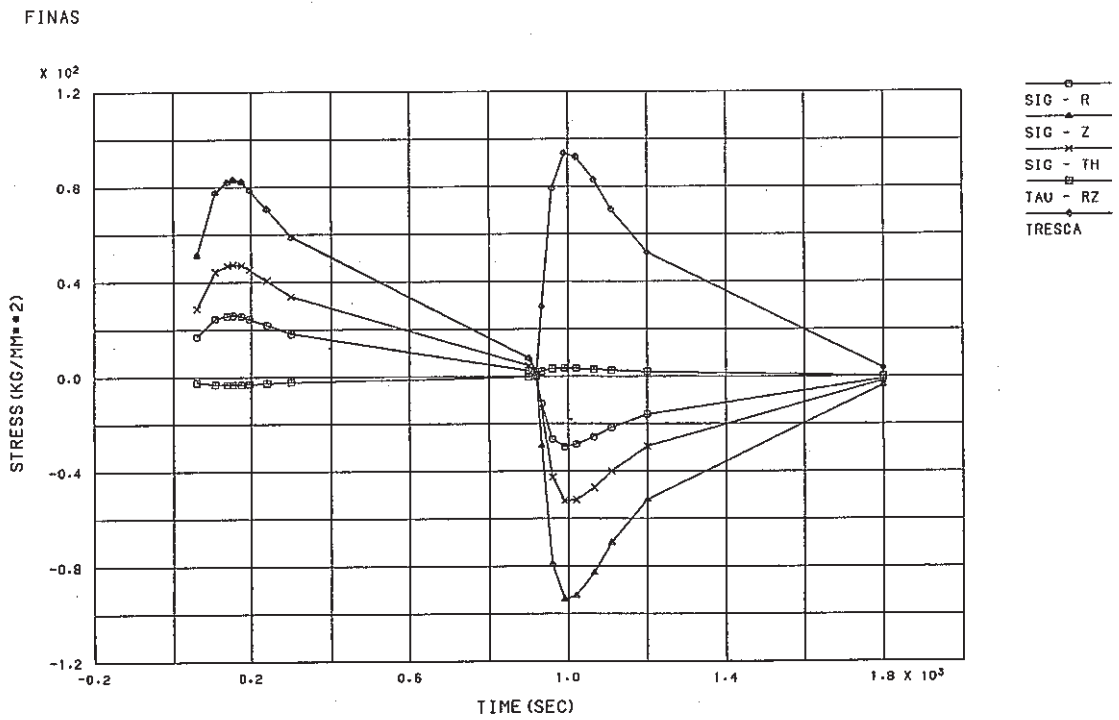


Fig. C.1.1-2 Stress History ahead of Crack Tip of Finally Welded Portion (crack depth a=5 mm)

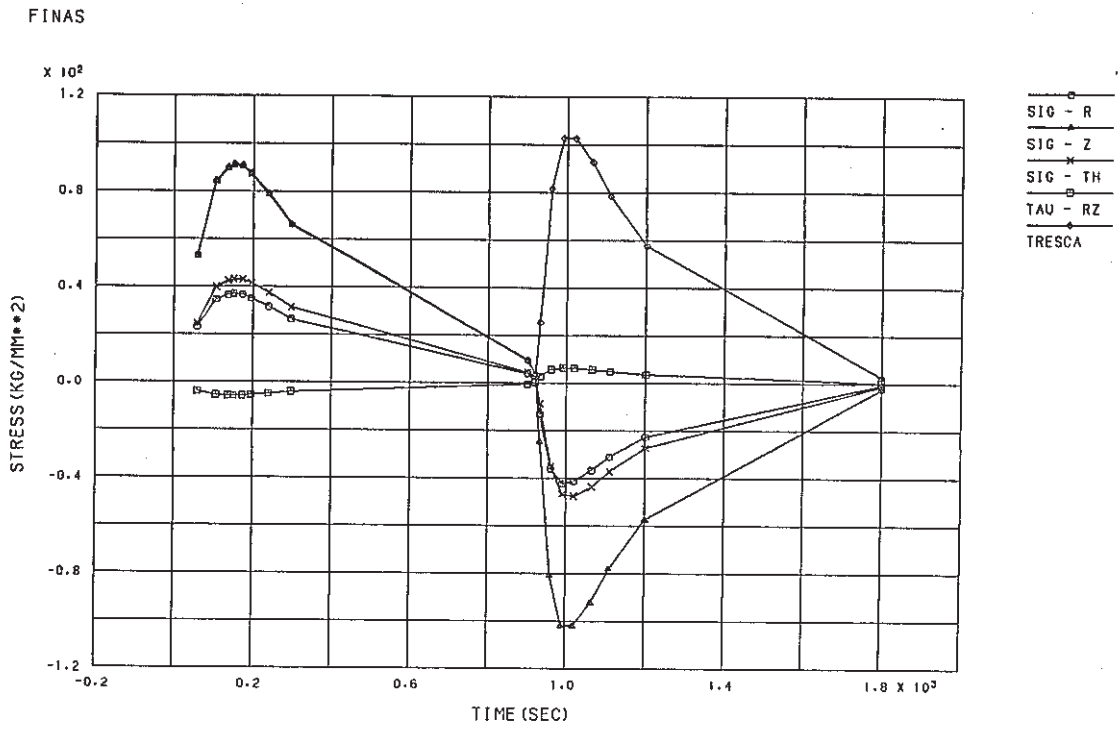


Fig. C.1.1-3 Stress History ahead of Crack Tip of Finally Welded Portion (crack depth a=10 mm)

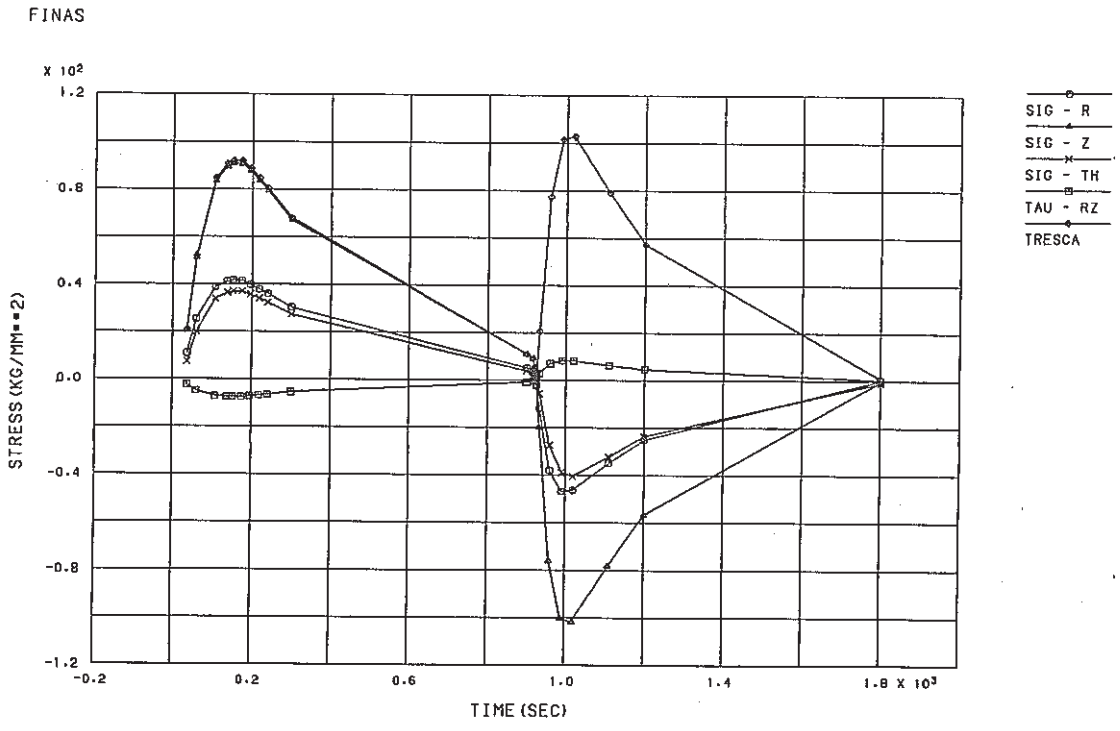


Fig. C.1.1-4 Stress History ahead of Crack Tip of Finally Welded Portion (crack depth a=15 mm)

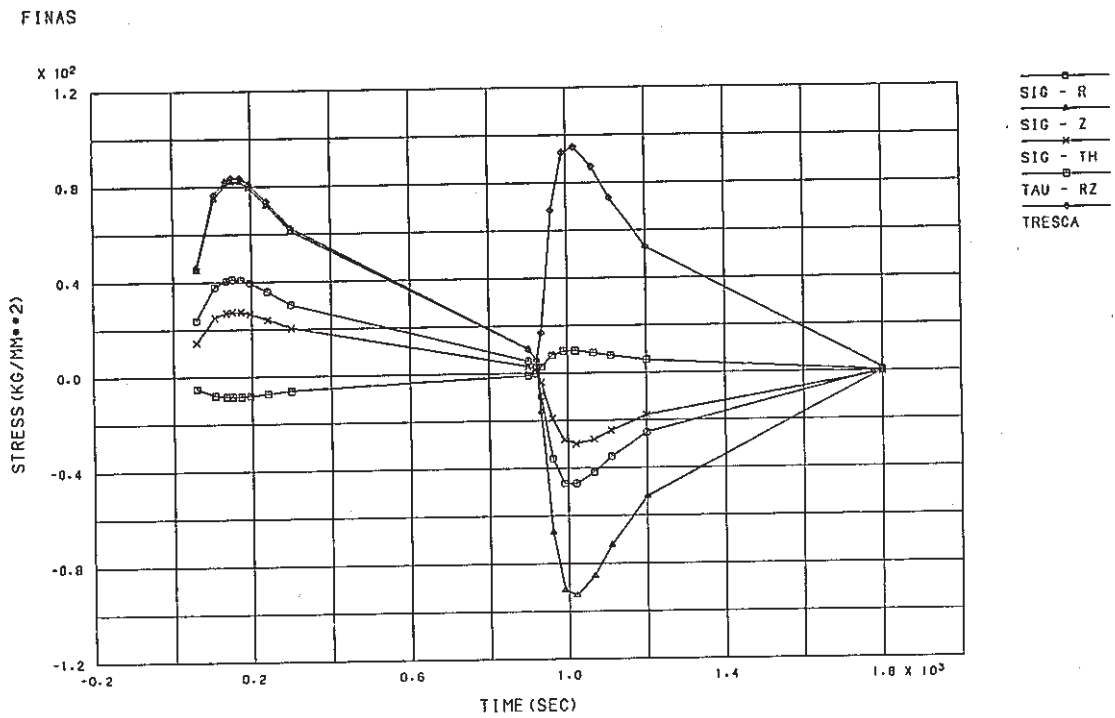


Fig. C.1.1.-5 Stress History ahead of Crack Tip of Finally Welded Portion (crack depth a=20 mm)

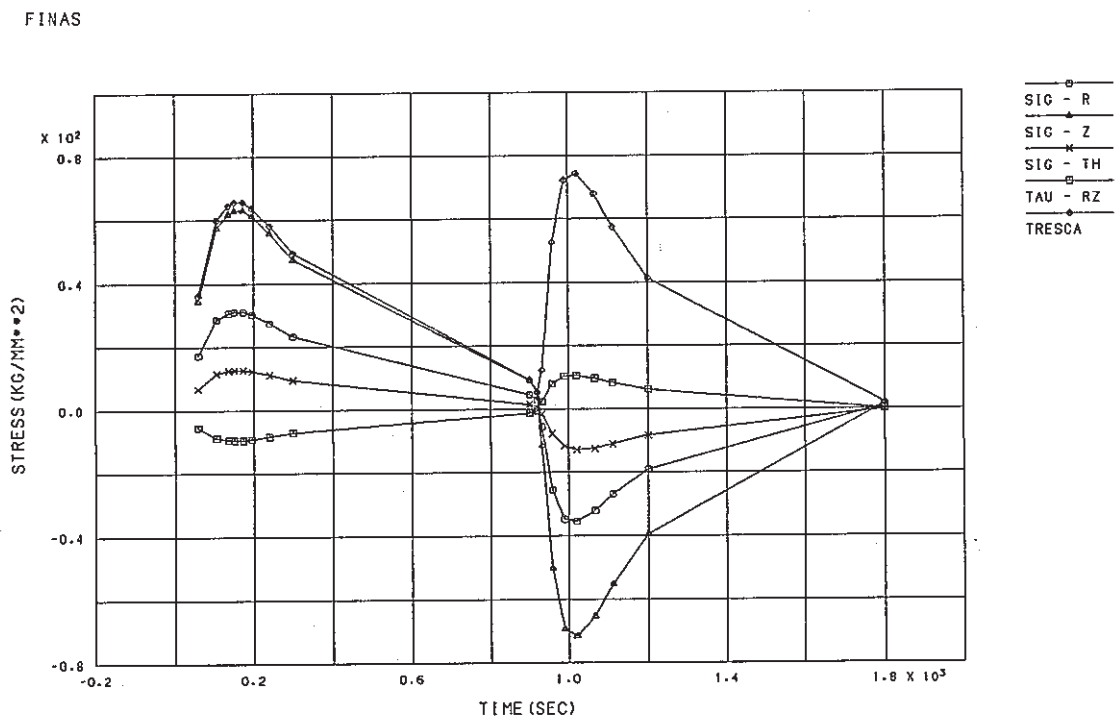


Fig. C.1.1-6 Stress History ahead of Crack Tip of Finally Portion (crack depth a=27 mm)

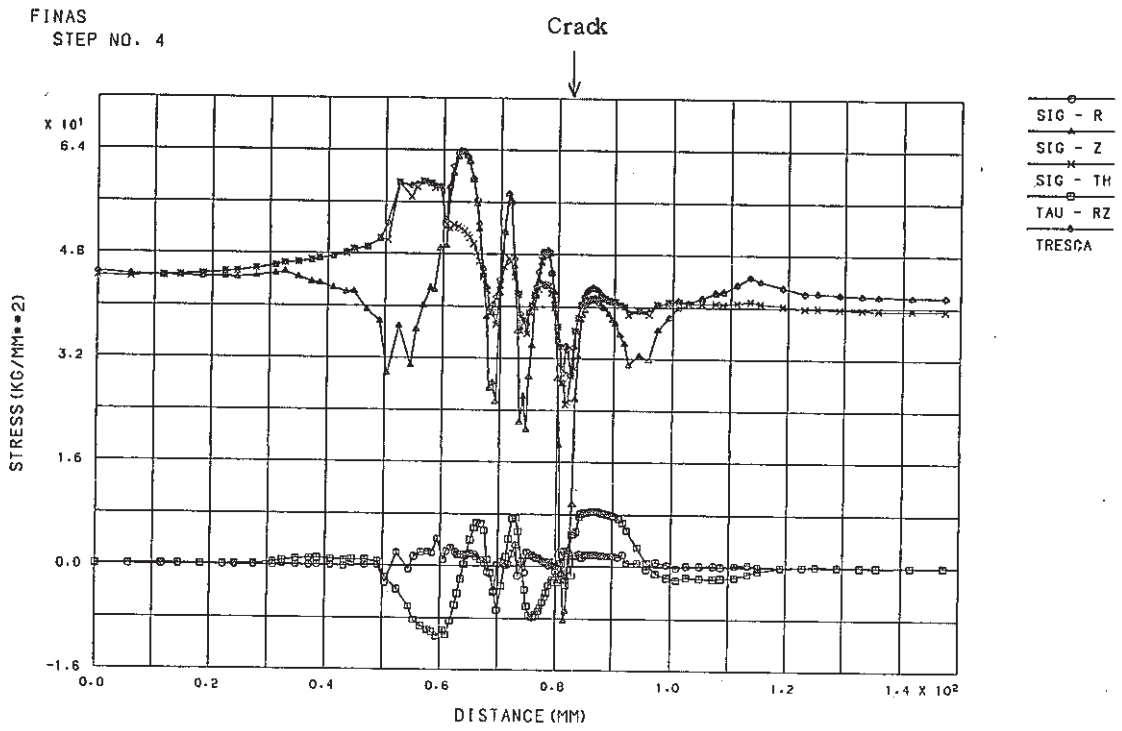


Fig. C.1.2-1 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth a=1 mm)

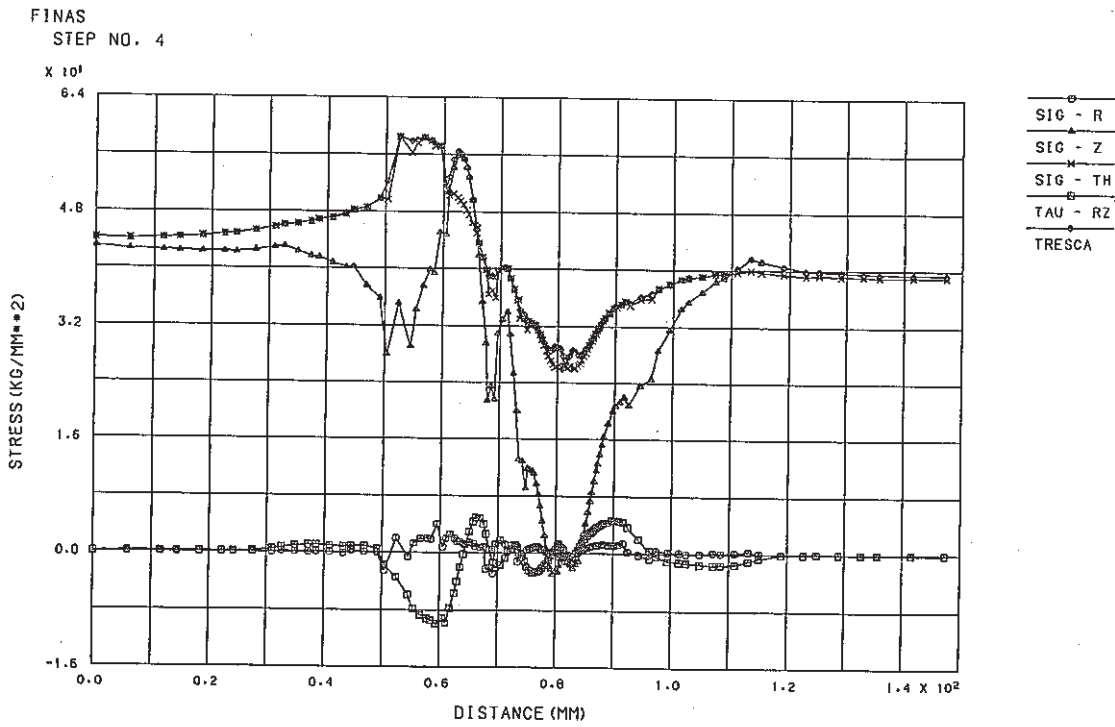


Fig. C.1.2-2 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth a=5 mm)

FINAS
STEP NO. 4

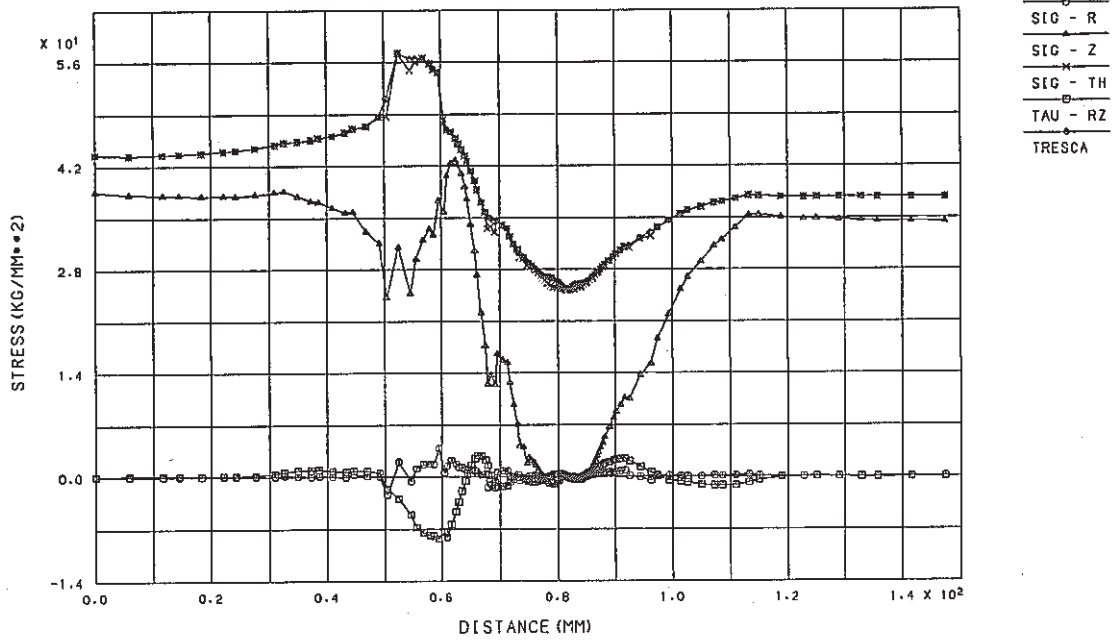


Fig. C.1.2-3 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth $a=10$ mm)

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STEP NO. 6

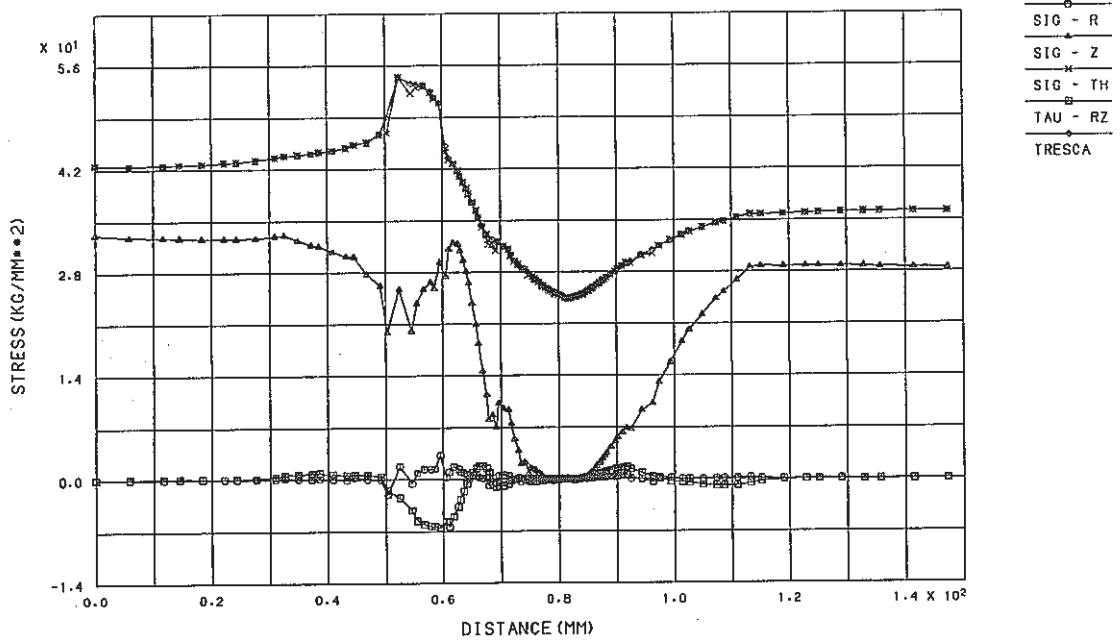


Fig. C.1.2-4 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth $a=15$ mm)

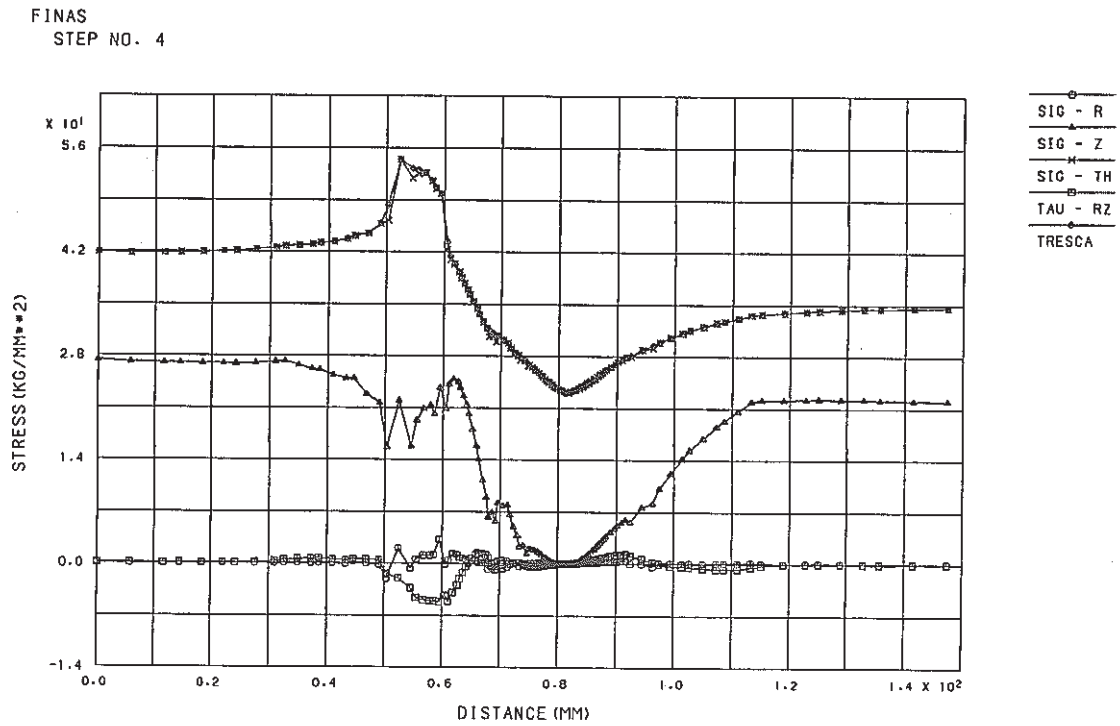


Fig. C.1.2-5 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth a=20 mm)

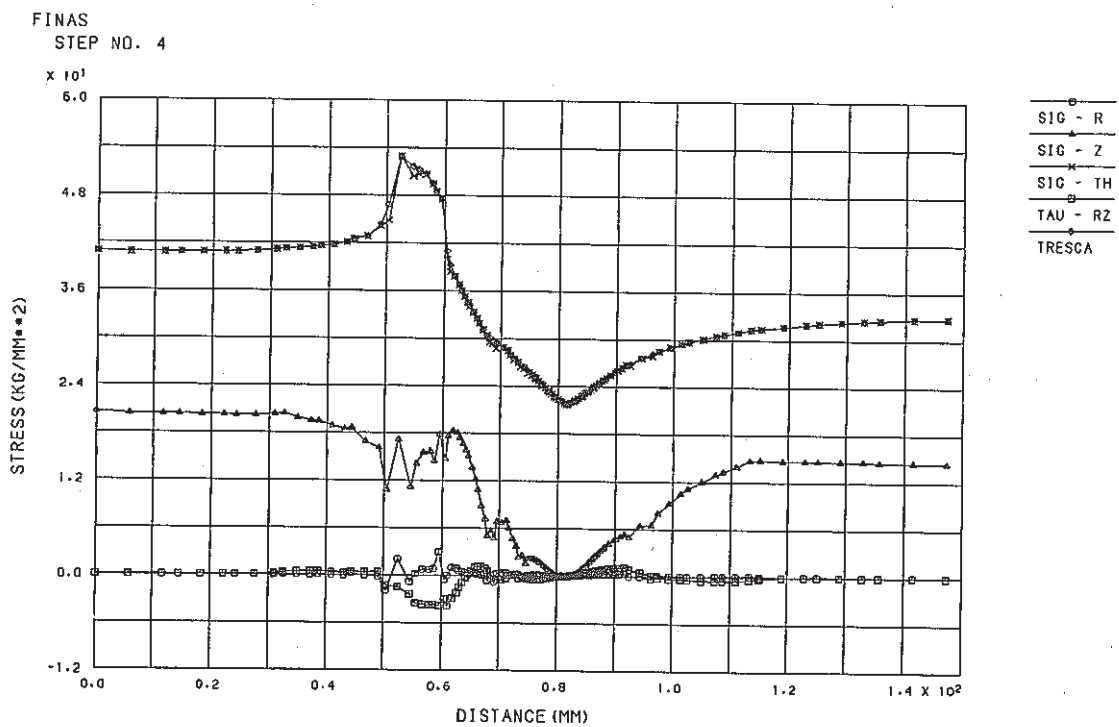


Fig. C.1.2-6 Stress Distribution along Inner Surface at Cold Shock of Finally Welded Portion (crack depth a=27 mm)

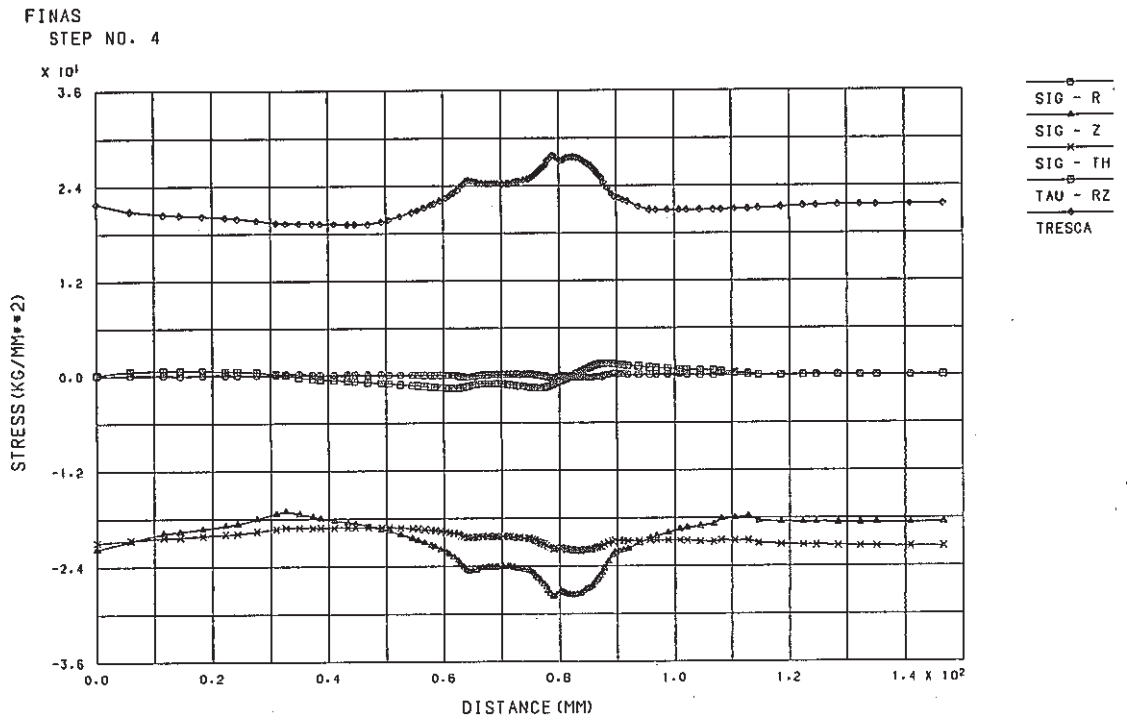


Fig. C.1.3-1 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=1 mm)

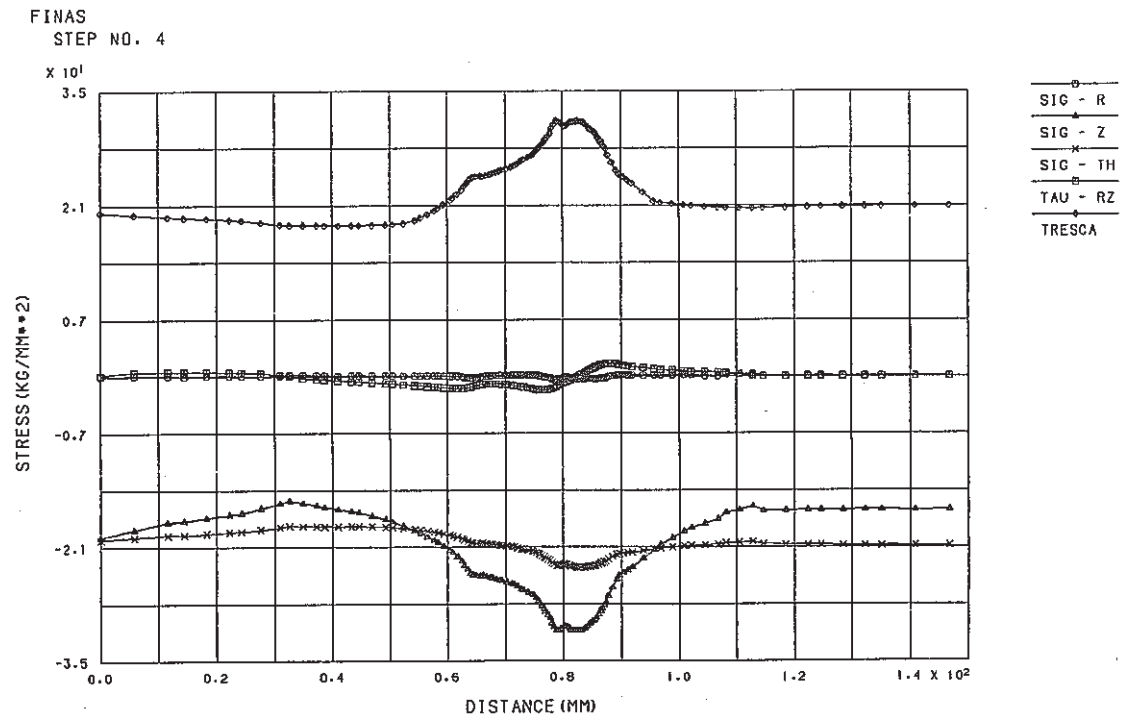


Fig. C.1.3-2 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=5 mm)

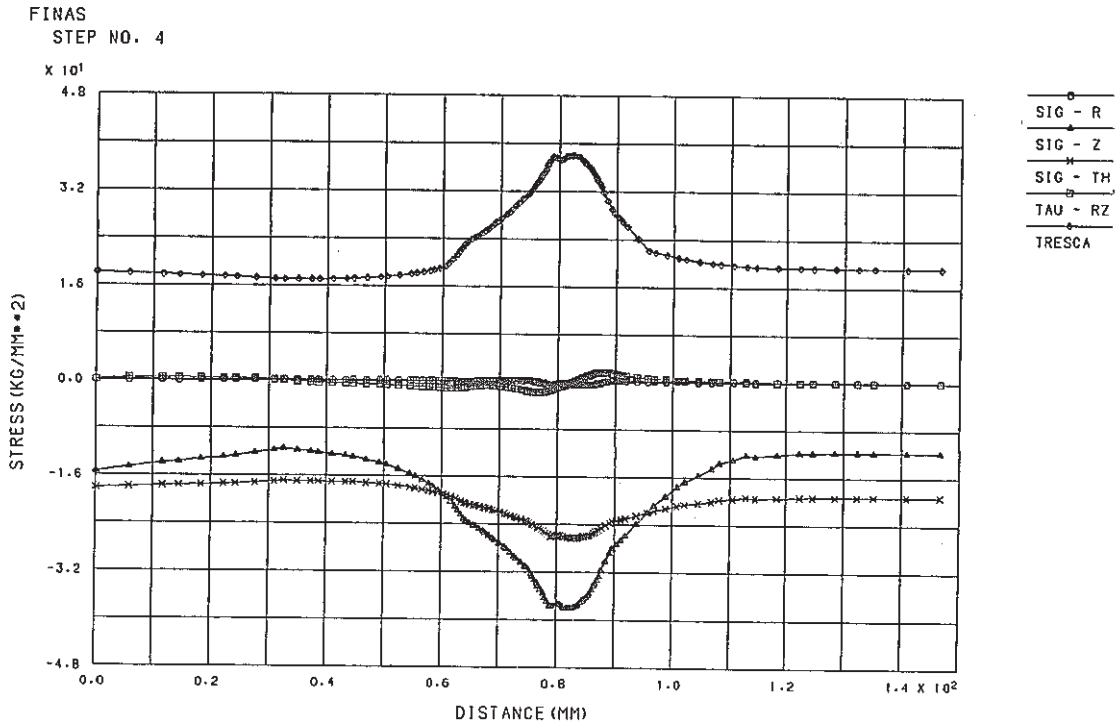


Fig. C.1.3-3 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=10 mm)

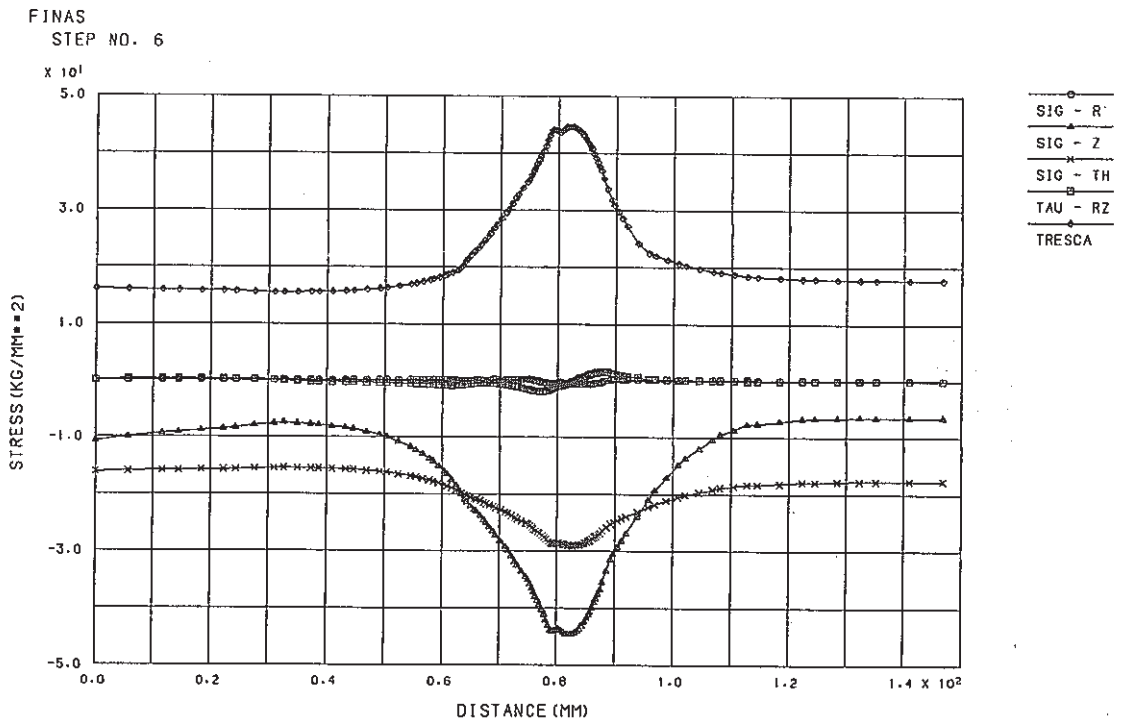


Fig. C.1.3-4 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=15 mm)

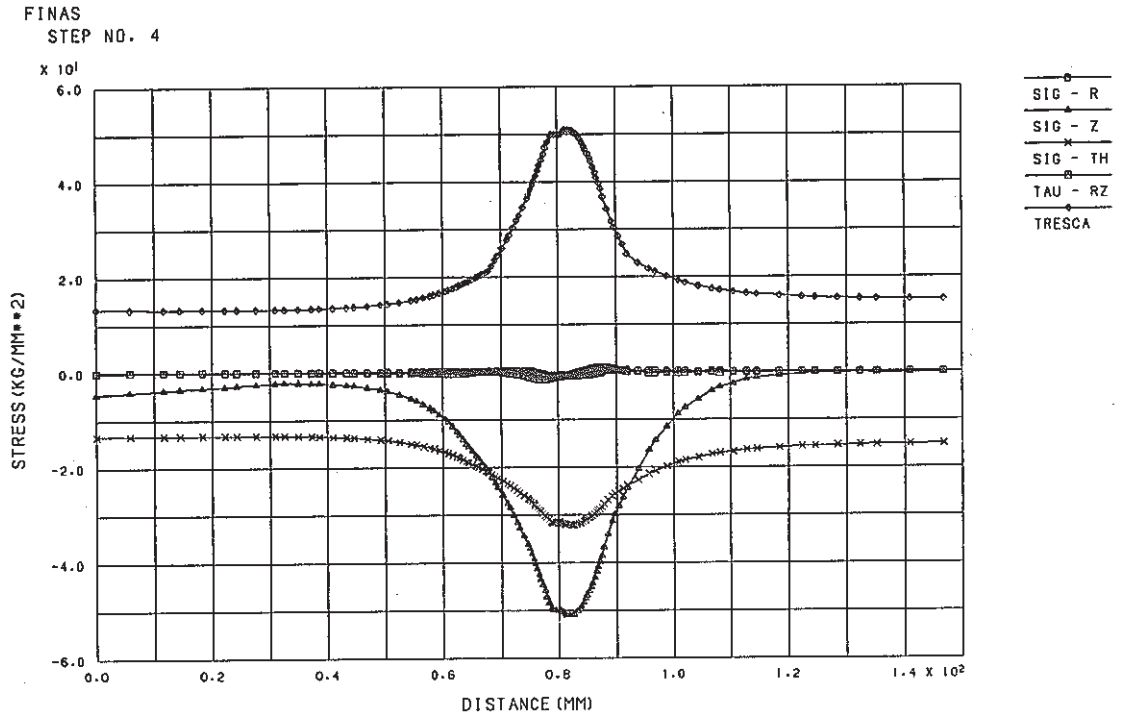


Fig. C.1.3-5 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=20 mm)

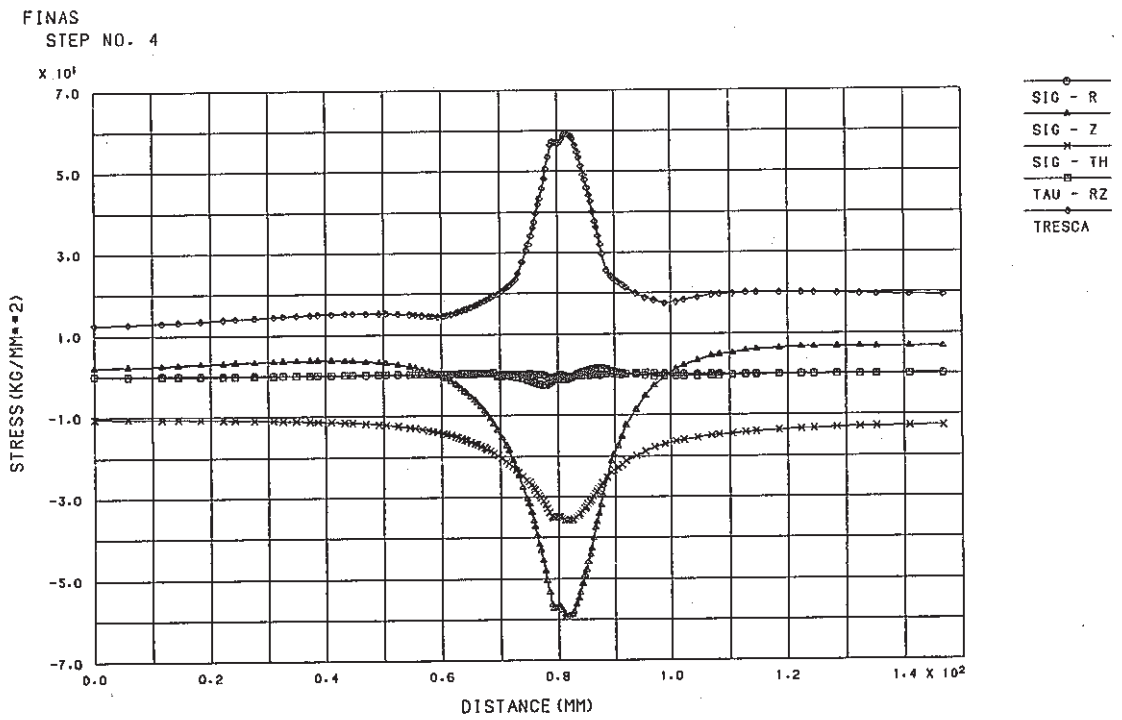


Fig. C.1.3-6 Stress Distribution along Outer Surface at Cold Shock of Finally Welded Portion (crack depth a=27 mm)

FINAS
STEP NO. 4

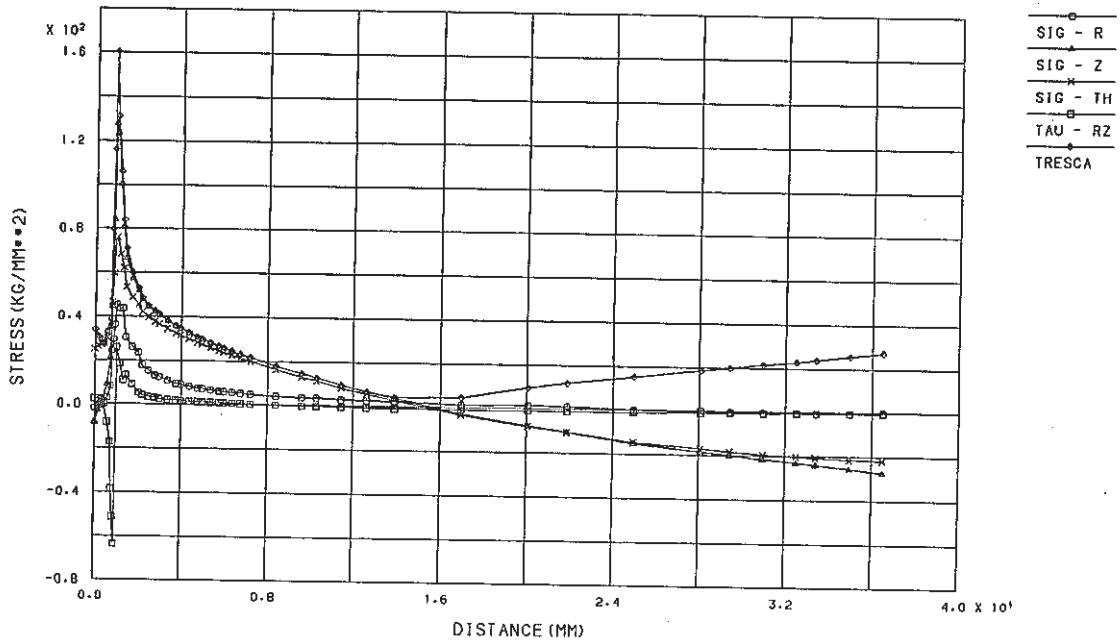


Fig. C.1.4-1 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=1 mm)

FINAS
STEP NO. 4

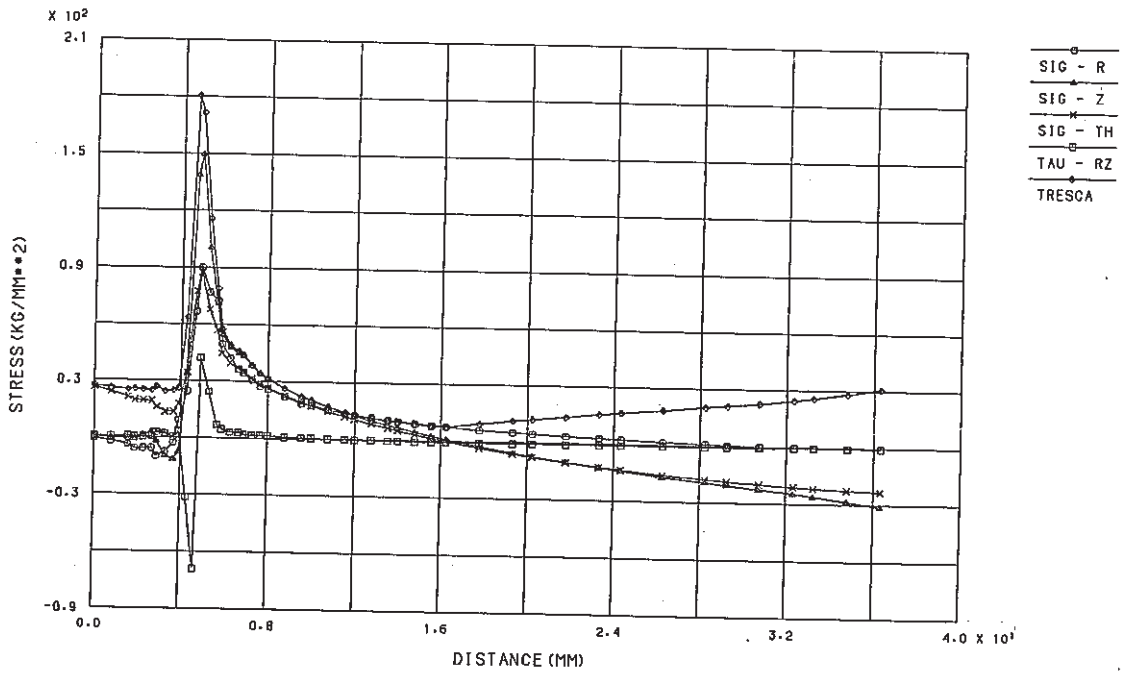


Fig. C.1.4-2 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=5 mm)

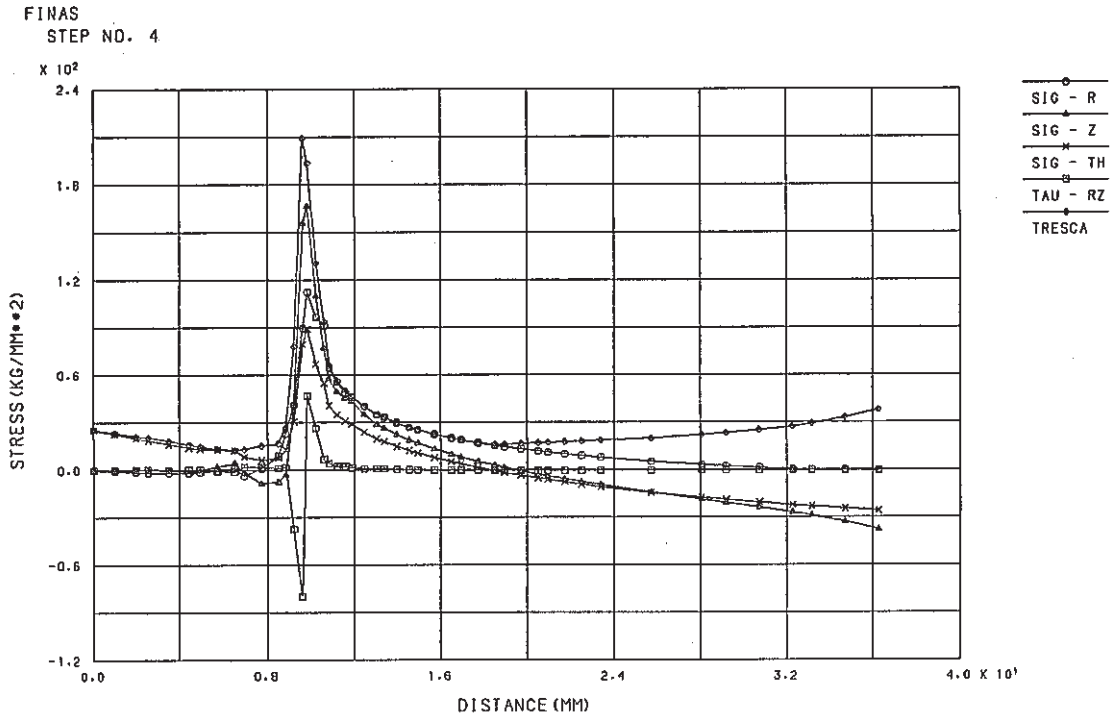


Fig. C.1.4-3 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=10 mm)

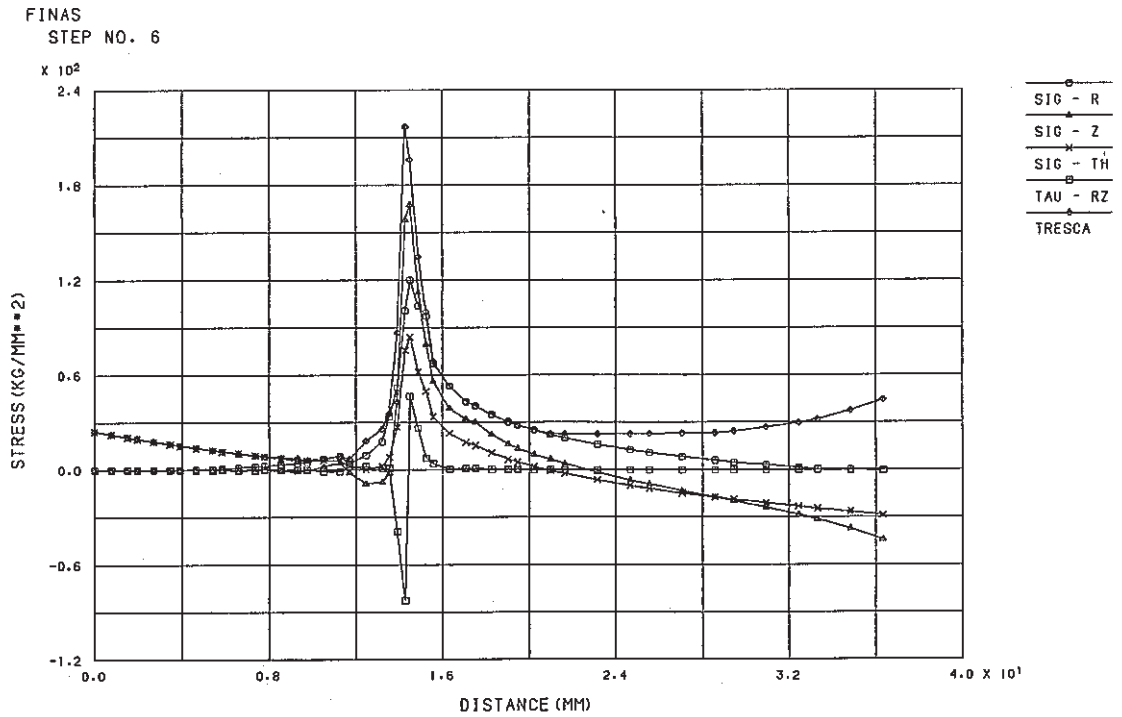


Fig. C.1.4-4 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=15 mm)

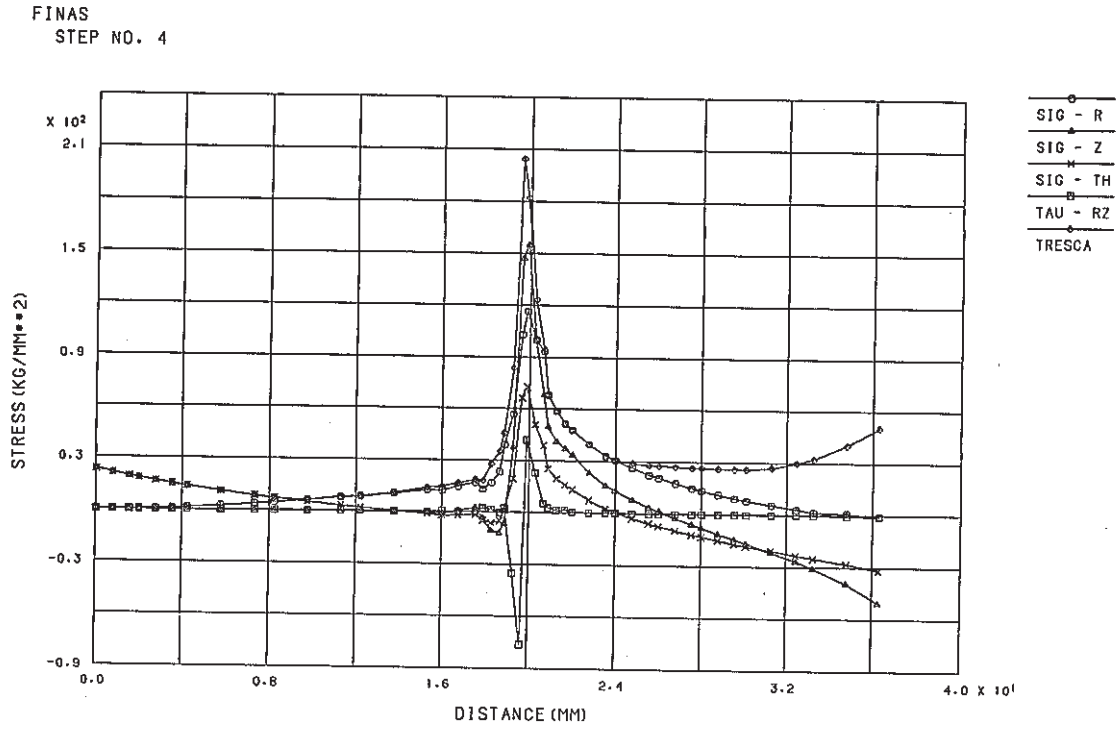


Fig. C.1.4-5 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=20 mm)

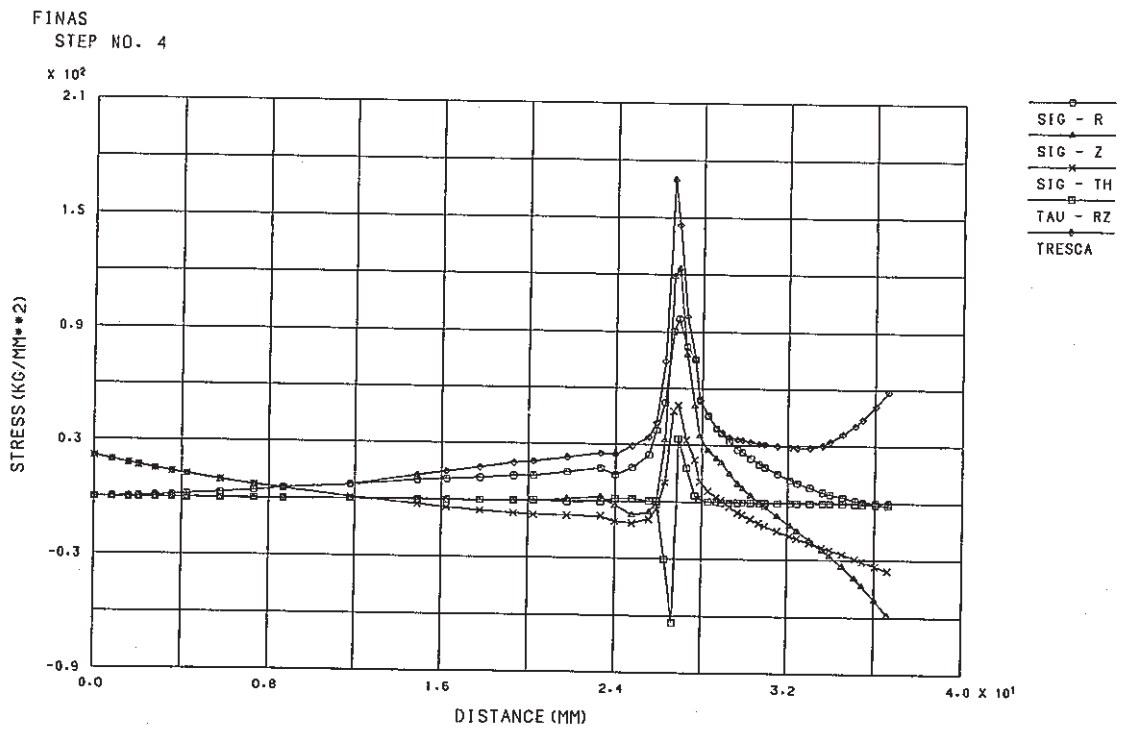
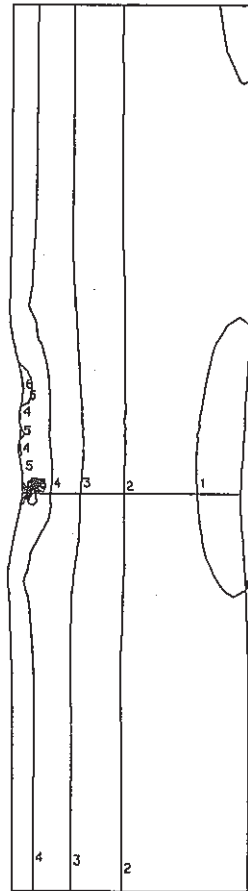


Fig. C.1.4-6 Stress Distribution along Crack Line at Cold Shock of Finally Welded Portion (crack depth a=27 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -20.0000
 2 -3.00000
 3 14.00000
 4 31.00000
 5 48.00000
 6 65.00000
 7 82.00000
 8 99.00000
 9 116.0000
 10 133.0000



Z
↑
R →

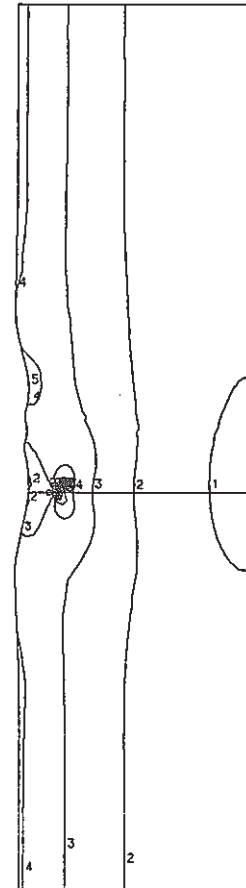
STEP NO. 4

GEOM. SCALE 20.0000

Fig. C.1.5-1 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth $a=1\text{mm}$)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -22.0000
 2 -2.00000
 3 18.00000
 4 38.00000
 5 58.00000
 6 78.00000
 7 98.00000
 8 118.0000
 9 138.0000
 10 158.0000



Z
↑
R →

STEP NO. 4

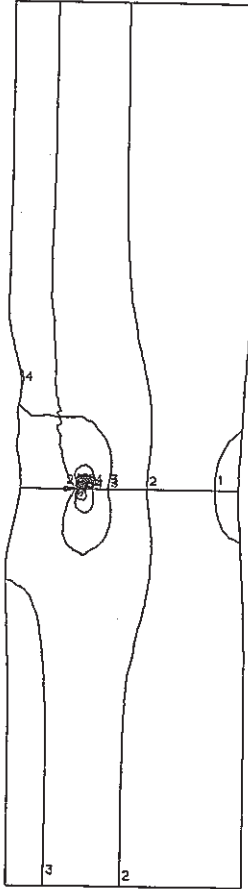
GEOM. SCALE 20.0000

Fig. C.1.5-2 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth $a=5\text{ mm}$)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-28.0000
2	-5.00000
3	18.00000
4	41.00000
5	64.00000
6	87.00000
7	110.0000
8	133.0000
9	156.0000
10	179.0000



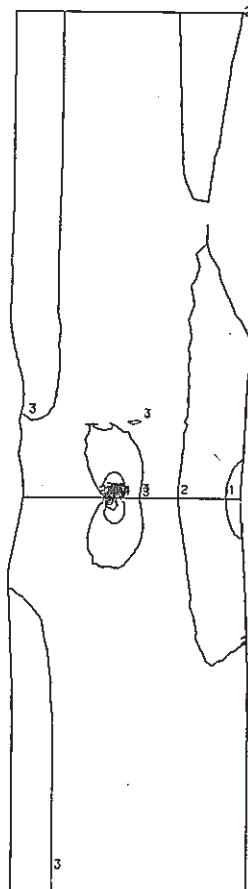
STEP NO. 4

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-35.0000
2	-11.0000
3	13.00000
4	37.00000
5	61.00000
6	85.00000
7	109.0000
8	133.0000
9	157.0000
10	181.0000



STEP NO. 5

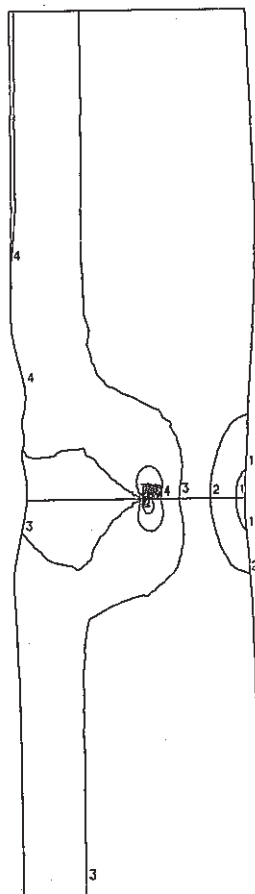
GEOM. SCALE 20.0000

Fig. C.1.5-3 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth a=10 mm)

Fig. C.1.5-4 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth a=15 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -43.0000
 2 -20.0000
 3 3.000000
 4 26.00000
 5 49.00000
 6 72.00000
 7 95.00000
 8 118.0000
 9 141.0000
 10 164.0000

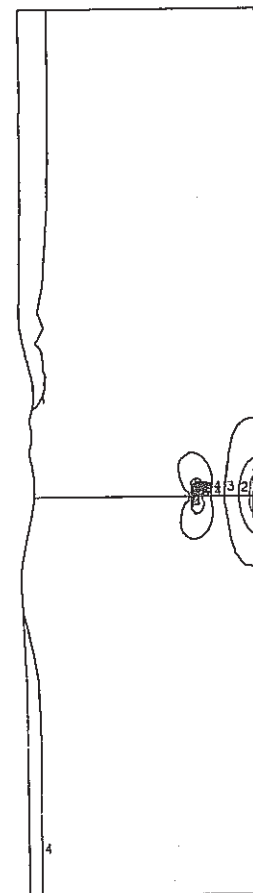


STEP NO. 4

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -52.0000
 2 -31.0000
 3 -10.0000
 4 11.00000
 5 32.00000
 6 53.00000
 7 74.00000
 8 95.00000
 9 116.0000
 10 137.0000



STEP NO. 4

GEOM. SCALE 20.0000

Fig. C.1.5-5 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth $a=20$ mm)

Fig. C.1.5-6 Contour of Axial Stress at Cold Shock of Finally Welded Portion (crack depth $a=27$ mm)

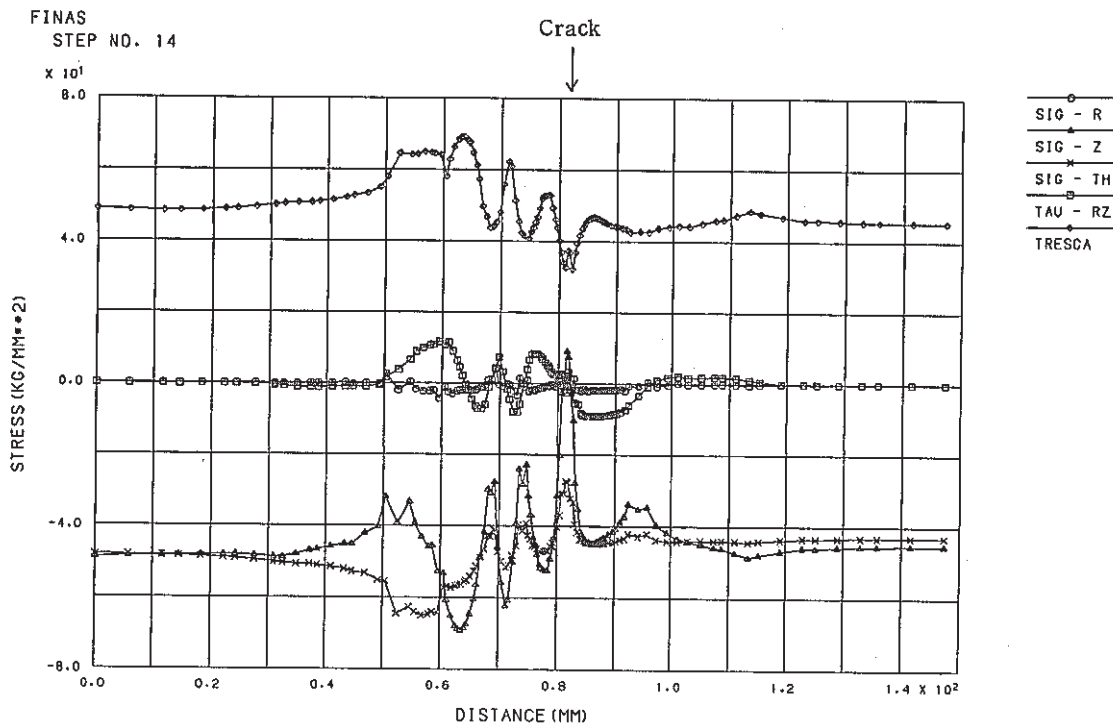


Fig. C.1.6-1 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=1 mm)

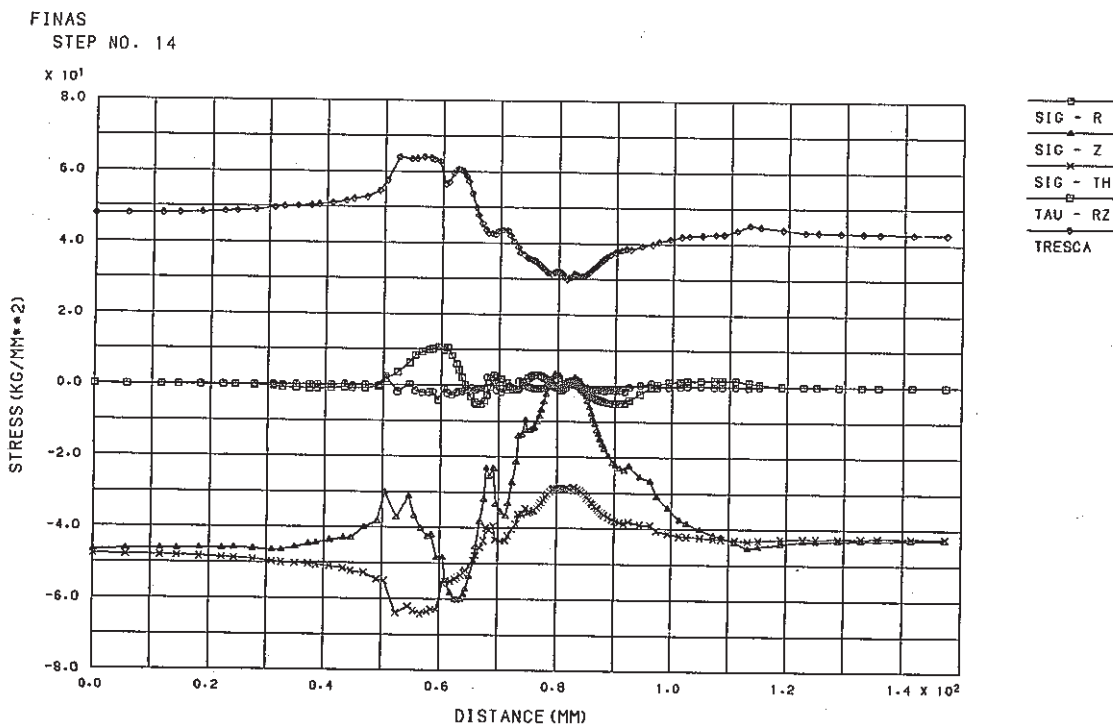


Fig. C.1.6-2 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=5 mm)

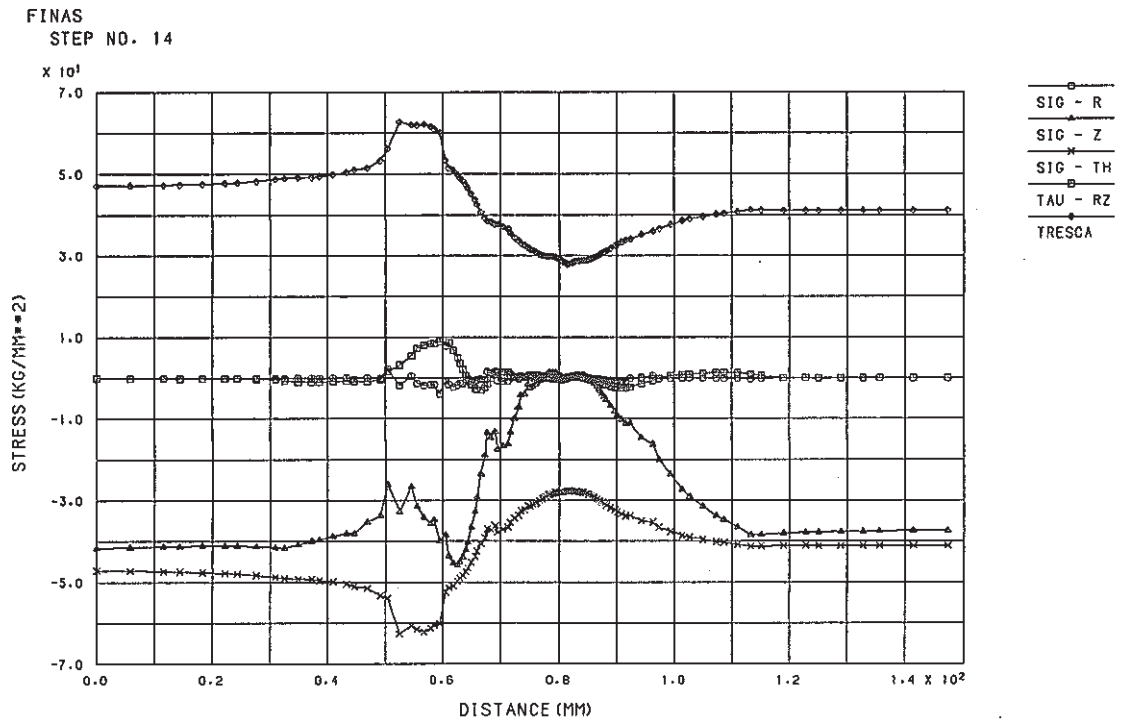


Fig. C.1.6-3 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=10 mm)

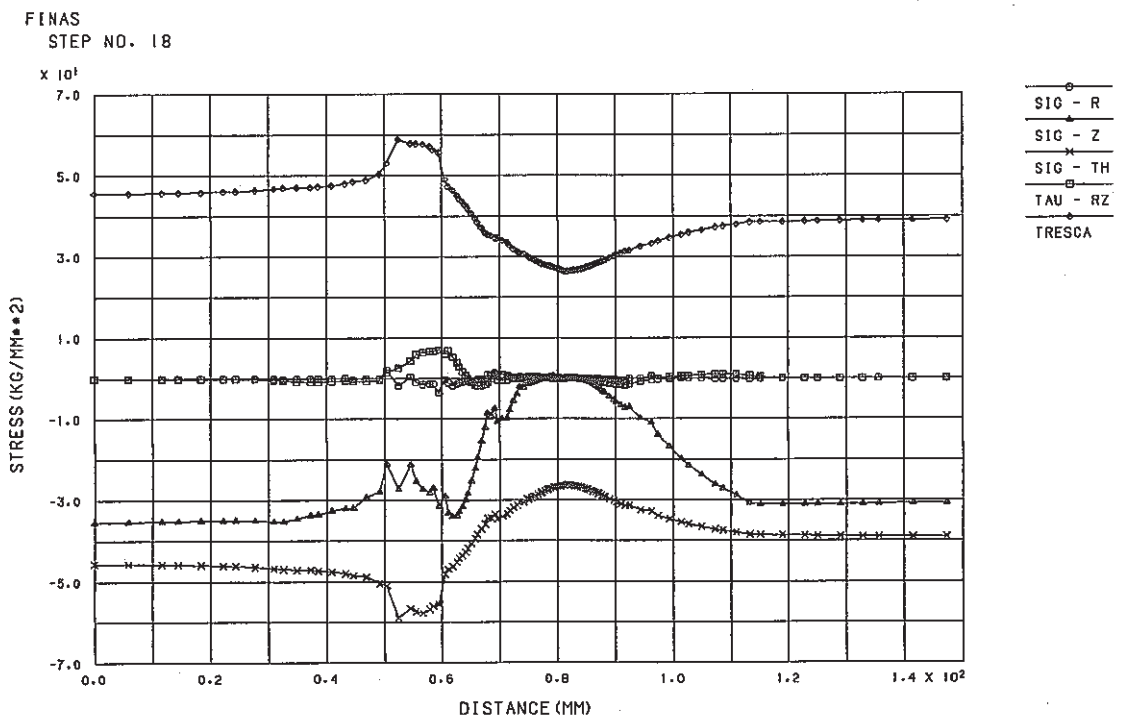


Fig. C.1.6-4 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=15 mm)

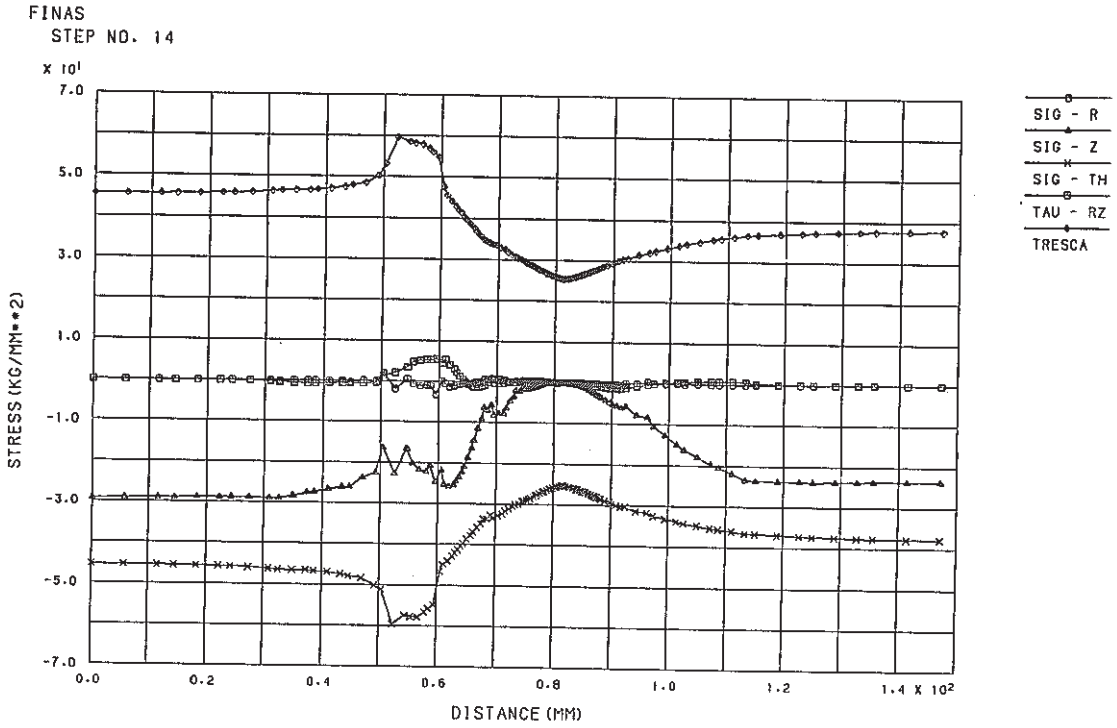


Fig. C.1.6-5 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=20 mm)

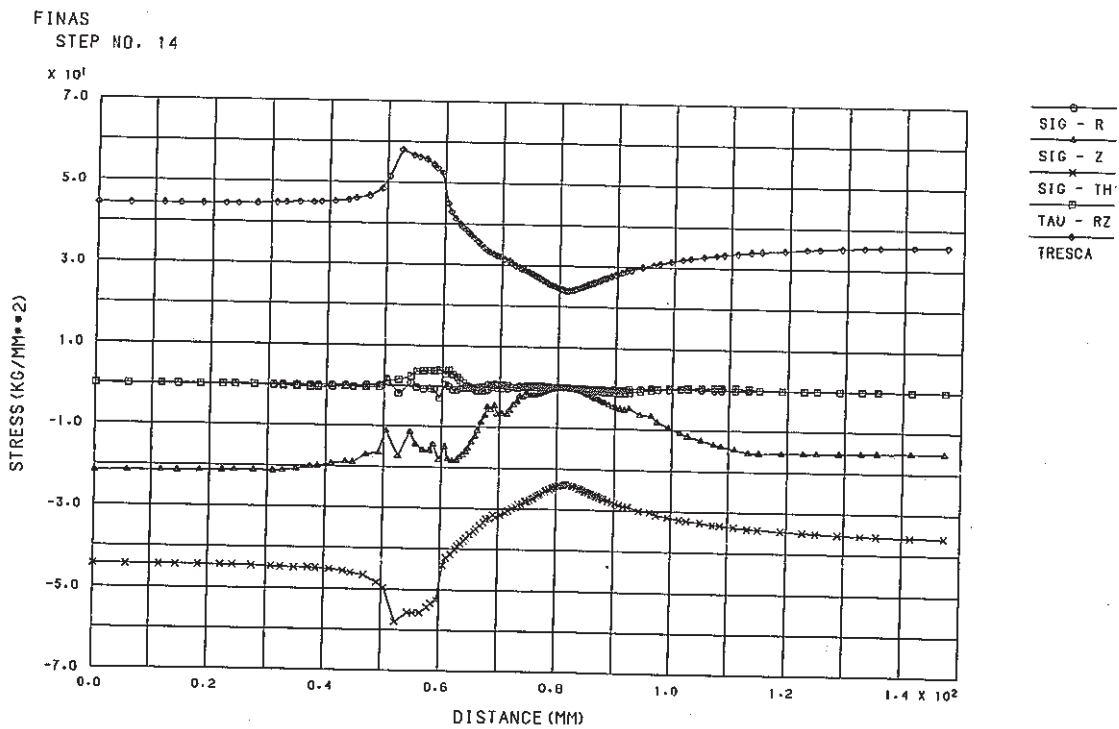


Fig. C.1.6-6 Stress Distribution along Inner Surface at Hot Shock of Finally Welded Portion (crack depth a=27 mm)

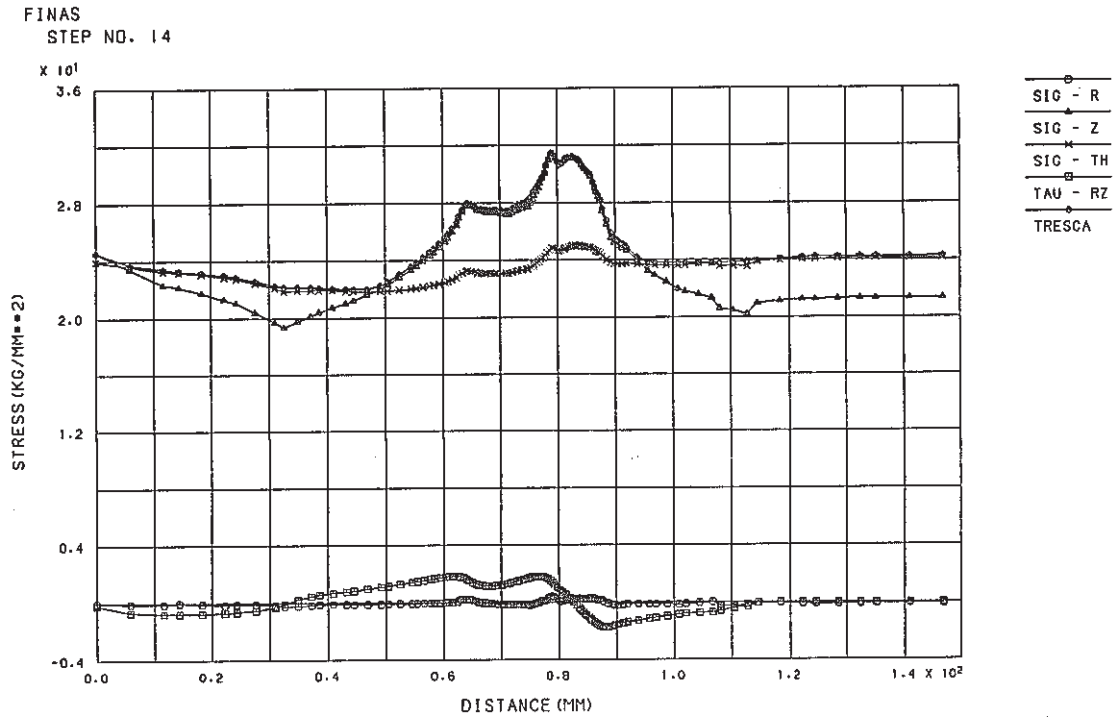


Fig. C.1.7-1 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=1 mm)

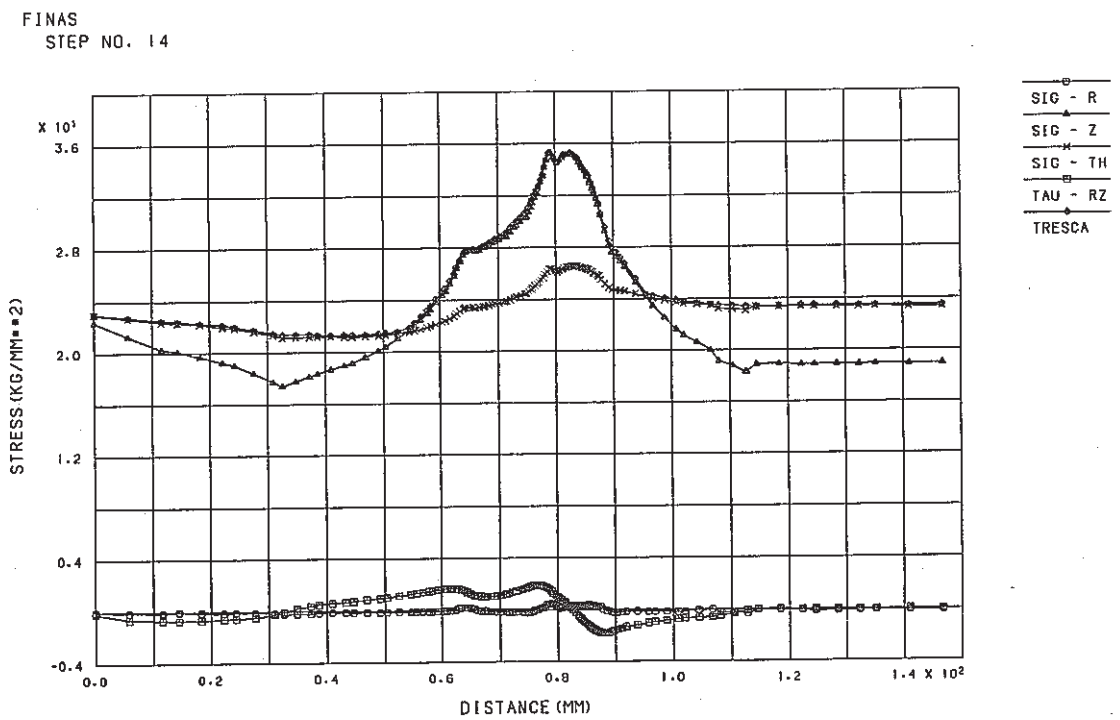


Fig. C.1.7-2 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=5 mm)

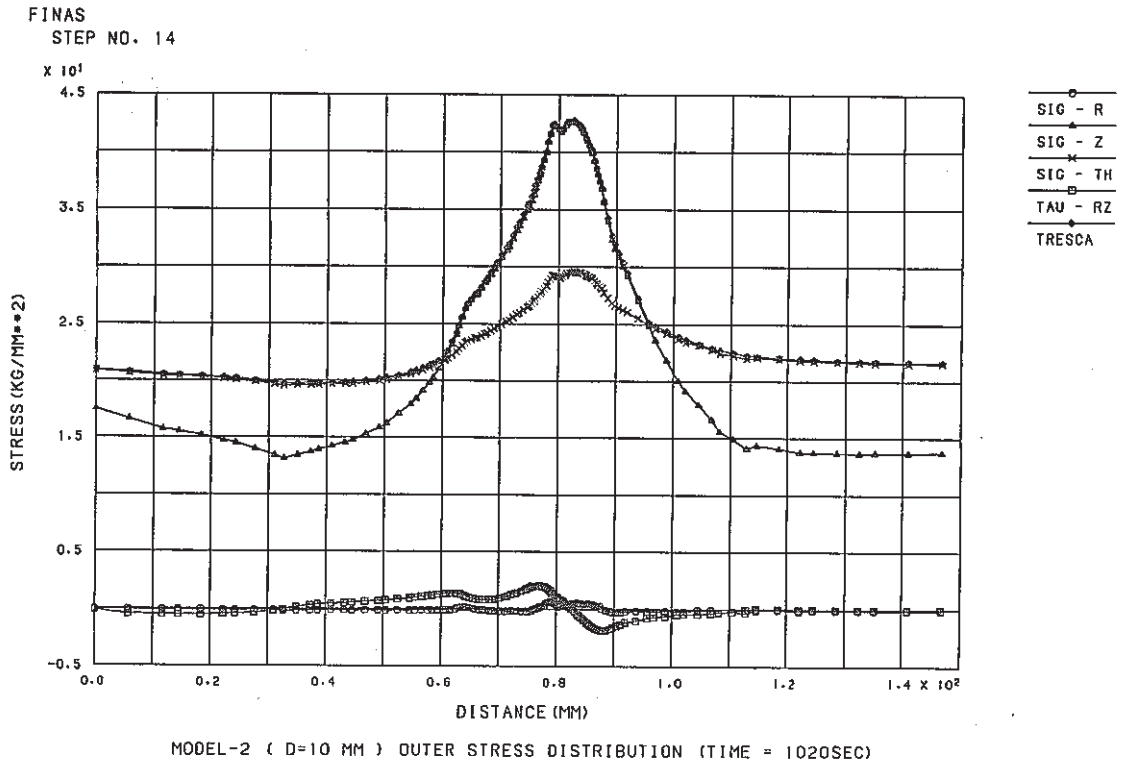


Fig. C.1.7-3 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=10 mm)

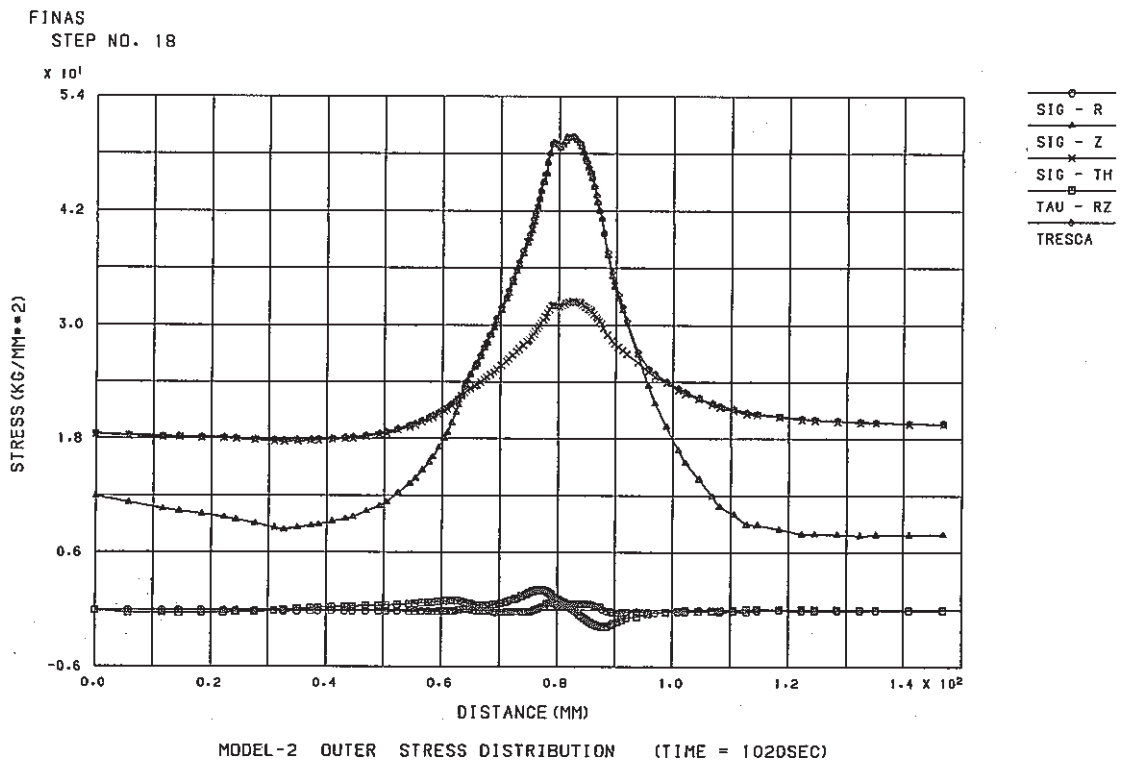


Fig. C.1.7-4 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=15 mm)

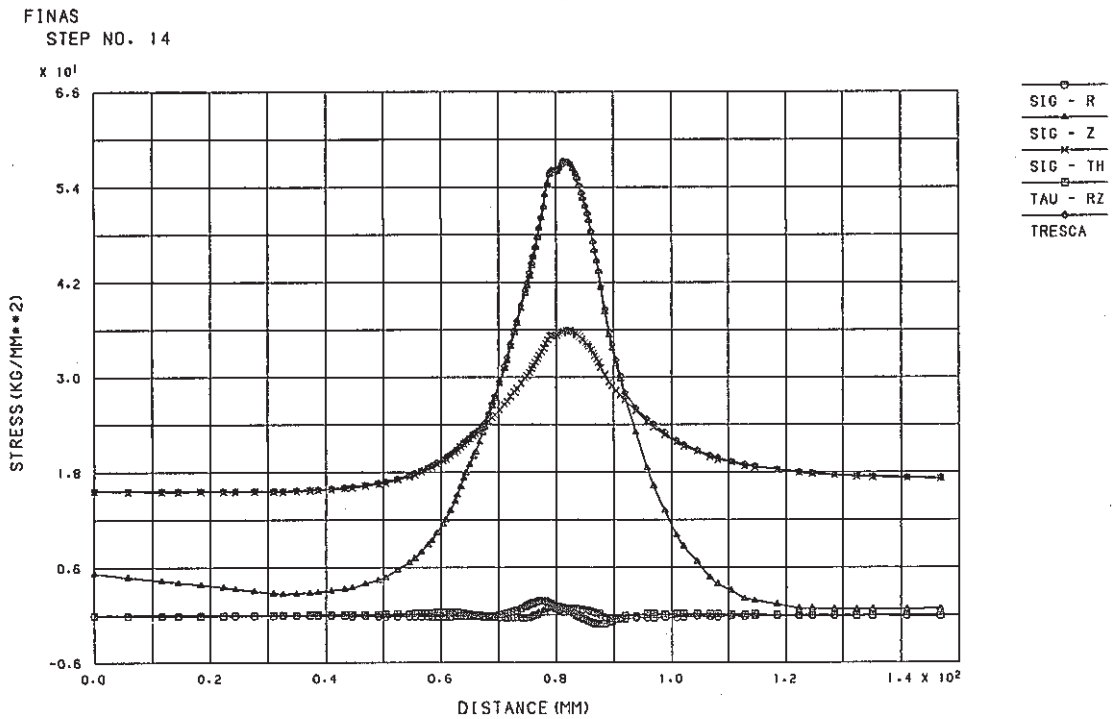


Fig. C.1.7-5 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=20 mm)

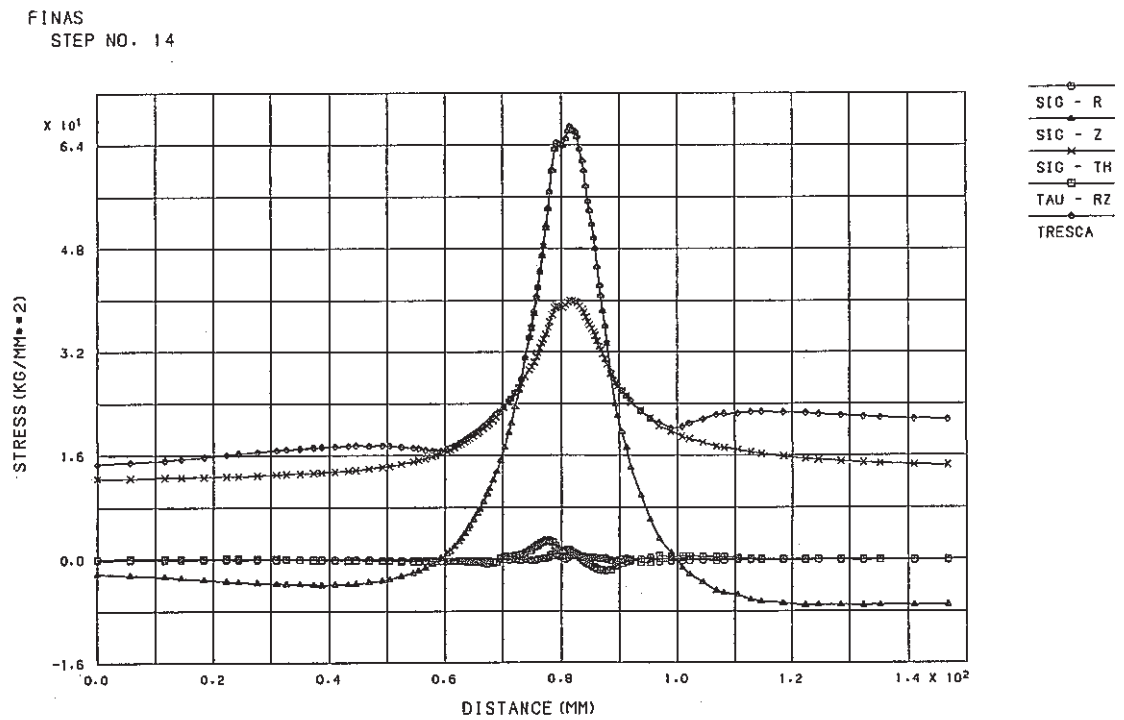


Fig. C.1.7-6 Stress Distribution along Outer Surface at Hot Shock of Finally Welded Portion (crack depth a=27 mm)

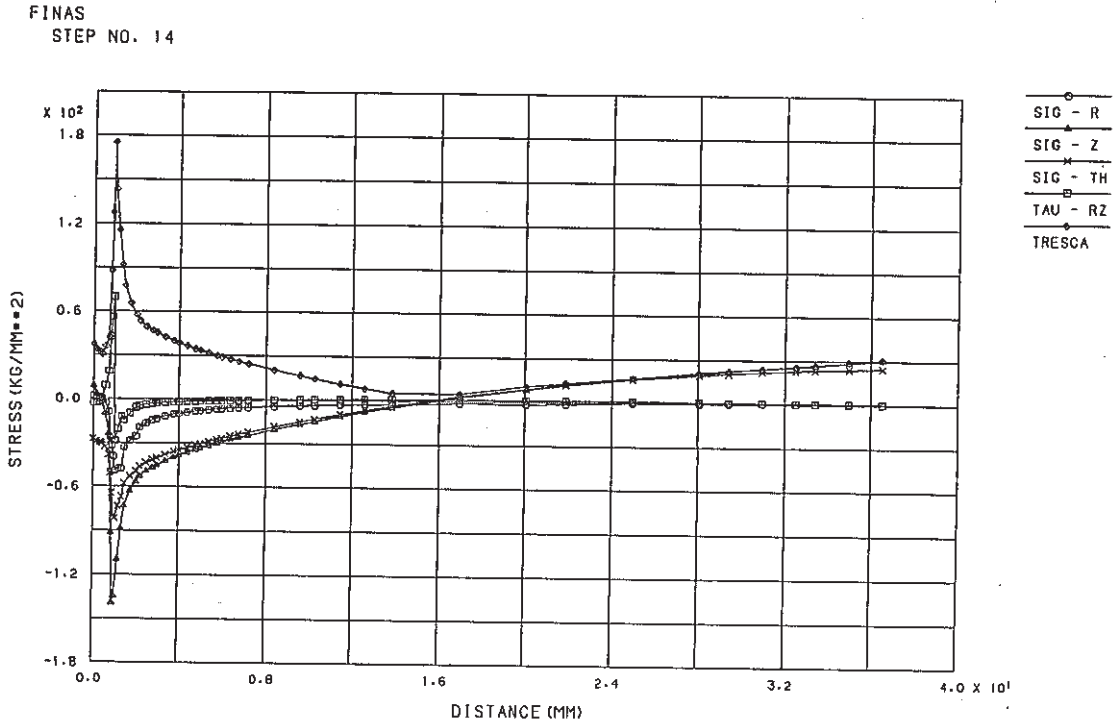


Fig. C.1.8-1 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=1 mm)

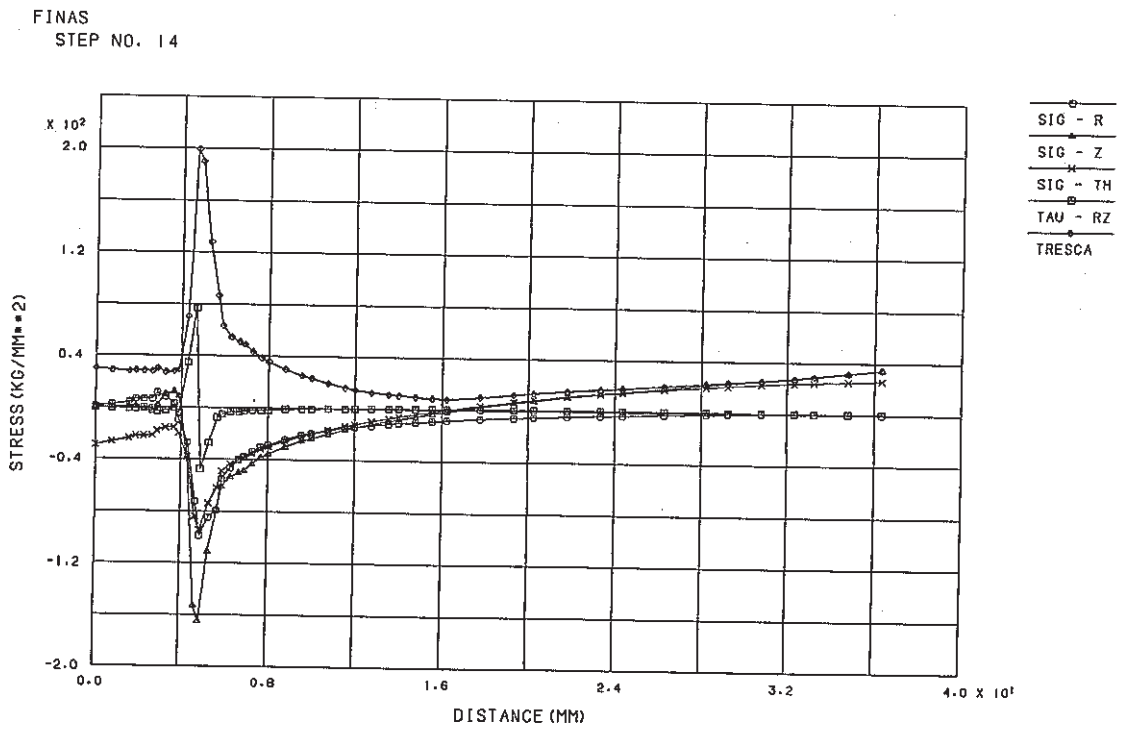


Fig. C.1.8-2 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=5 mm)

FINAS
STEP NO. 14

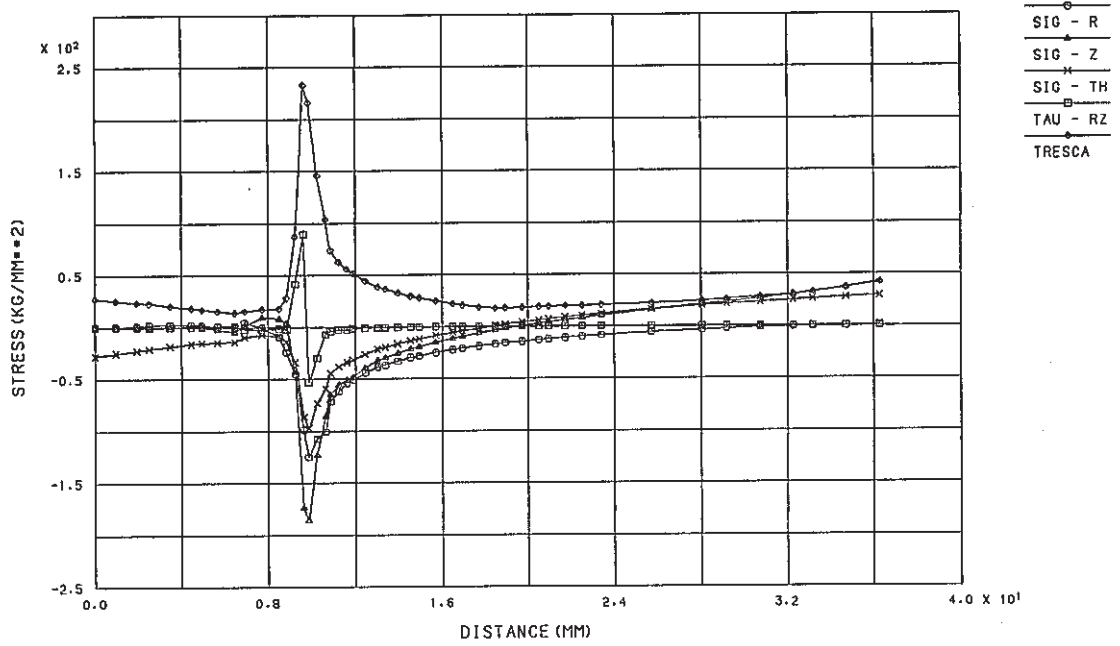


Fig. C.1.8-3 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=10 mm)

FINAS
STEP NO. 18

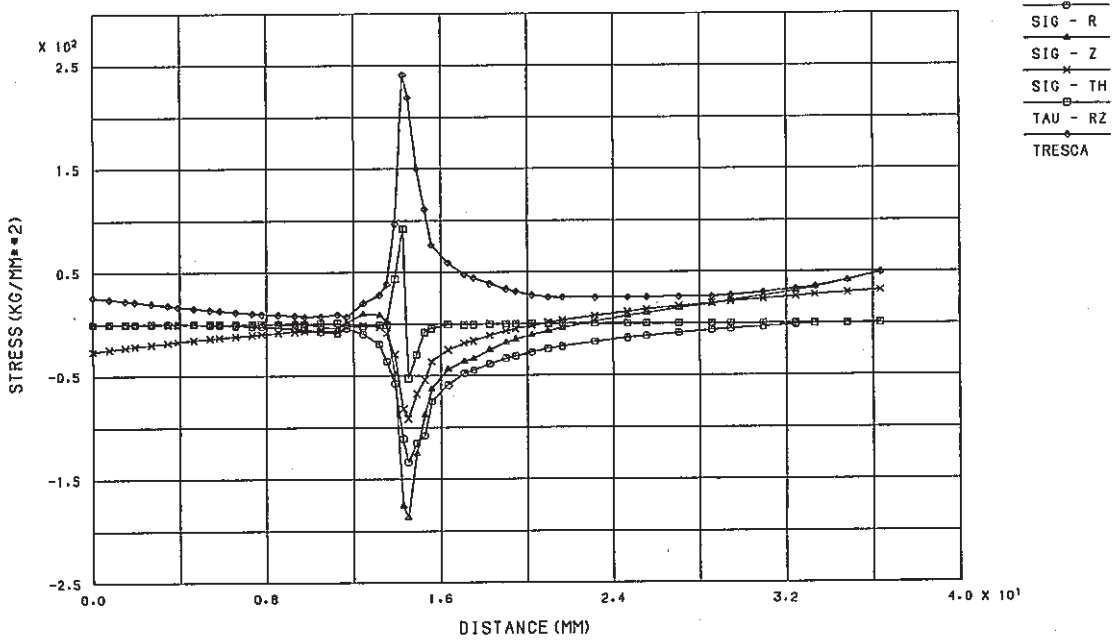


Fig. C.1.8-4 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=15 mm)

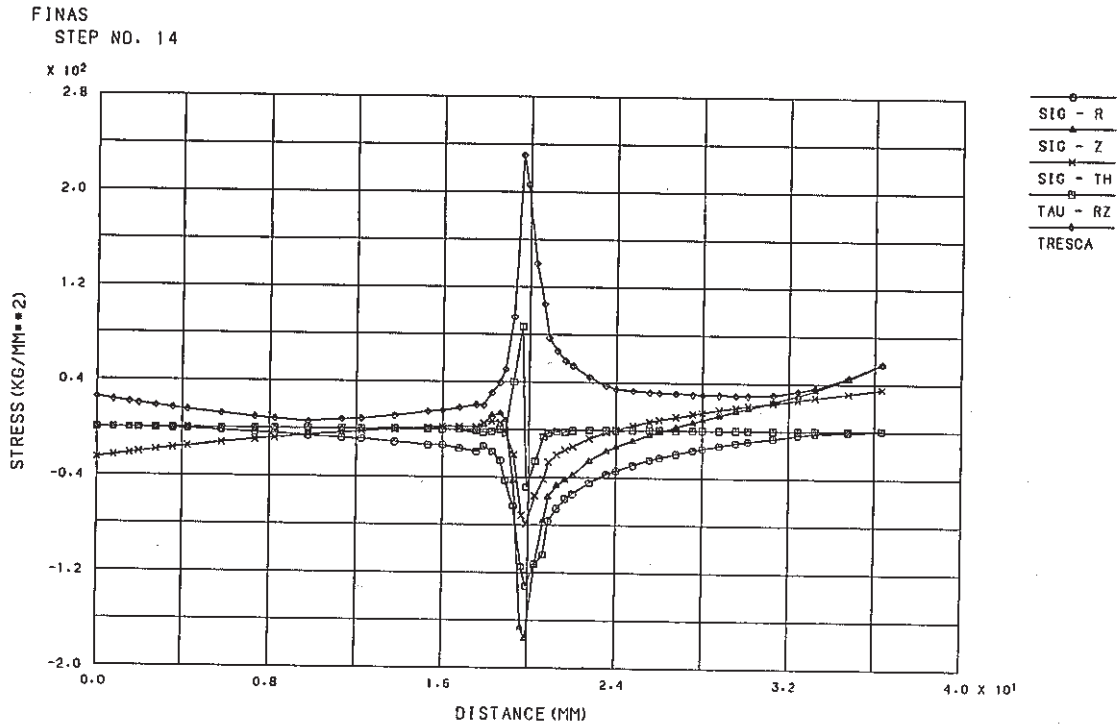


Fig. C.1.8-5 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=20 mm)

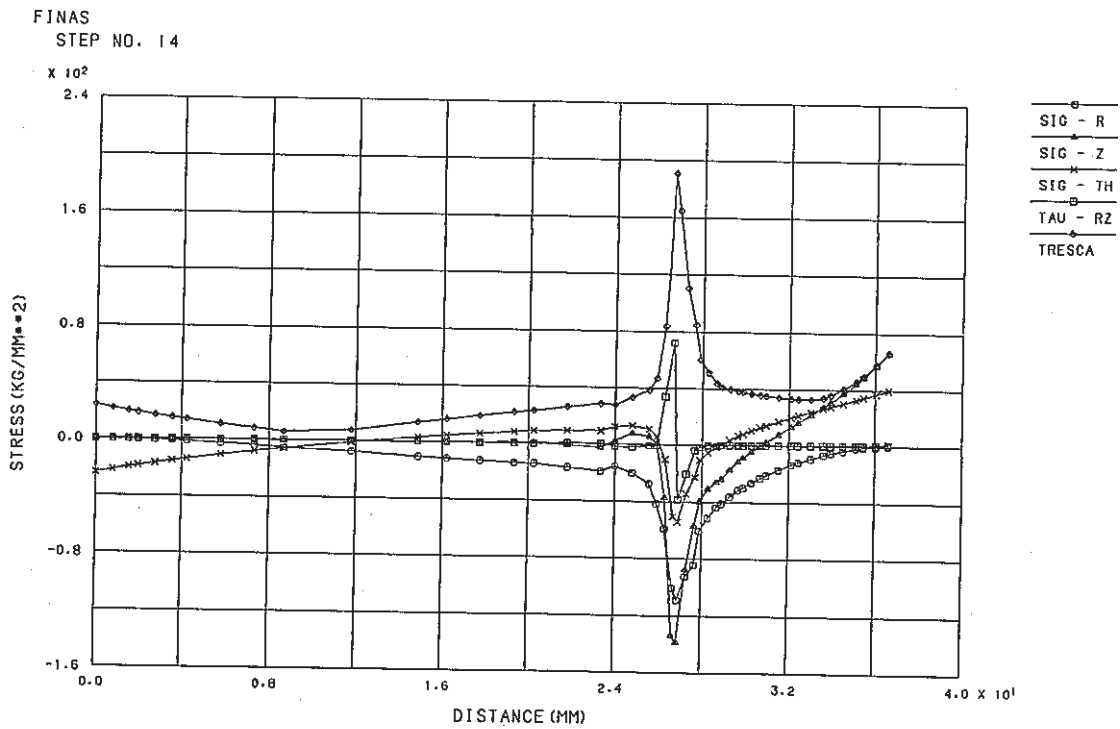
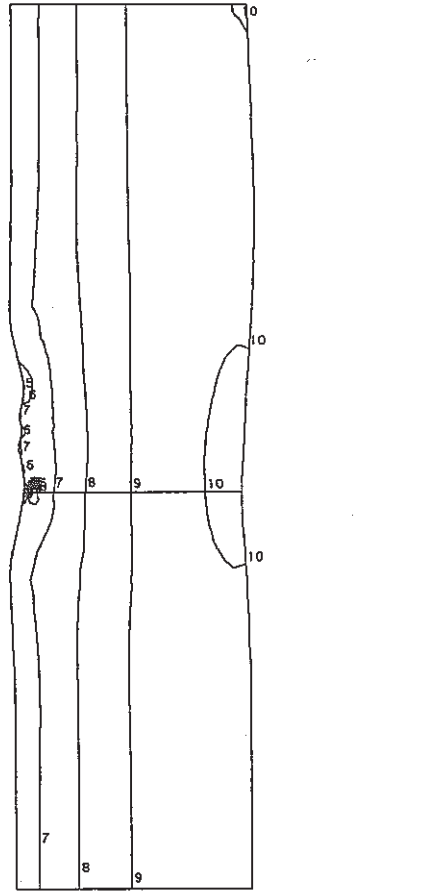


Fig C.1.8-6 Stress Distribution along Crack Line at Hot Shock of Finally Welded Portion (crack depth a=27 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -147.000
 2 -128.000
 3 -109.000
 4 -90.0000
 5 -71.0000
 6 -52.0000
 7 -33.0000
 8 -14.0000
 9 5.000000
 10 24.00000

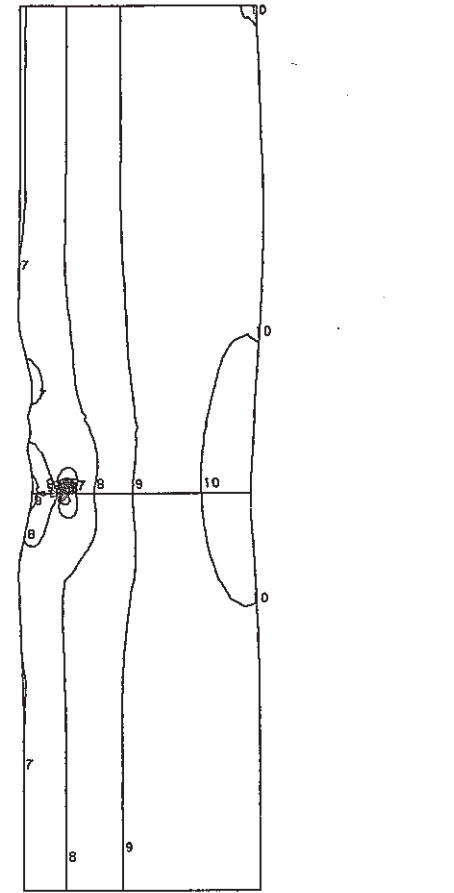


STEP NO. 14

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -178.000
 2 -154.000
 3 -132.000
 4 -110.000
 5 -88.0000
 6 -66.0000
 7 -44.0000
 8 -22.0000
 9 0.0
 10 22.00000



STEP NO. 14

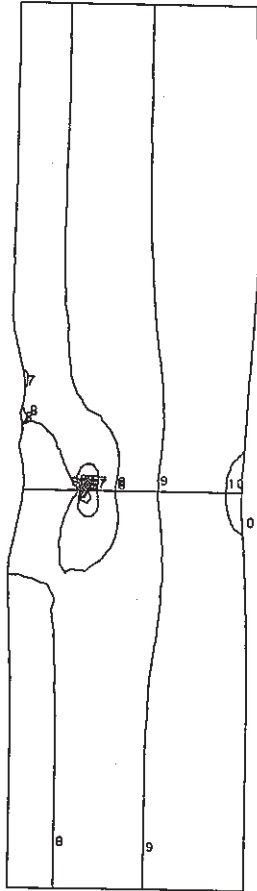
GEOM. SCALE 20.0000

Fig. C.1.9-1 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth a=1 mm)

Fig. C.1.9-2 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth a=5 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -199.000
 2 -173.000
 3 -147.000
 4 -121.000
 5 -95.0000
 6 -69.0000
 7 -43.0000
 8 -17.0000
 9 9.000000
 10 35.00000

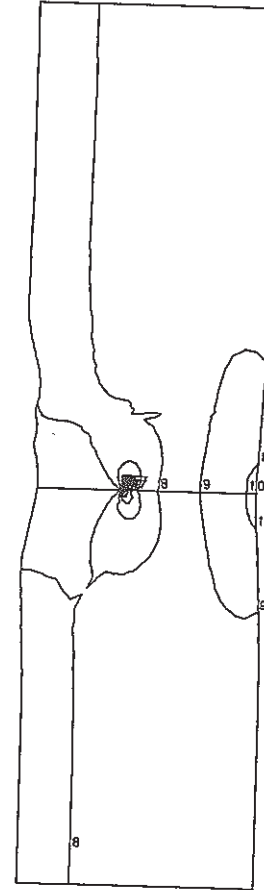


STEP NO. 14

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -200.000
 2 -173.000
 3 -146.000
 4 -119.000
 5 -92.0000
 6 -65.0000
 7 -38.0000
 8 -11.0000
 9 16.00000
 10 43.00000



STEP NO. 18

GEOM. SCALE 20.0000

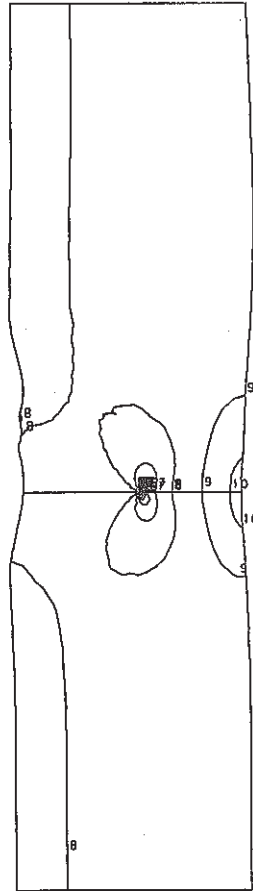
Fig. C.1.9-3 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth $a=10$ mm)

Fig. C.1.9-4 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth $a=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-189.000
2	-163.000
3	-137.000
4	-111.000
5	-85.0000
6	-59.0000
7	-33.0000
8	-7.00000
9	19.00000
10	45.00000



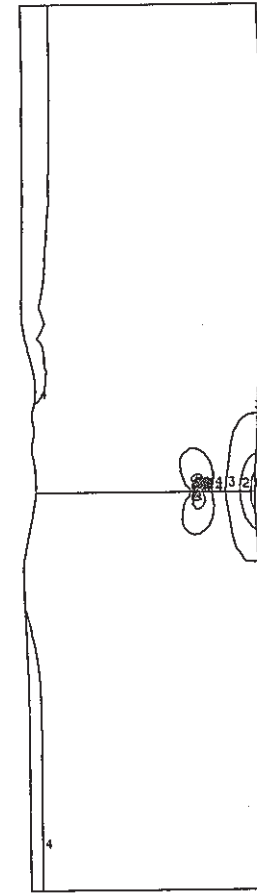
STEP NO. 14

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-52.0000
2	-31.0000
3	-10.0000
4	11.00000
5	32.00000
6	53.00000
7	74.00000
8	95.00000
9	116.0000
10	137.0000



STEP NO. 4

GEOM. SCALE 20.0000

Fig. C.1.9-5 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth $a=20$ mm)

Fig. C.1.9-6 Contour of Axial Stress at Hot Shock of Finally Welded Portion (crack depth $a=27$ mm)

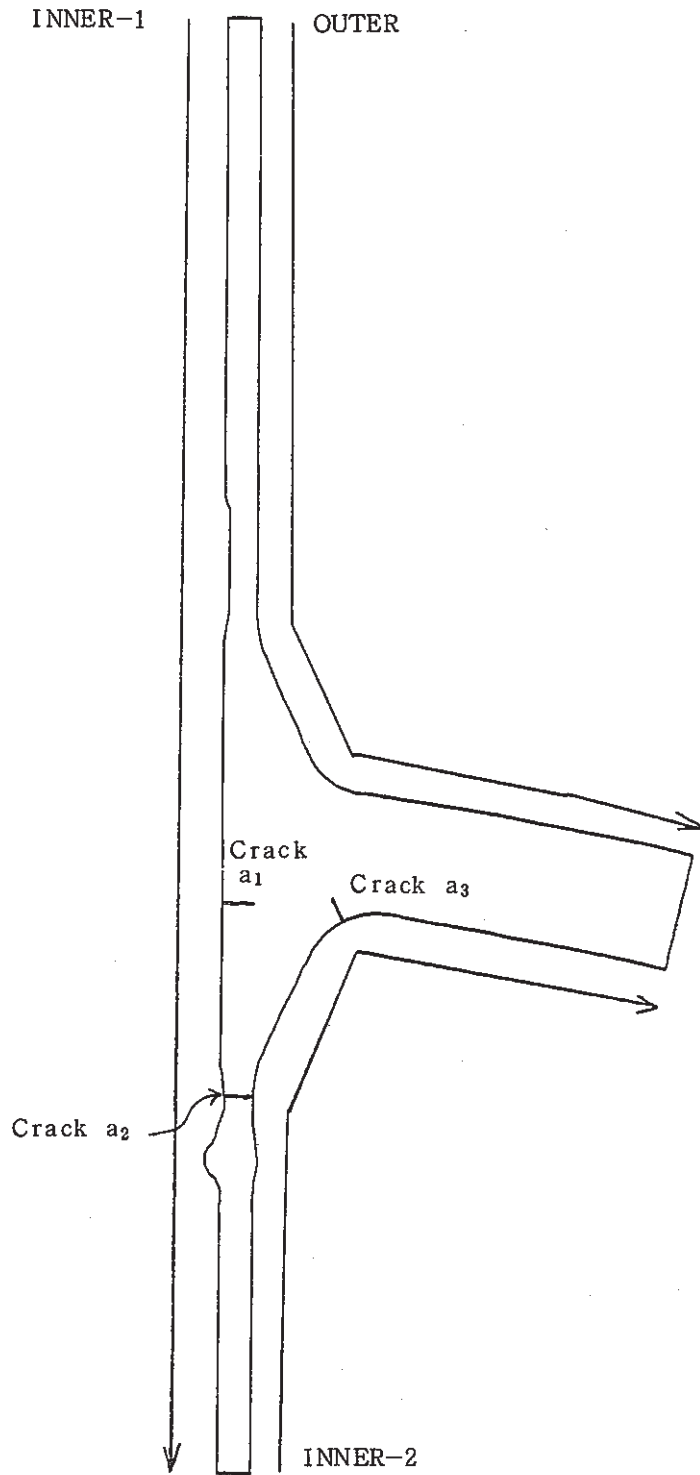


Fig. C.2-1 Evaluation Lines for Surface Stress Distribution of Inlet Nozzle

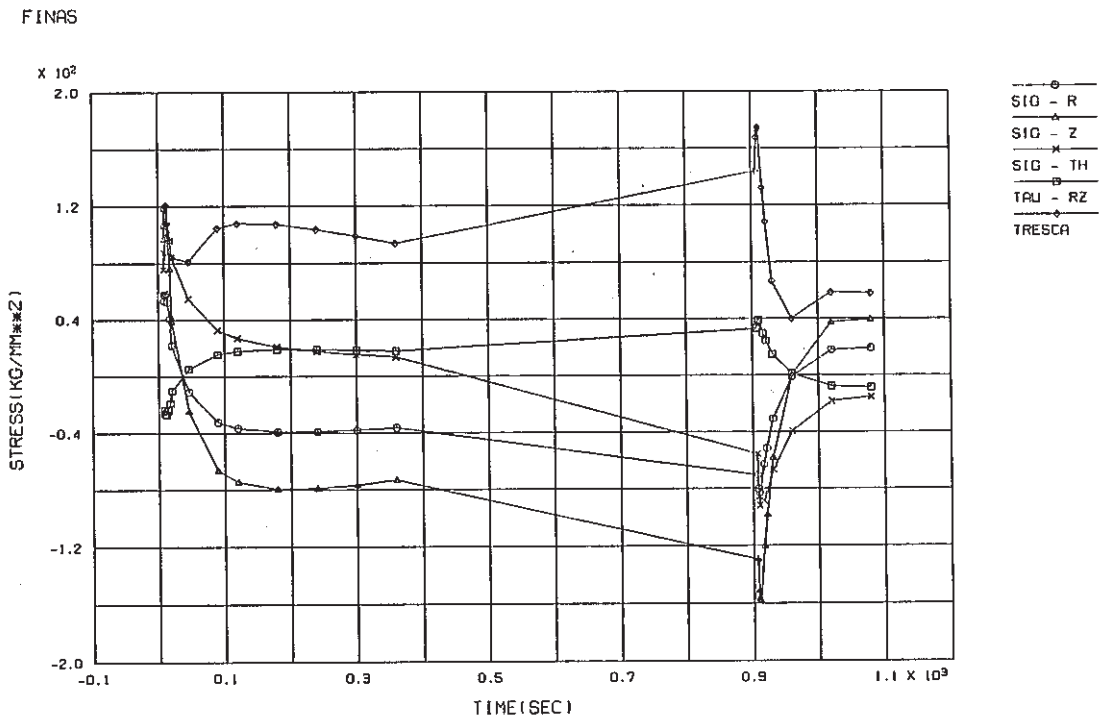


Fig. C.2.1-1 Stress History ahead of Crack Tip of Inlet Nozzle, crack a₁
 (crack depth a₁=1 mm, a₂=1 mm, a₃=1 mm)

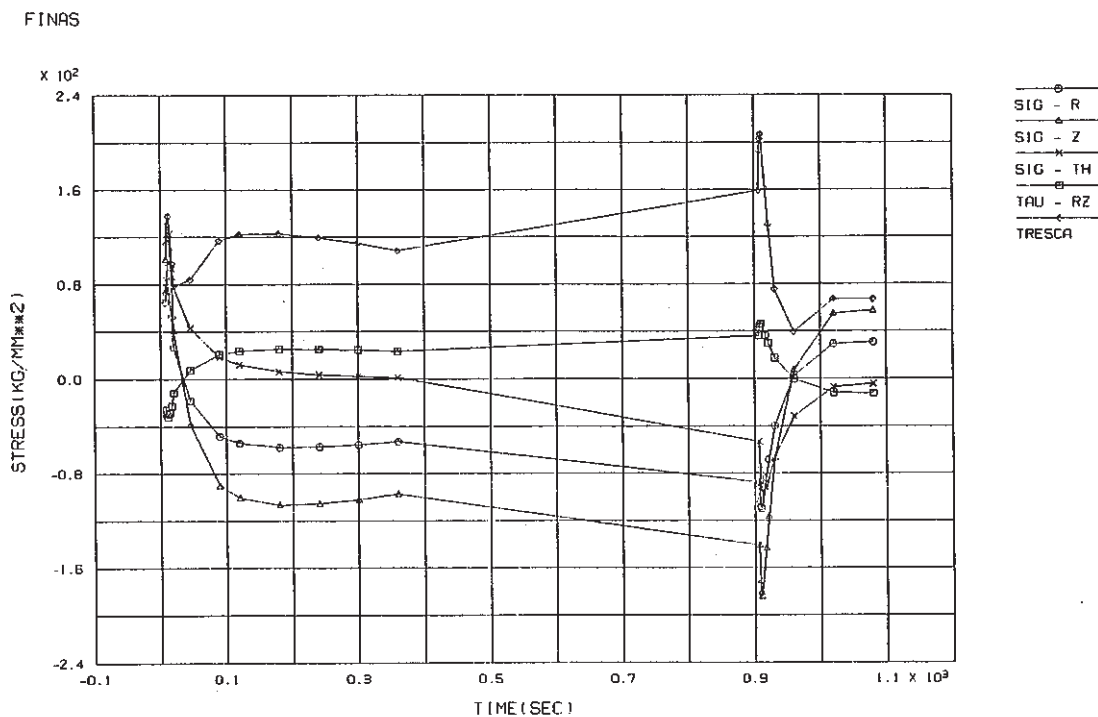


Fig.C.2.1-2 Stress History ahead of Crack Tip of Inlet Nozzle, crack a₁
 (crack depth a₁=2 mm, a₂=2.65 mm, a₃=2 mm)

FINAS

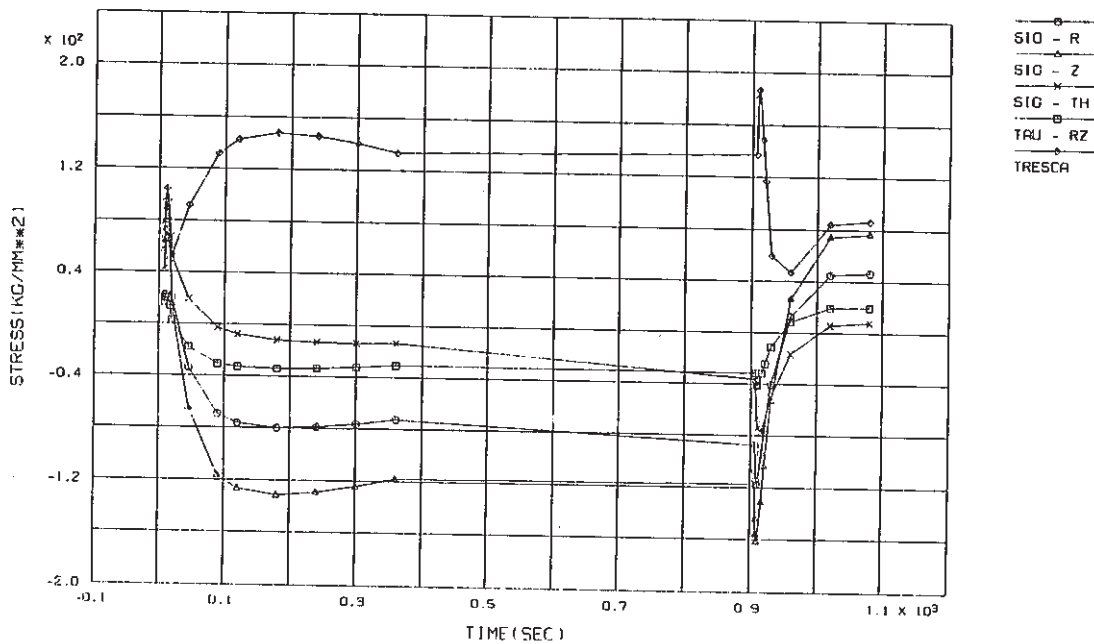


Fig. C.2.1-3 Stress History ahead of Crack Tip of Inlet Nozzle, crack a_1 (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

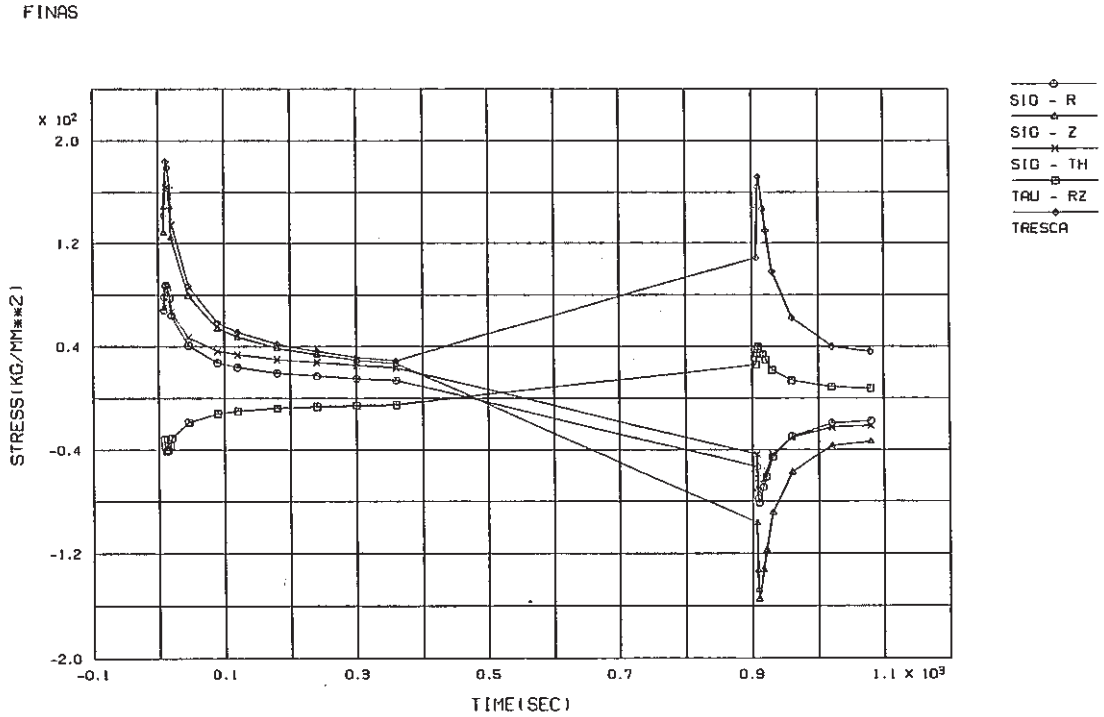


Fig. C.2.2-1 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_2 (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

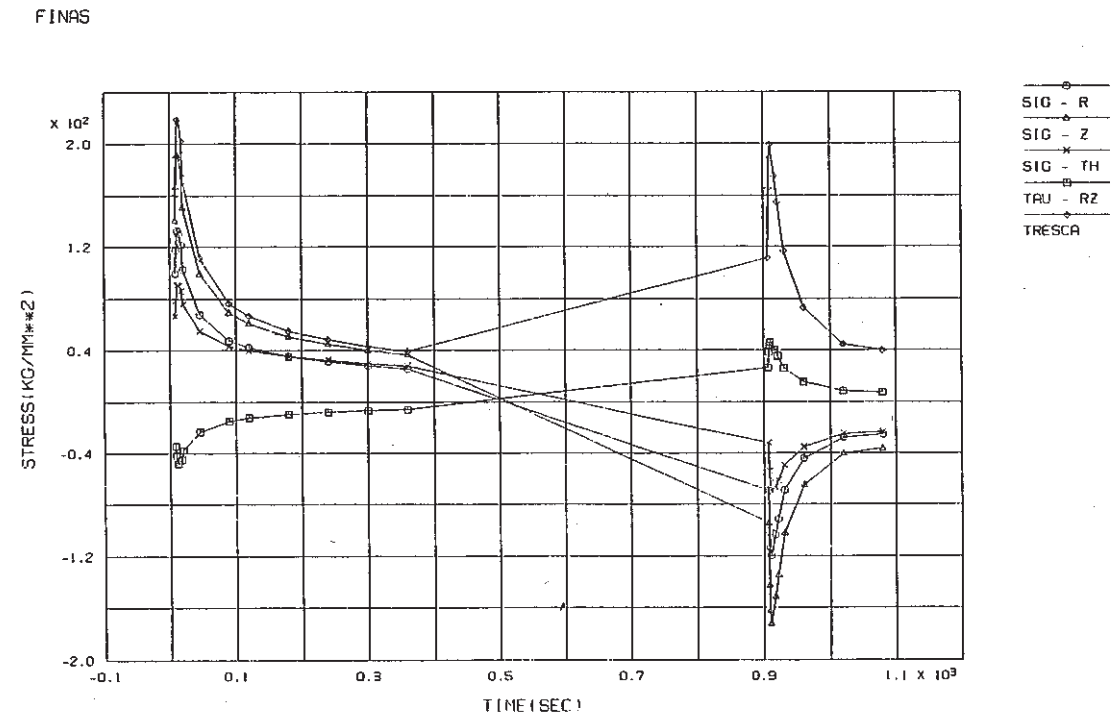


Fig. C.2.2.-2 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_2 (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

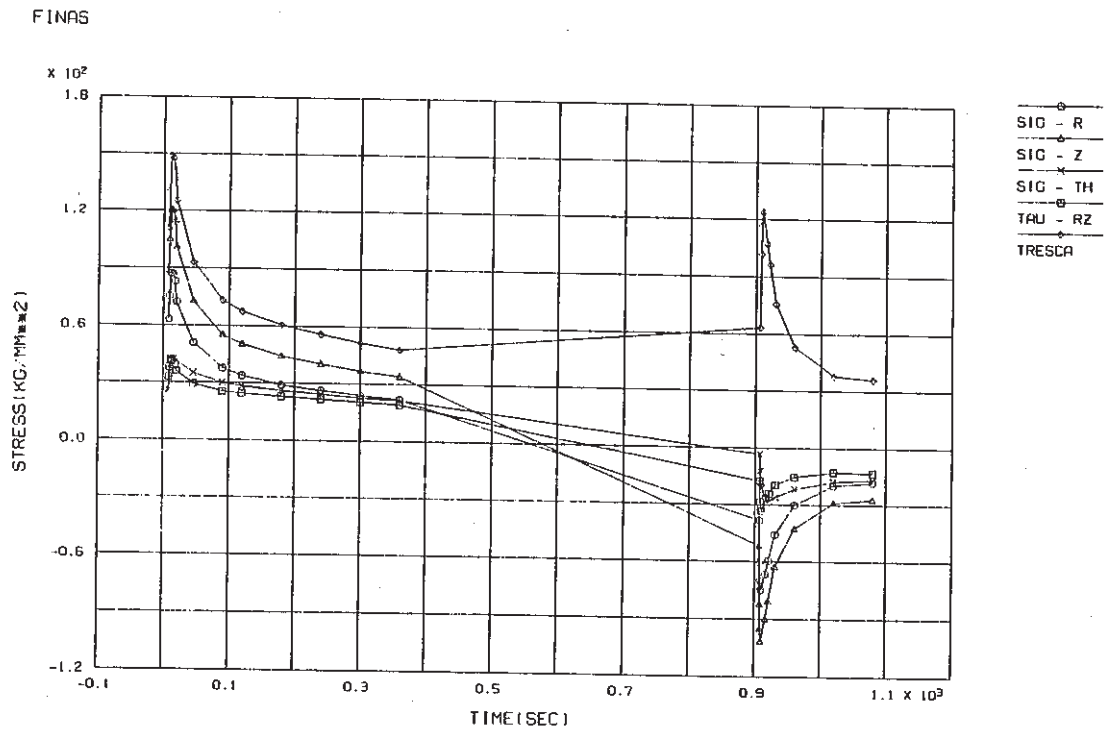


Fig. C.2.2-3 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_2
 (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

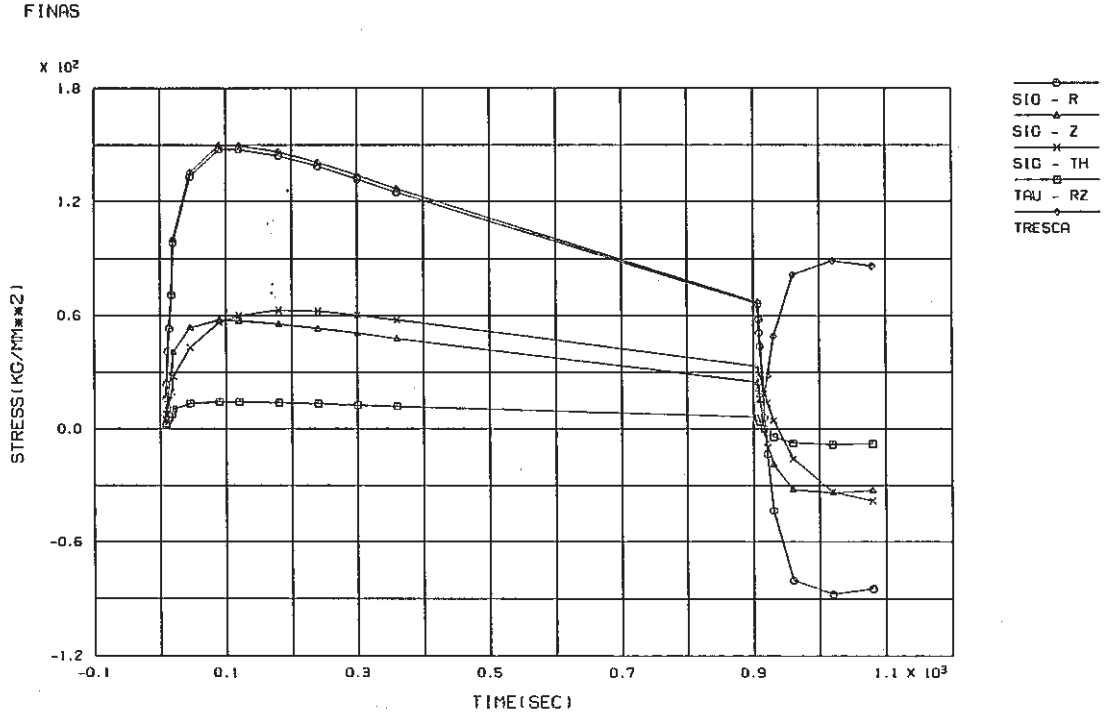


Fig. C.2.3-1 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_3 (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

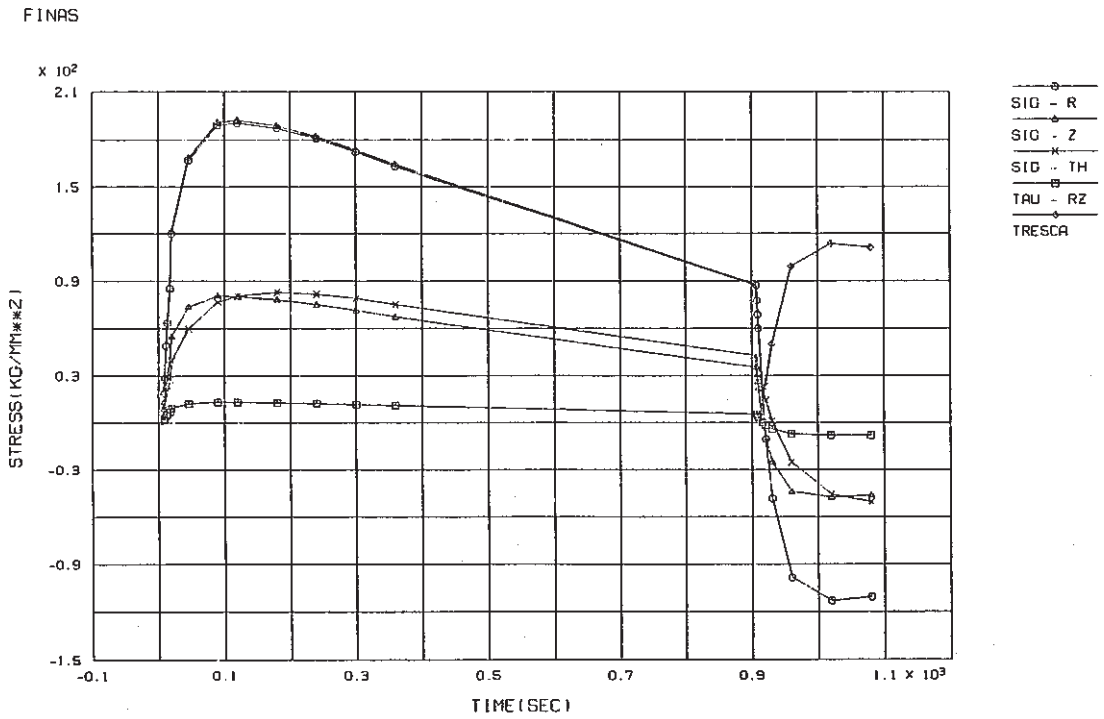


Fig. C.2.3-2 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_3 (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

FINAS

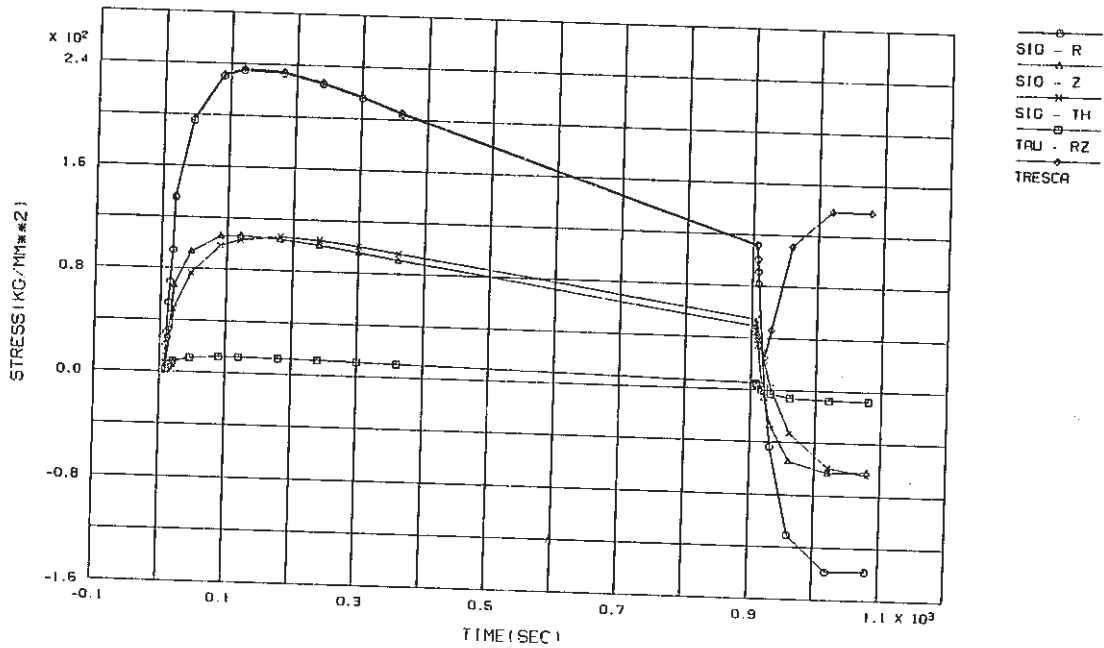


Fig. C.2.3-3 Stress History of ahead of Crack Tip of Inlet Nozzle, crack a_3
 (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

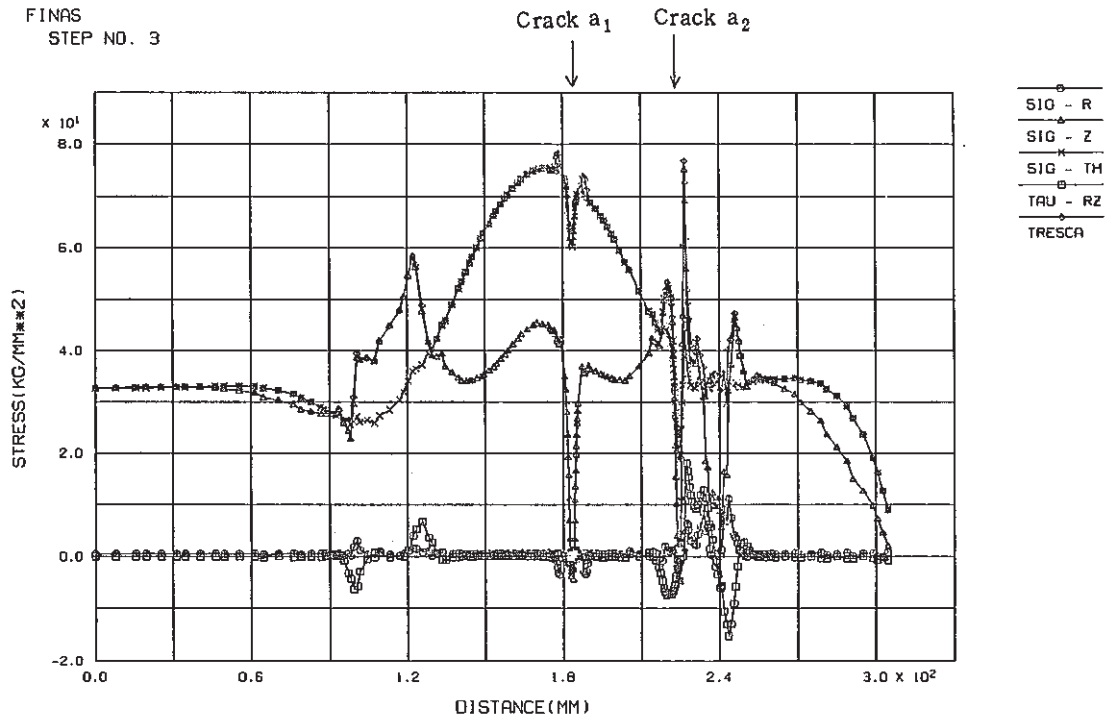


Fig. C.2.4-1 Stress Distribution along Inner-1 Surface at Cold Shock of Inlet Nozzle (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

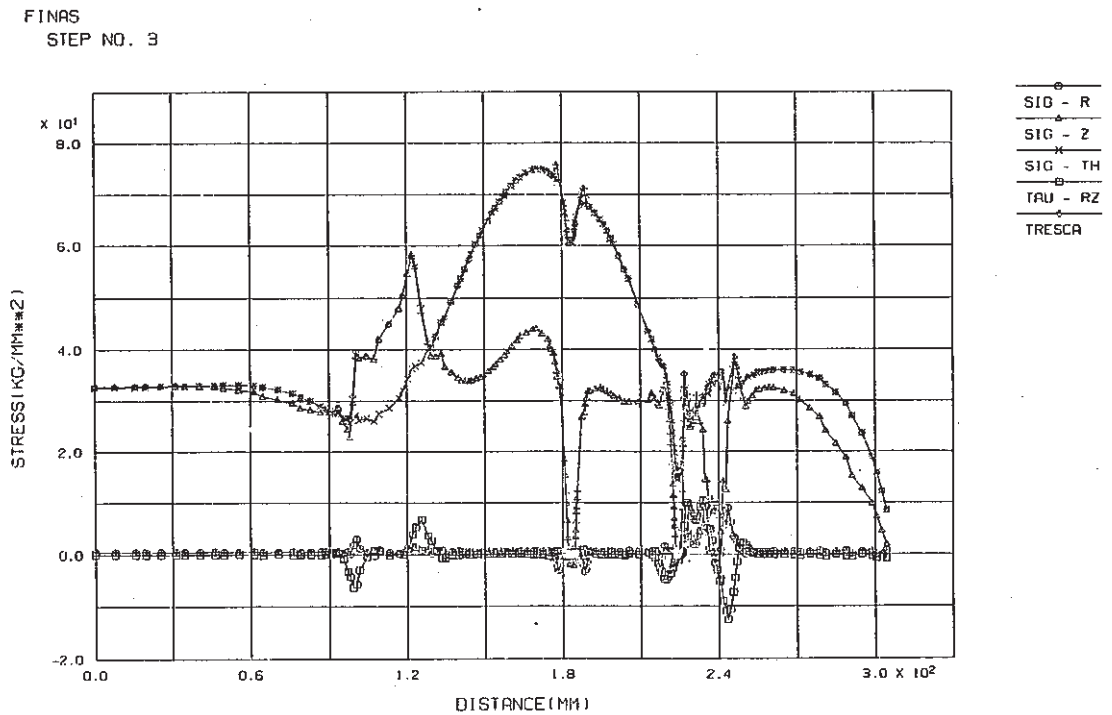


Fig. C.2.4-2 Stress Distribution along Inner-1 Surface at Cold Shock of Inlet Nozzle (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

FINAS
SIEP NO. 3

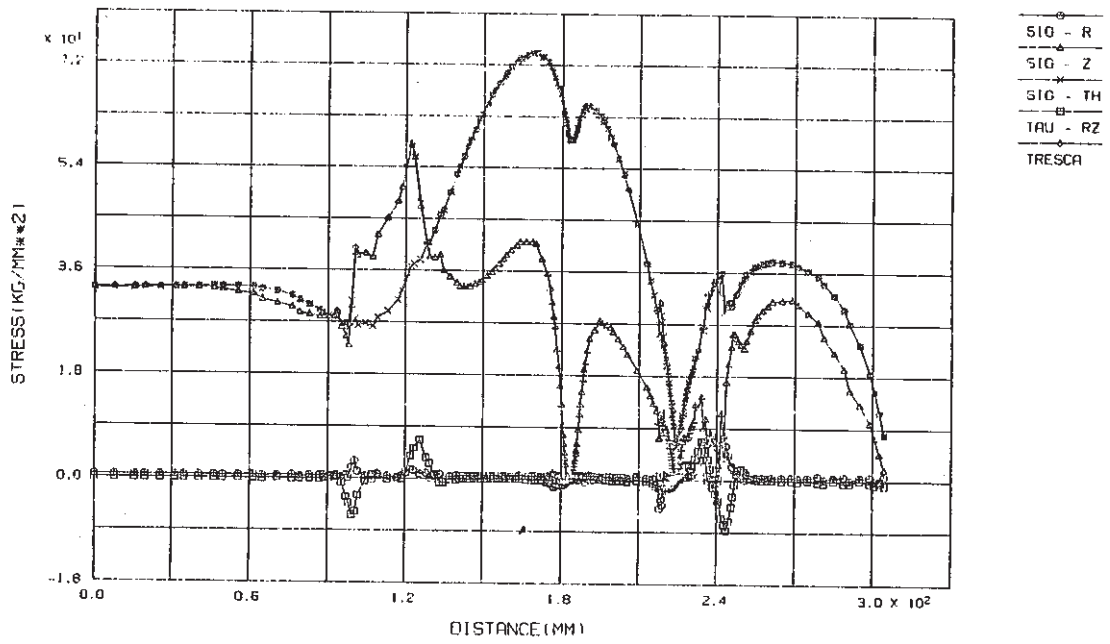


Fig. C.2.4-3 Stress Distribution along Inner-1 Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

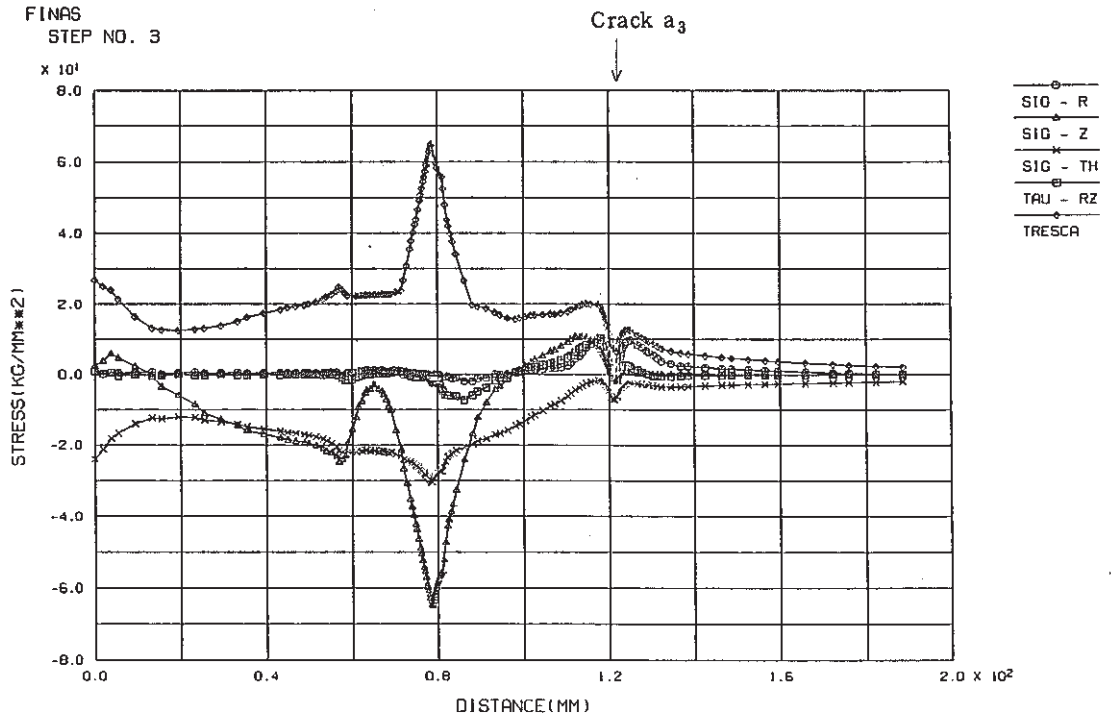


Fig. C.2.5-1 Stress Distribution along Inner-2 Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

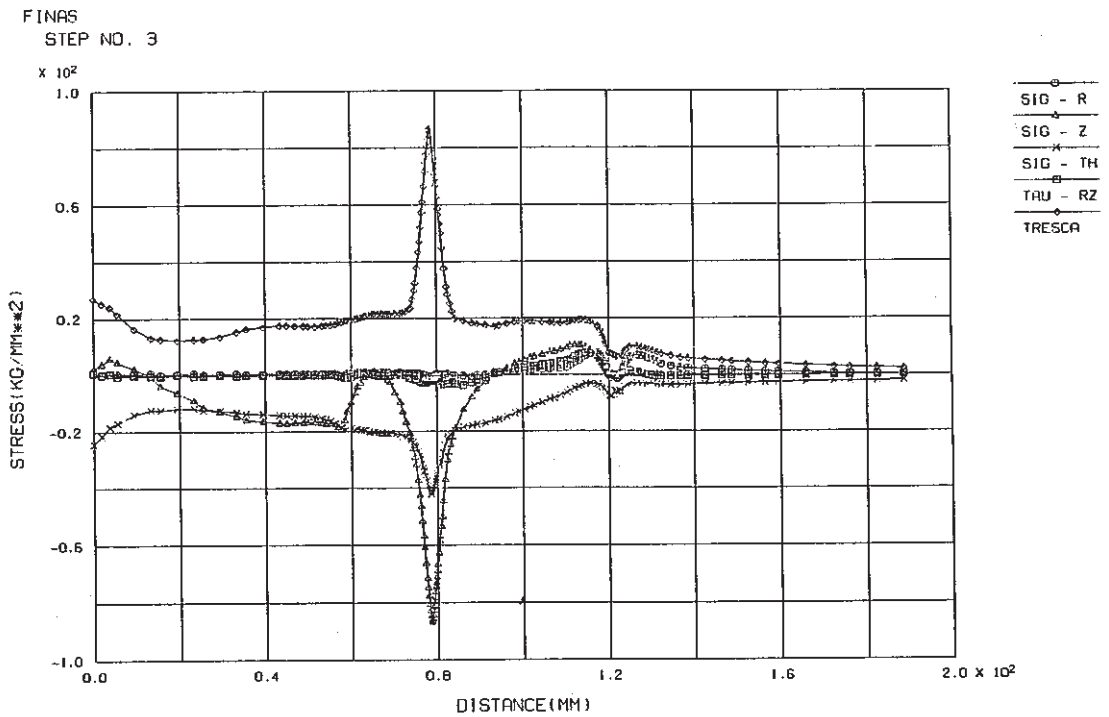


Fig. C.2.5-2 Stress Distribution along Inner-2 Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

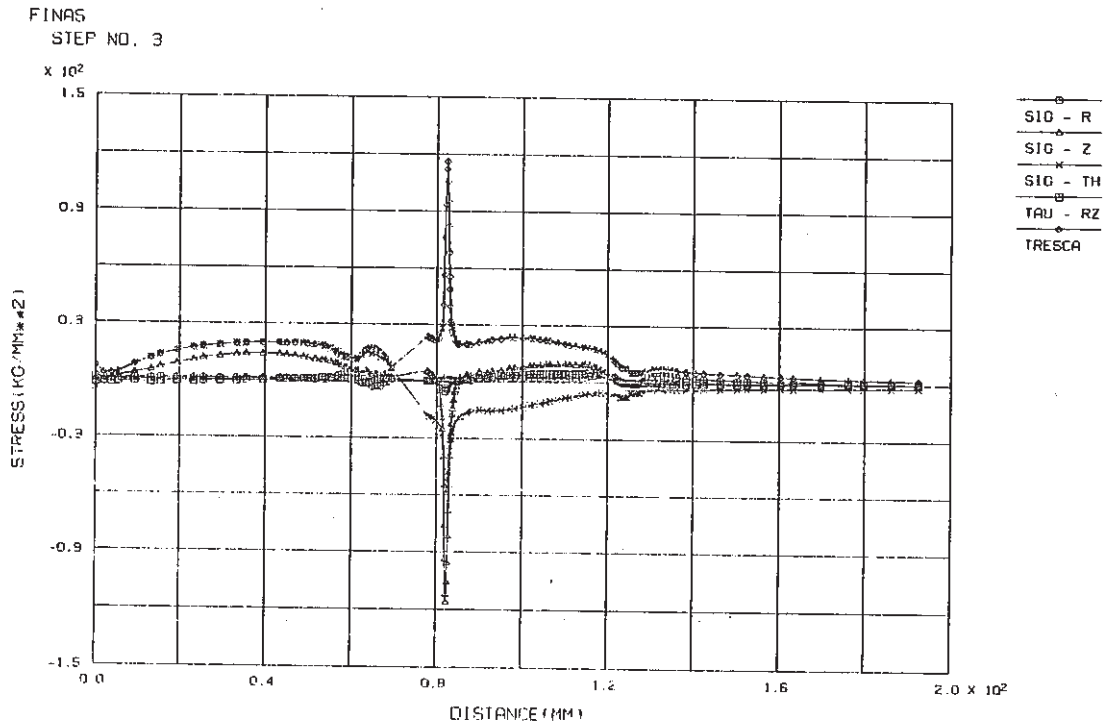


Fig. C.2.5-3 Stress Distribution along Inner-2 Surface at Cold Shock of Inlet Nozzle (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

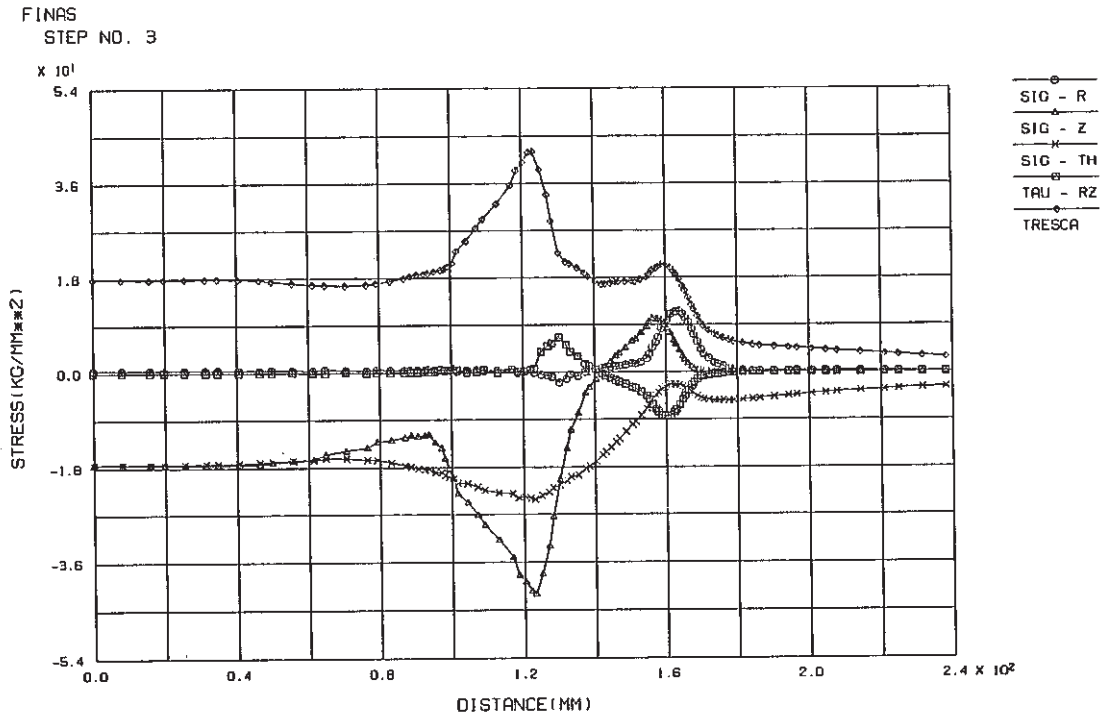


Fig. C.2.6-1 Stress Distribution along outer Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

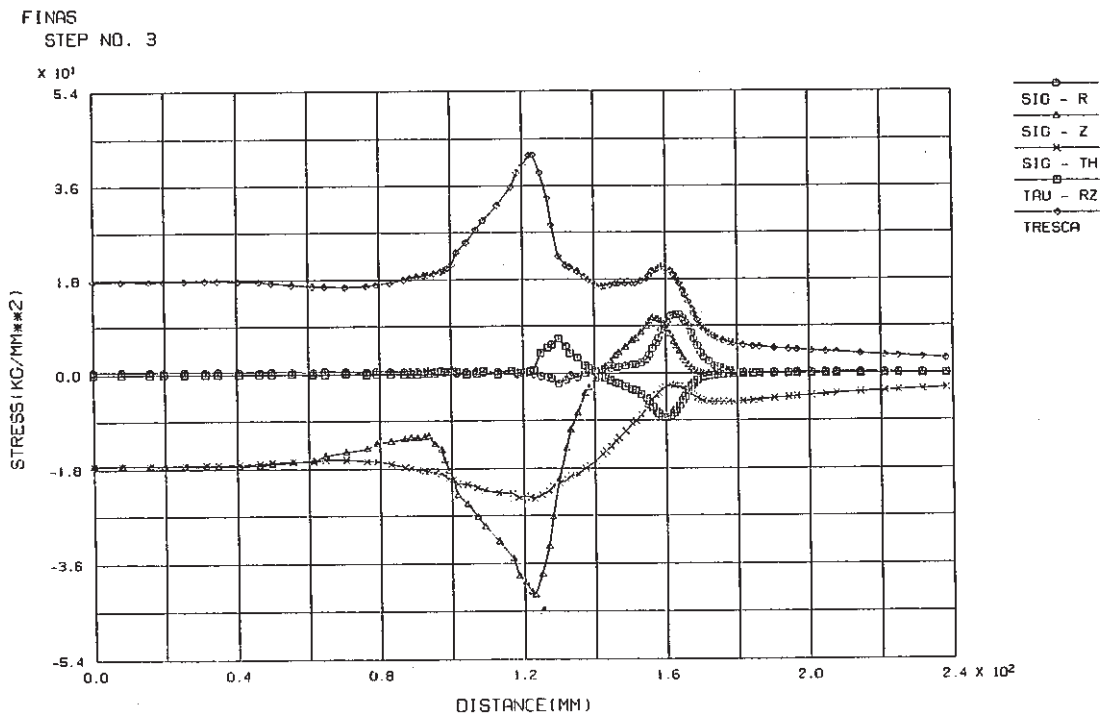


Fig. C.2.6-2 Stress Distribution along Outer Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

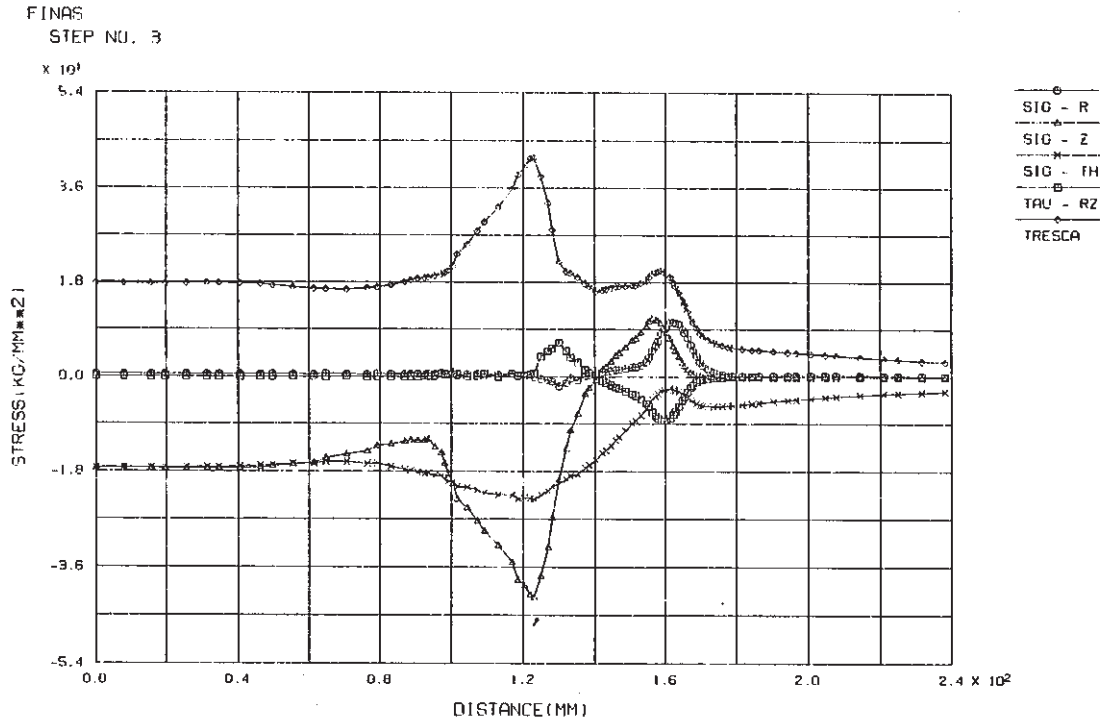


Fig. C.2.6-3 Stress Distribution along Outer Surface at Cold Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

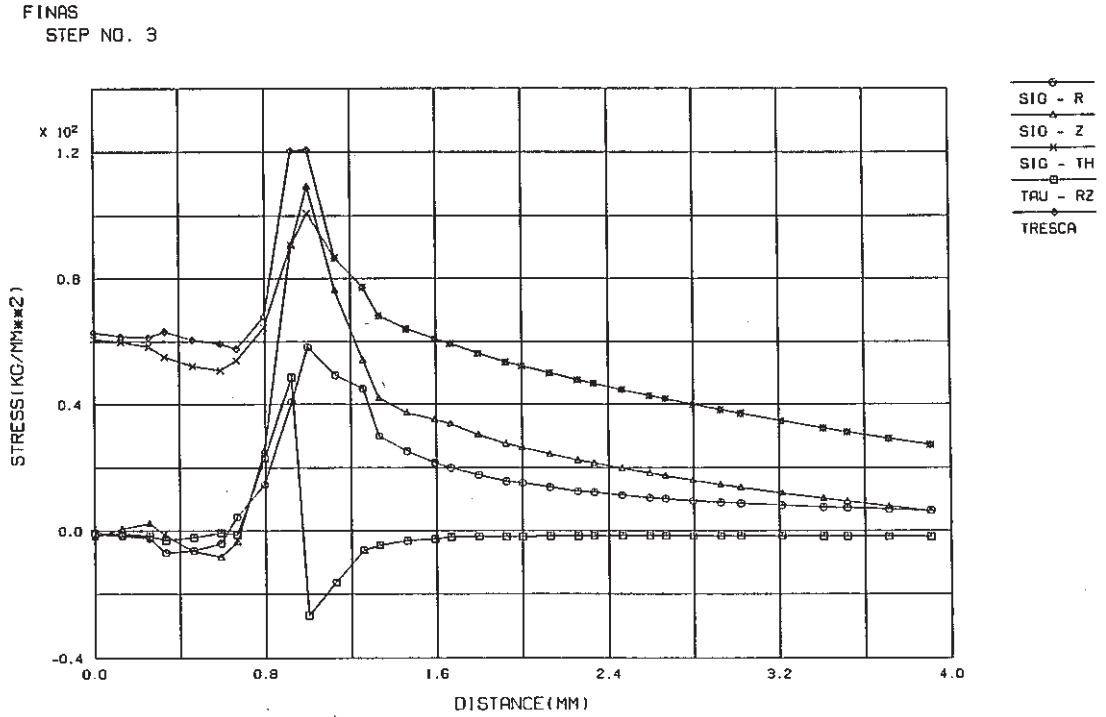


Fig. C.2.7-1 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

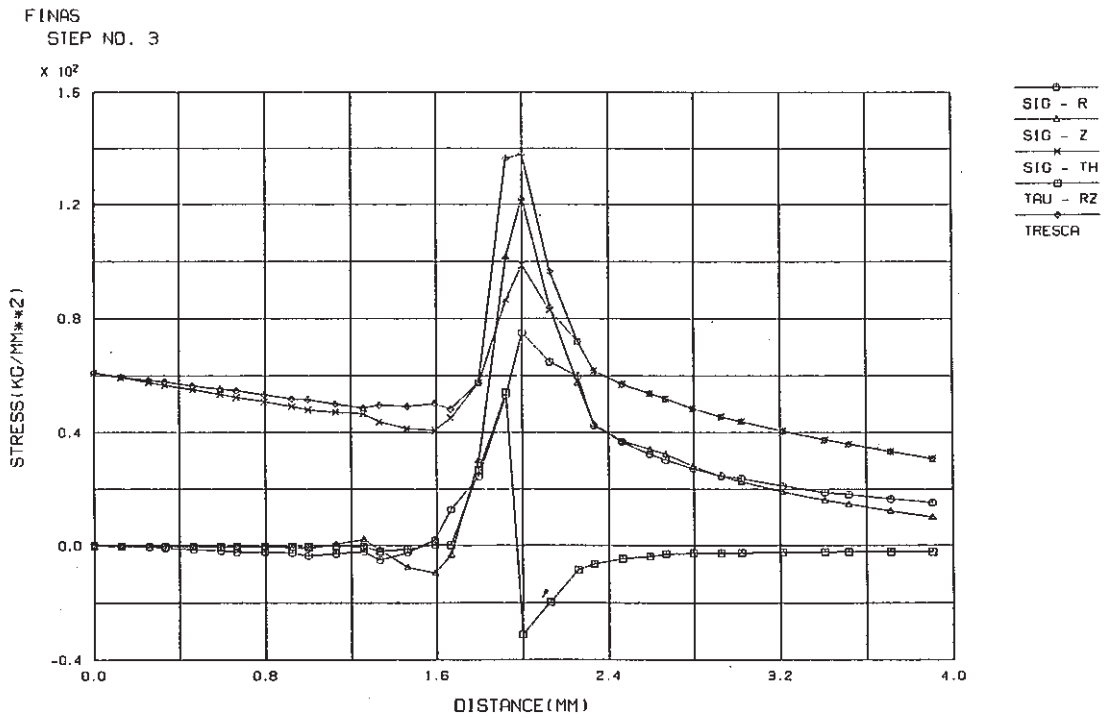


Fig. C.2.7-2 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

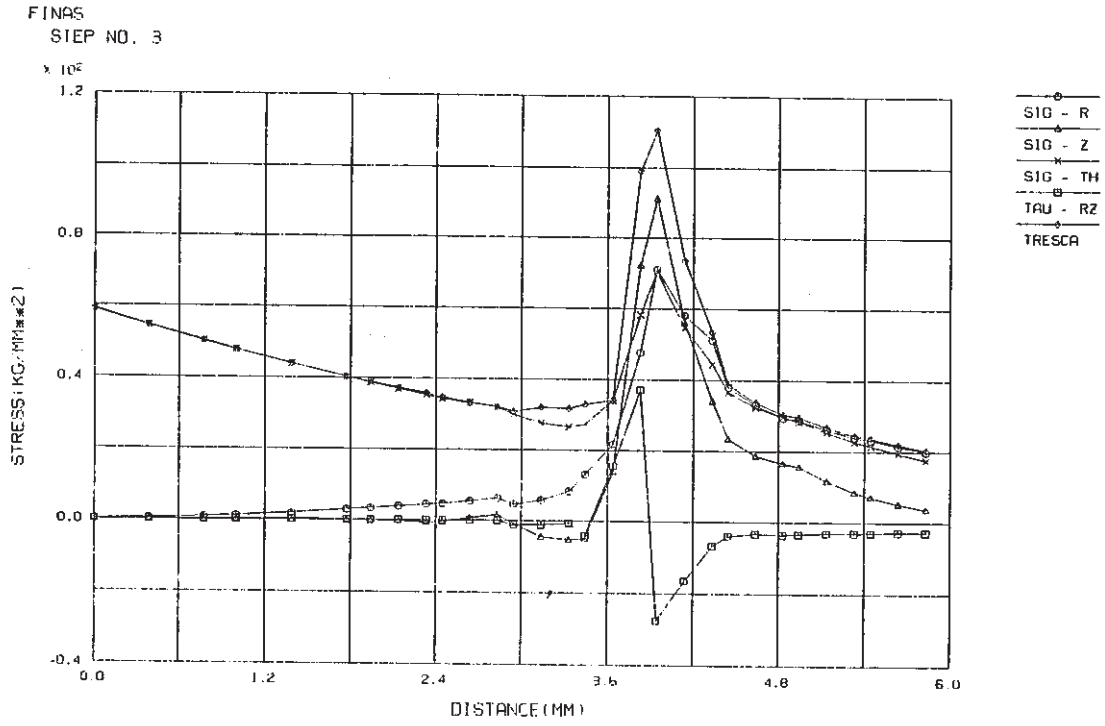


Fig. C.2.7-3 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

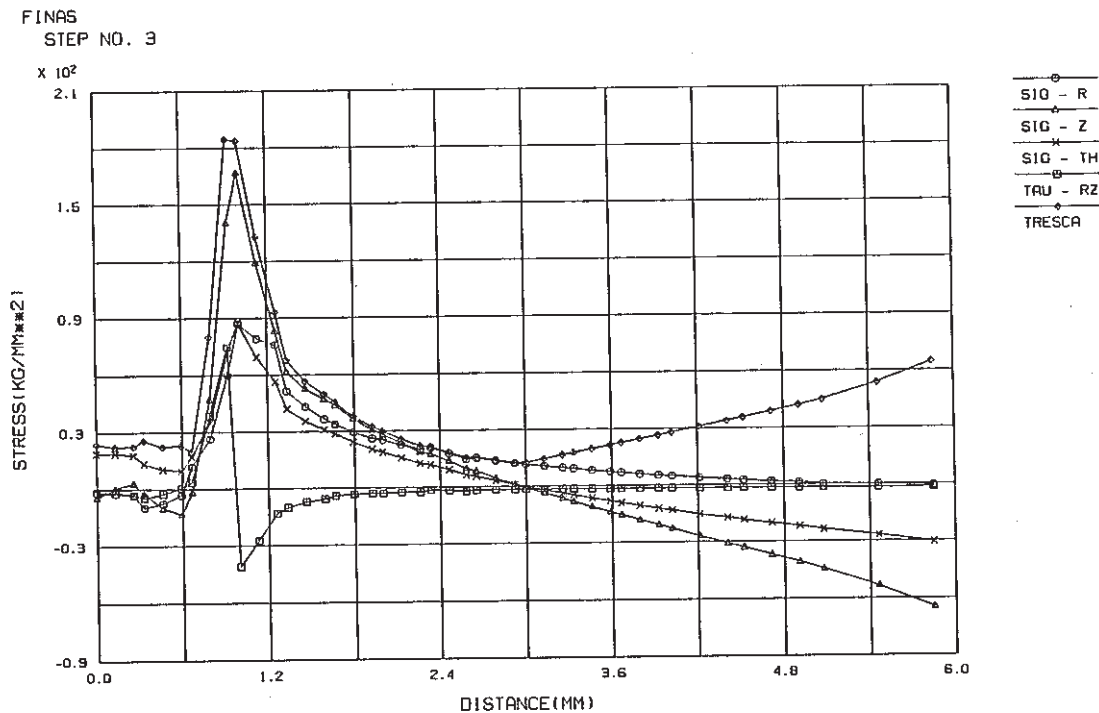


Fig. C.2.8-1 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_2 (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

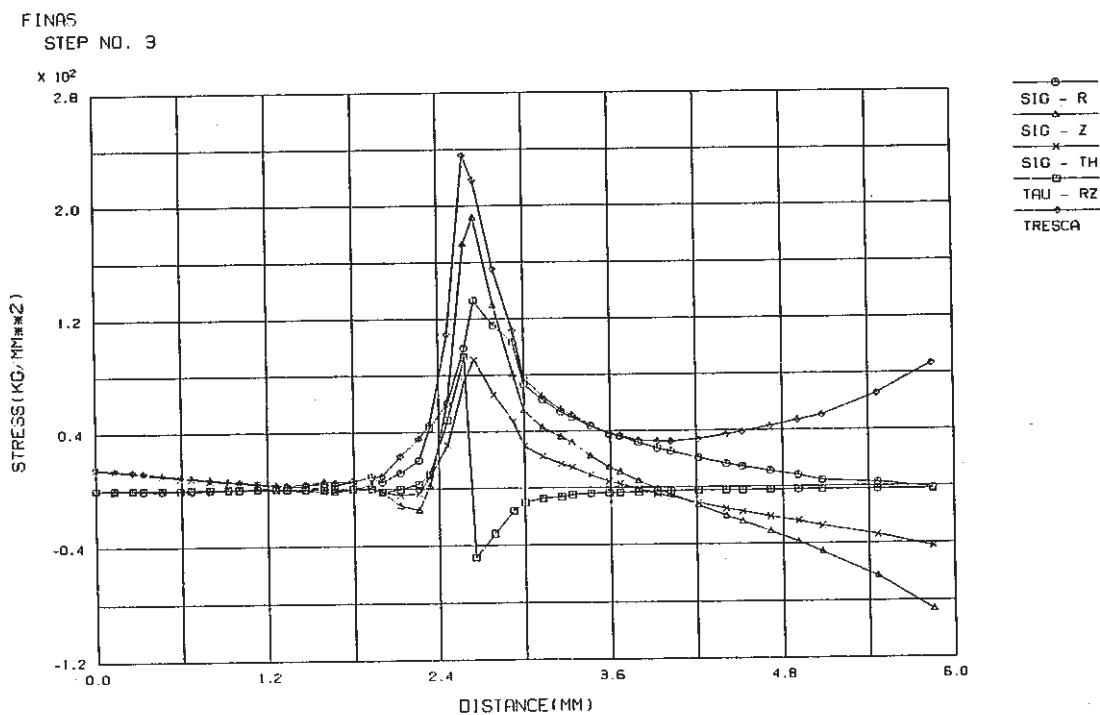


Fig. C.2.8-2 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_2 (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

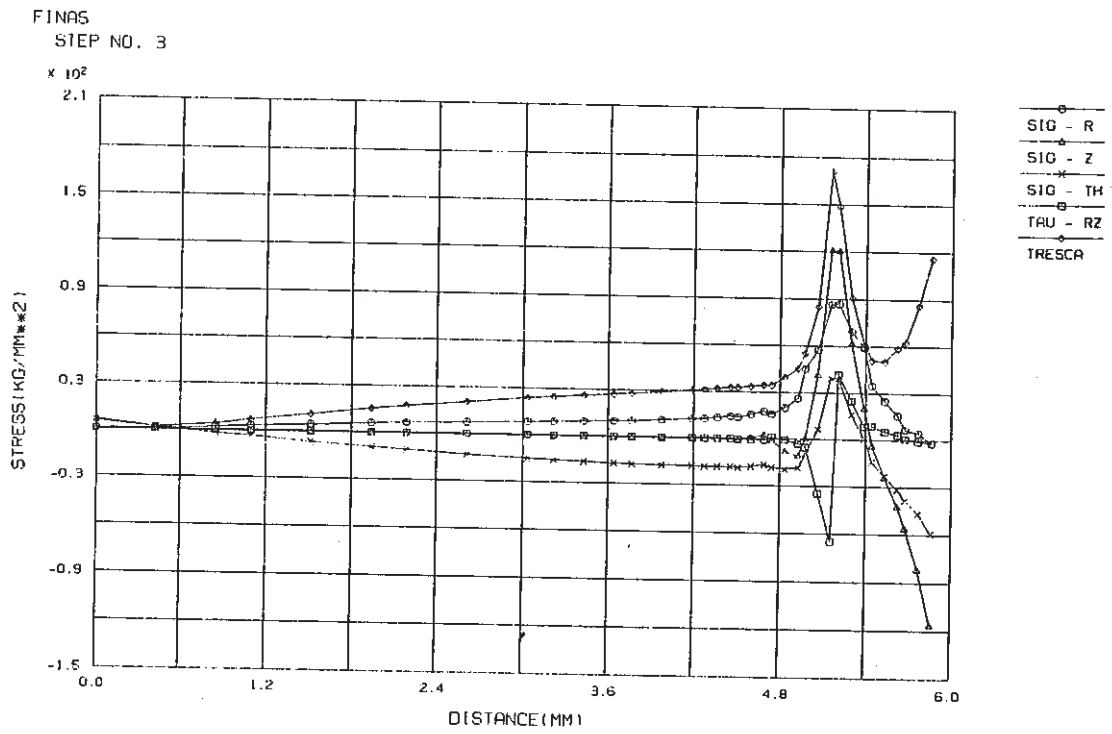


Fig. C.2.8-3 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a₂
(crack depth a₁=4 mm, a₂=5.3 mm, a₃=4 mm)

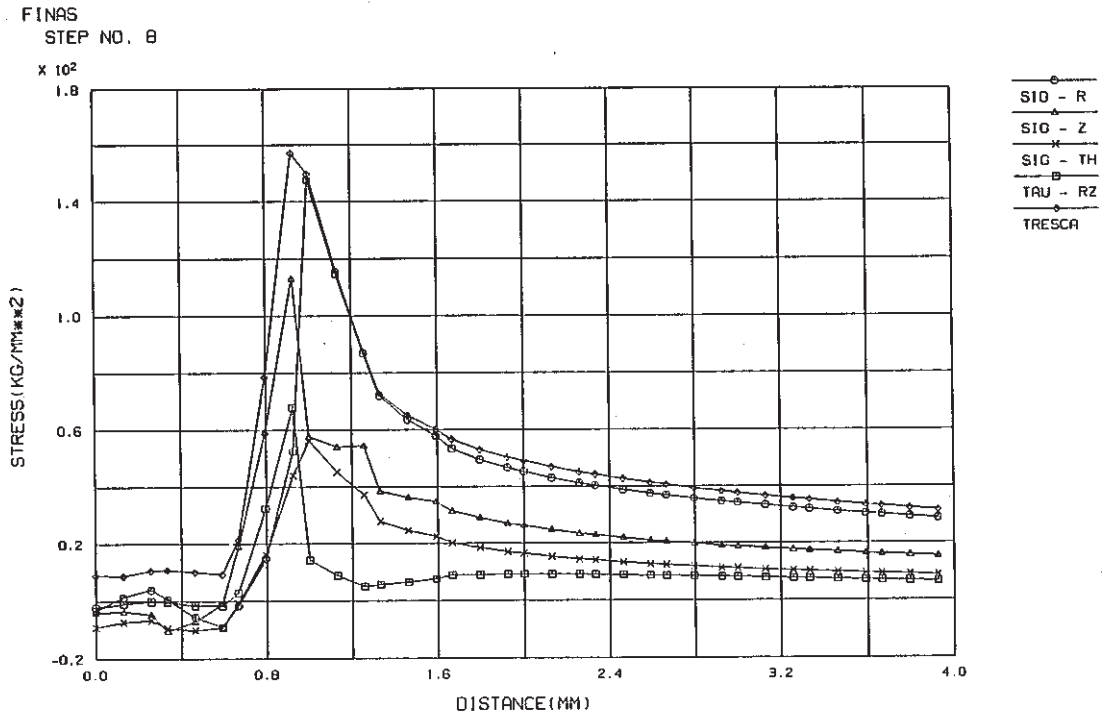


Fig. C.2.9-1 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a₃ (crack depth a₁=1 mm, a₂=1 mm, a₃=1 mm)

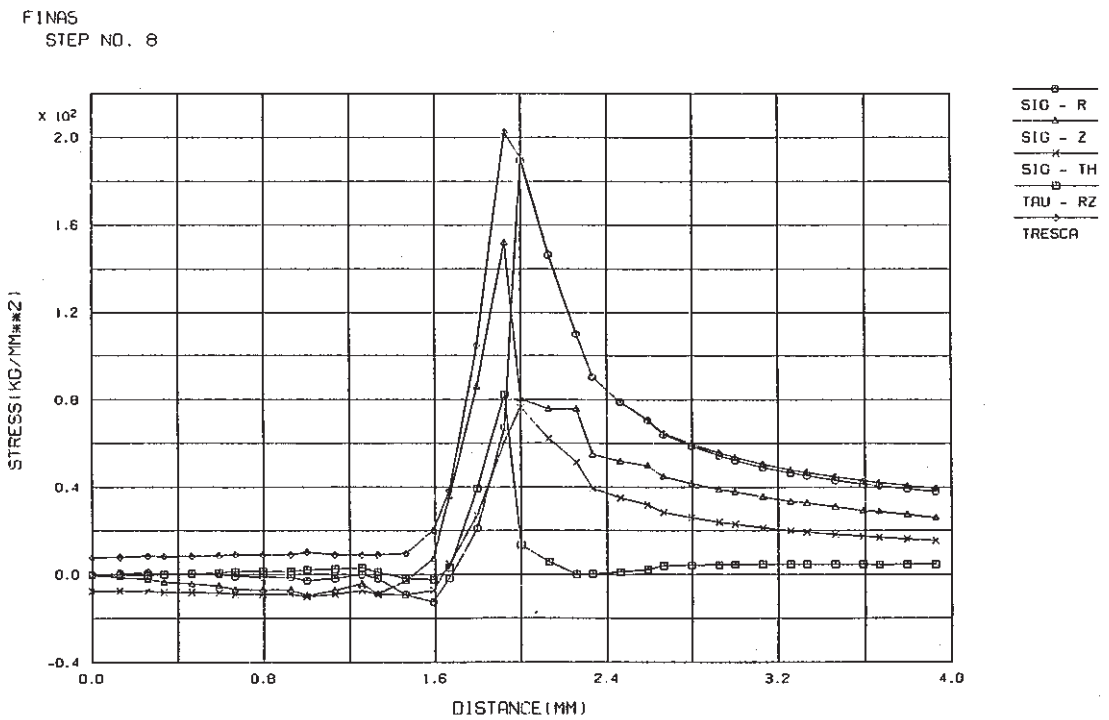


Fig. C.2.9-2 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a₃ (crack depth a₁=2 mm, a₂=2.65 mm, a₃=2 mm)

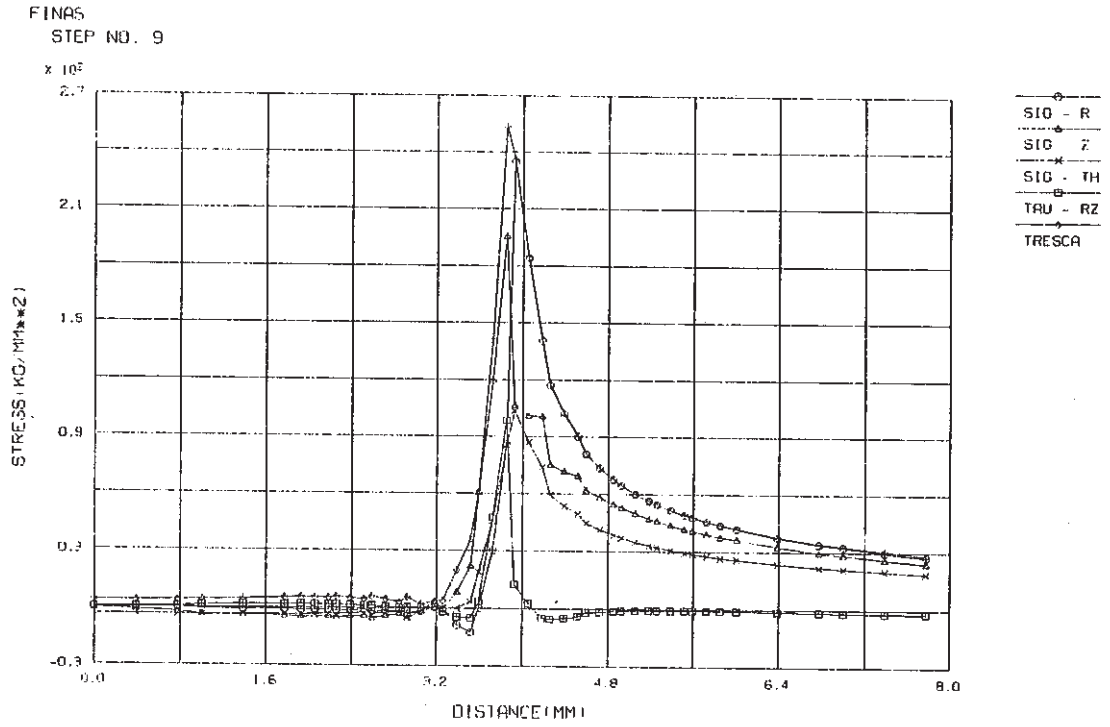


Fig. C.2.9-3 Stress Distribution along Crack Line at Cold Shock of Inlet Nozzle, crack a_3
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-55.0000
2	-29.0000
3	-3.00000
4	23.00000
5	49.00000
6	75.00000
7	100.9999
8	126.9999
9	152.9999
10	178.9999

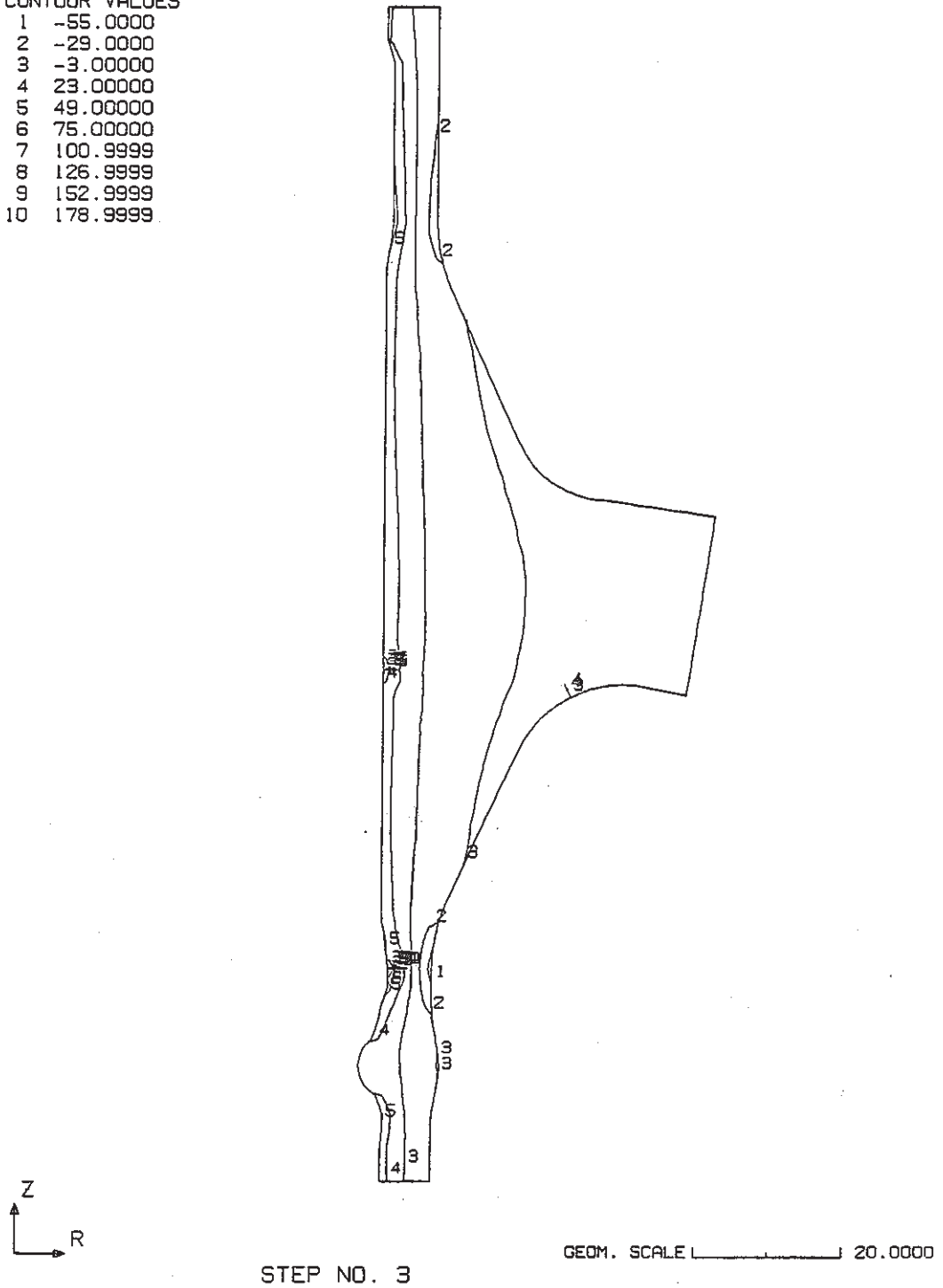
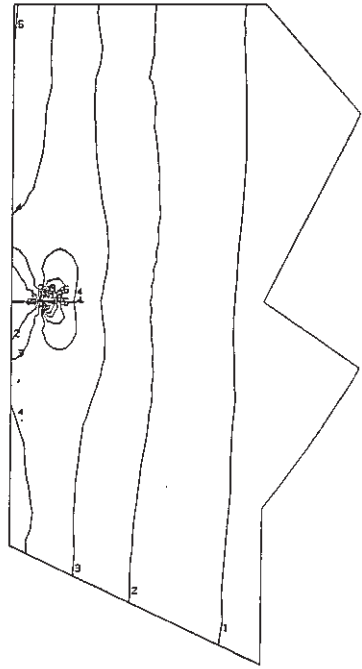


Fig. C.2.10-1 Contour of Axial Stress at Cold Shock of Inlet Nozzle
(crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -6.00000
2 7.00000
3 20.00000
4 39.00000
5 46.00000
6 59.00000
7 72.00001
8 85.00001
9 98.00002
10 110.99999

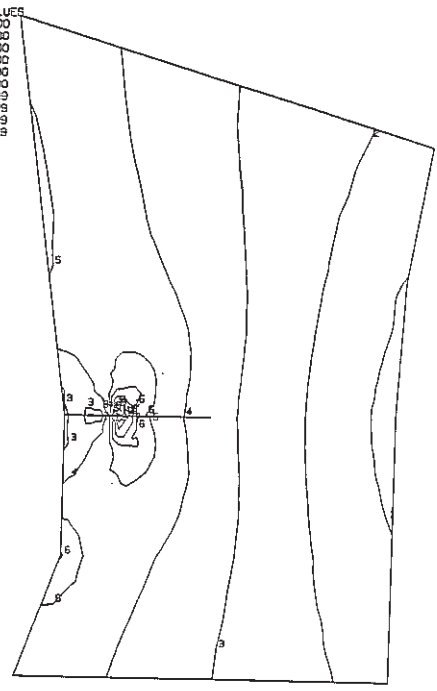


STEP NO. 3

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -55.0000
2 -29.0000
3 -3.00000
4 23.00000
5 49.00000
6 75.00000
7 100.9999
8 125.9999
9 152.9999
10 178.9999

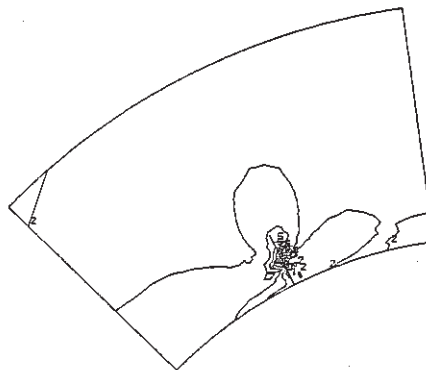


STEP NO. 3

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -9.00000
2 3.00000
3 15.00000
4 26.99999
5 39.00000
6 51.00000
7 63.00001
8 75.00000
9 87.00001
10 99.00001



STEP NO. 8

Crack a₃

Fig. C.2.10-1 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-78.0000
2	-46.0000
3	-14.0000
4	18.00000
5	50.00000
6	82.00001
7	113.99999
8	146.0000
9	177.99999
10	209.99999

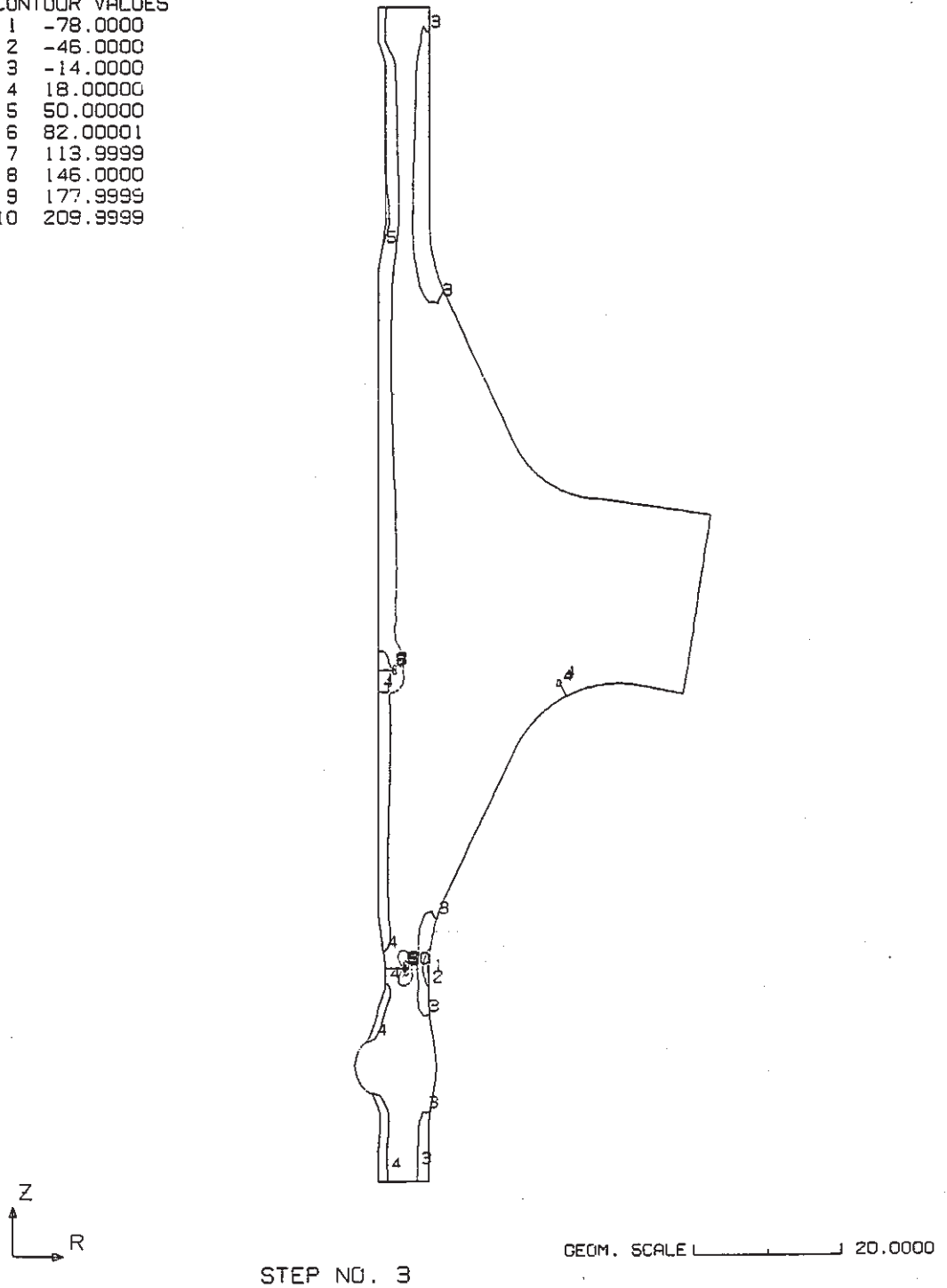
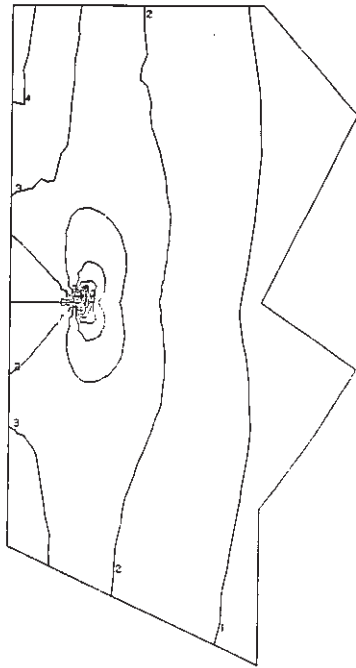


Fig. C.2.10-2 Contour of Axial Stress at Cold Shock of
Inlet Nozzle
(crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -8.00000
2 8.000000
3 21.99999
4 36.00000
5 50.00000
6 64.00001
7 78.00001
8 92.00001
9 105.9999
10 119.9999



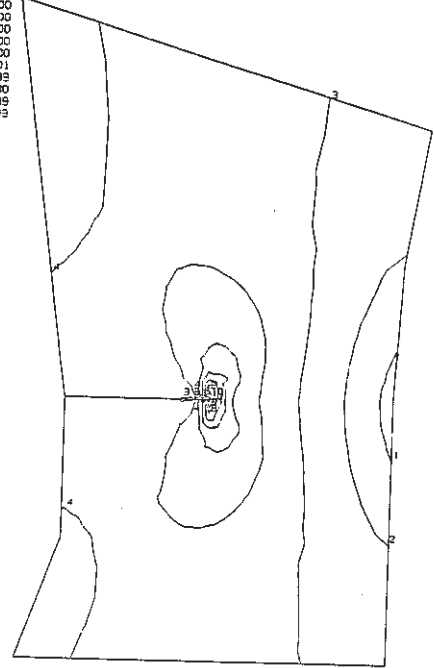
STEP NO. 3

GEOM. SCALE 2.00000

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -79.0000
2 -46.0000
3 -14.0000
4 18.00000
5 50.00000
6 82.00001
7 113.9999
8 145.0000
9 177.9999
10 209.9999



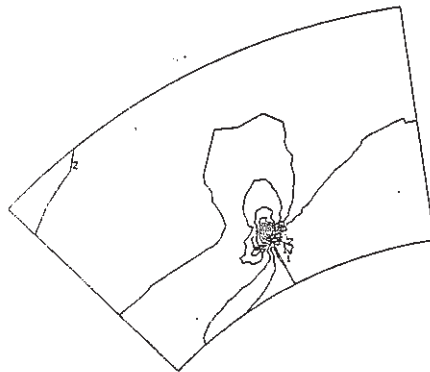
STEP NO. 3

GEOM. SCALE 1.50000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -9.00000
2 4.000000
3 15.99999
4 30.00000
5 43.00000
6 56.00001
7 69.00001
8 82.00001
9 95.00001
10 107.9999



STEP NO. 8

GEOM. SCALE 3.00000

Crack a₃

Fig. C.2.10-2 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

- 1 -114.000
- 2 -88.0000
- 3 -62.0000
- 4 -36.0000
- 5 -10.0000
- 6 16.00000
- 7 42.00000
- 8 68.00000
- 9 94.00000
- 10 119.9999

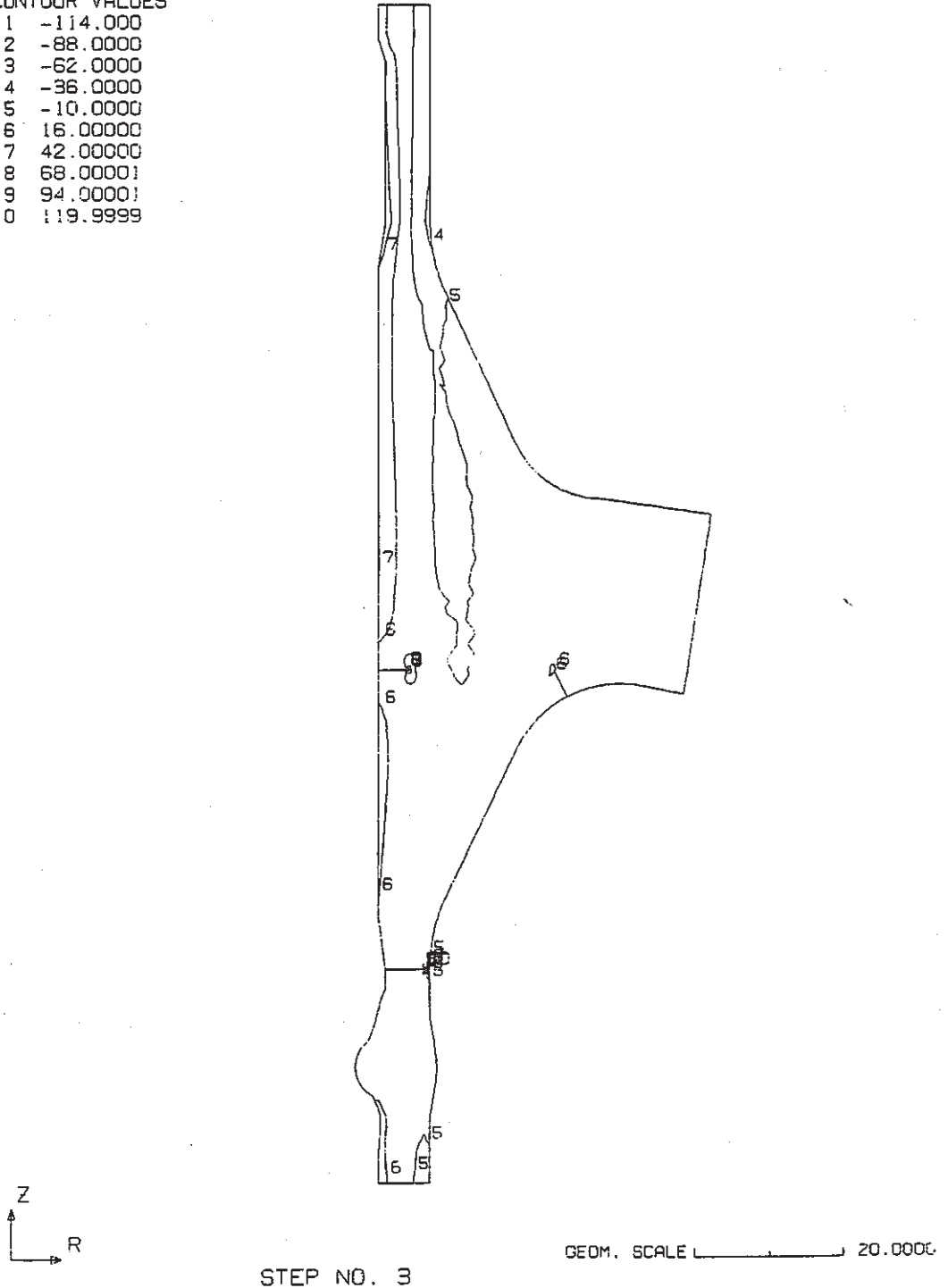
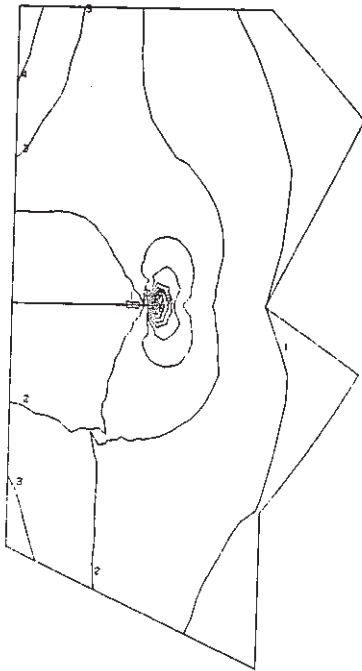


Fig. C.2.10-3 Contour of Axial Stress at Cold Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -4.00000
2 7.00000
3 18.00000
4 29.00000
5 40.00000
6 51.00000
7 62.00000
8 73.00001
9 84.00001
10 95.00001



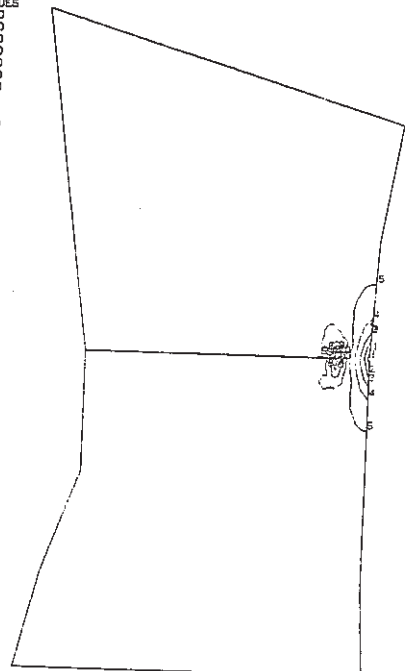
STEP NO. 3

GEOM. SCALE 2.00000

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -114.000
2 -88.0000
3 -62.0000
4 -36.0000
5 -10.0000
6 16.00000
7 42.00000
8 68.00001
9 94.00001
10 119.9999



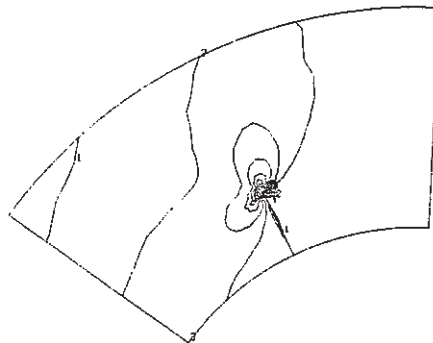
STEP NO. 3

GEOM. SCALE 2.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -4.00000
2 11.99999
3 28.00000
4 44.00000
5 60.00000
6 76.00001
7 92.00001
8 107.99999
9 123.99999
10 139.99999



STEP NO. 9

GEOM. SCALE 5.00000

Crack a₃

Fig. C.2.10-3 (Cont'd)

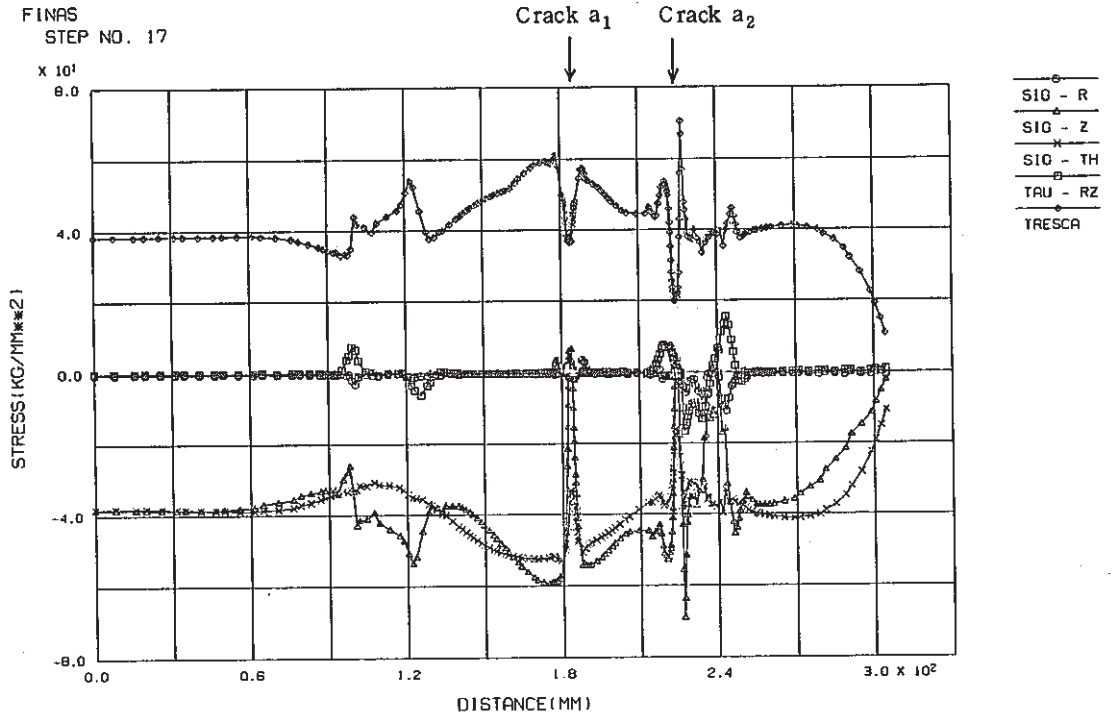


Fig. C.2.11-1 Stress Distribution along Inner-1 Surface at Hot Shock of Inlet Nozzle
(crack depth a₁=1 mm, a₂=1 mm, a₃=1 mm)

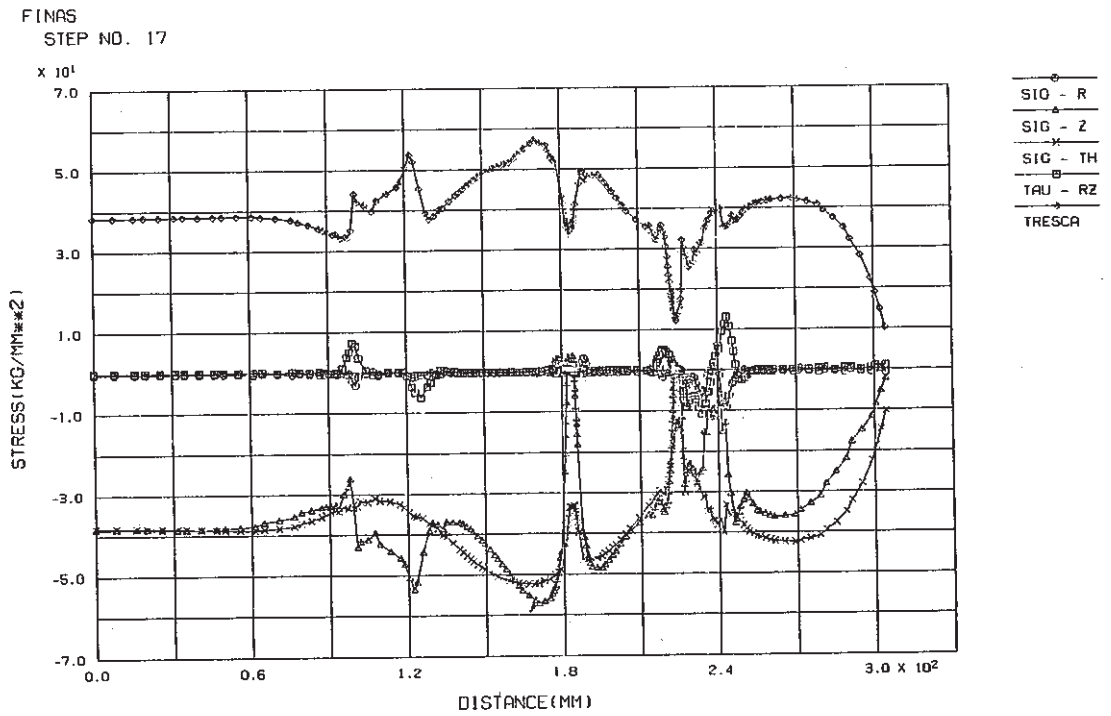


Fig. C.2.11-2 Stress Distribution along Inner-1 Surface at Hot Shock of Inlet Nozzle
(crack depth a₁=2 mm, a₂=2.65 mm, a₃=2 mm)

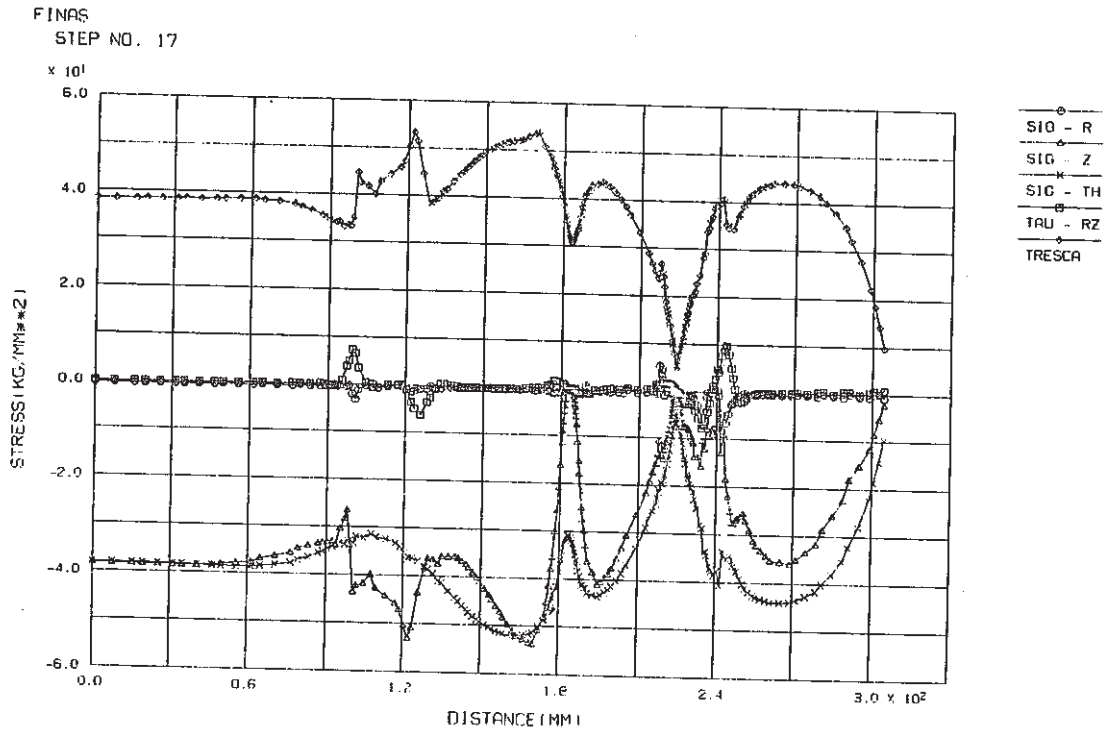


Fig. C.2.11-3 Stress Distribution along Inner-1 Surface at
Hot Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

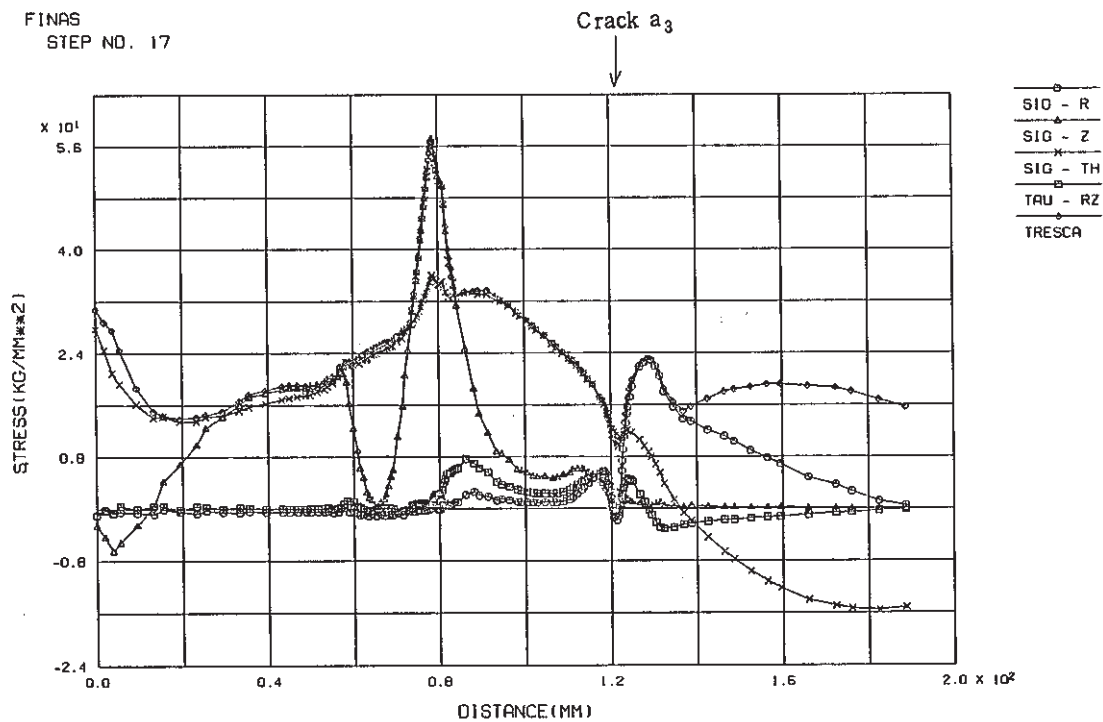


Fig. C.2.12-1 Stress Distribution along Inner-2 Surface at Hot Shock of Inlet Nozzle (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

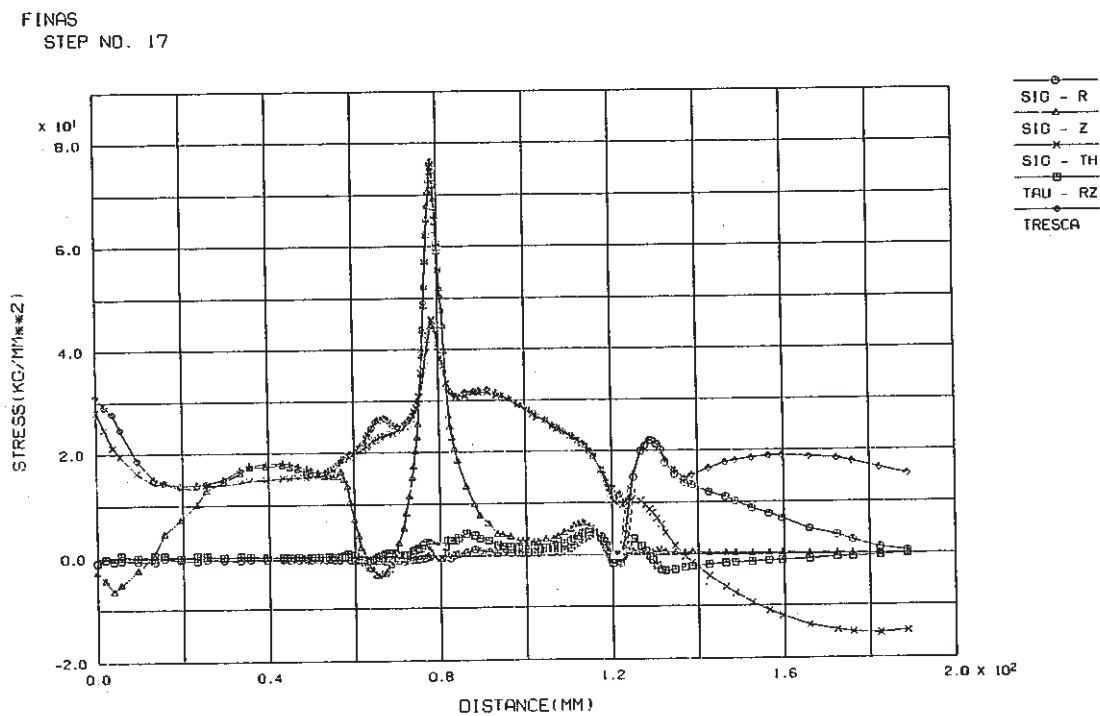


Fig. C.2.12-2 Stress Distribution along Inner-2 Surface at Hot Shock of Inlet Nozzle (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

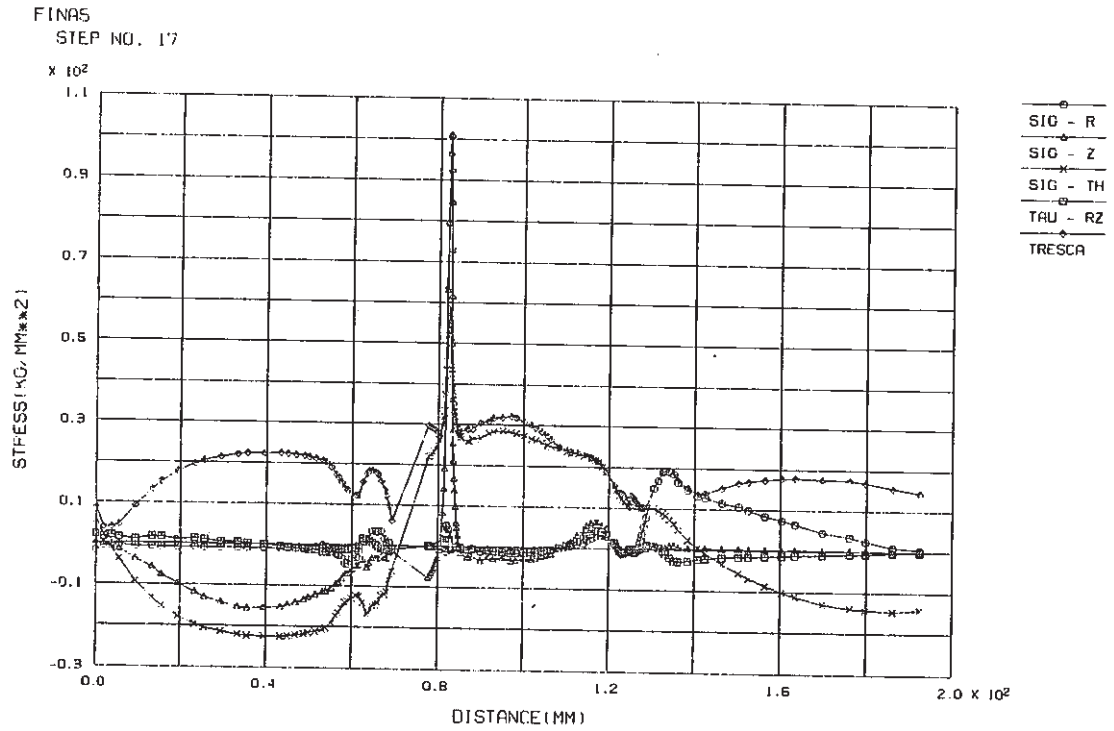


Fig. C.2.12-3 Stress Distribution along Inner-2 Surface at
Hot Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

FINAS
STEP NO. 17

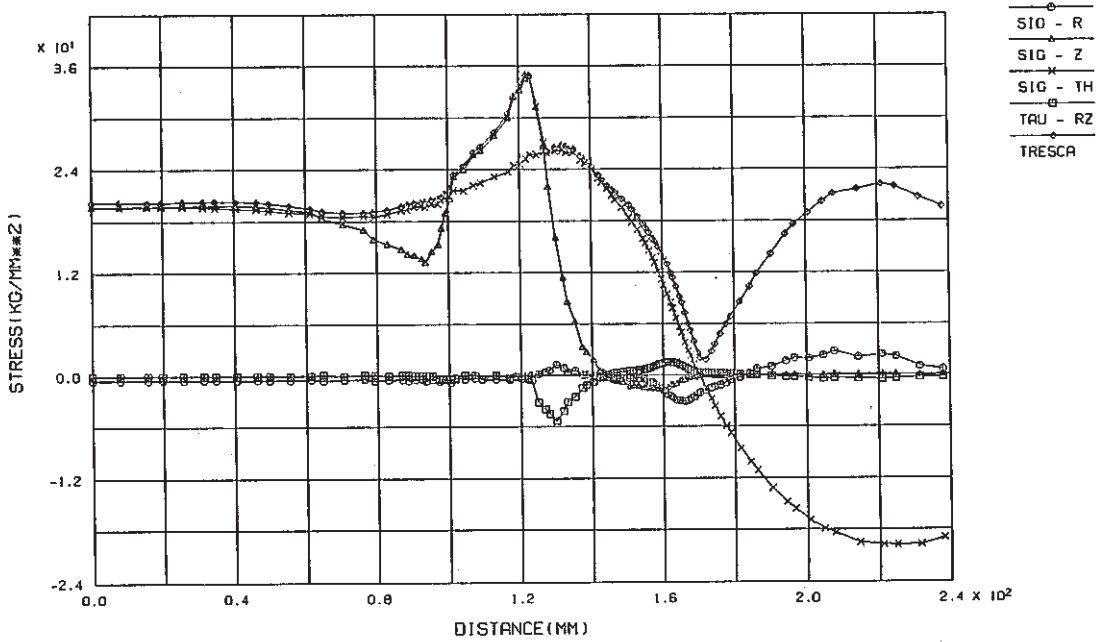


Fig. C.2.13-1 Stress Distribution along Outer Surface at Hot Shock of Inlet Nozzle (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

FINAS
STEP NO. 17

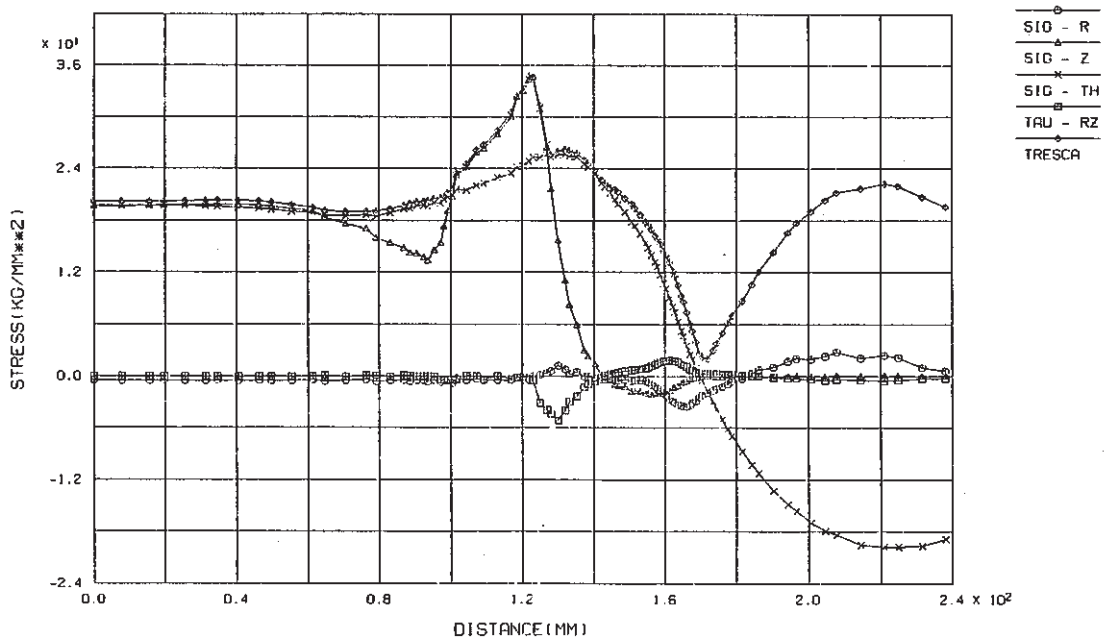


Fig. C.2.13-2 Stress Distribution along Outer Surface at Hot Shock of Inlet Nozzle (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

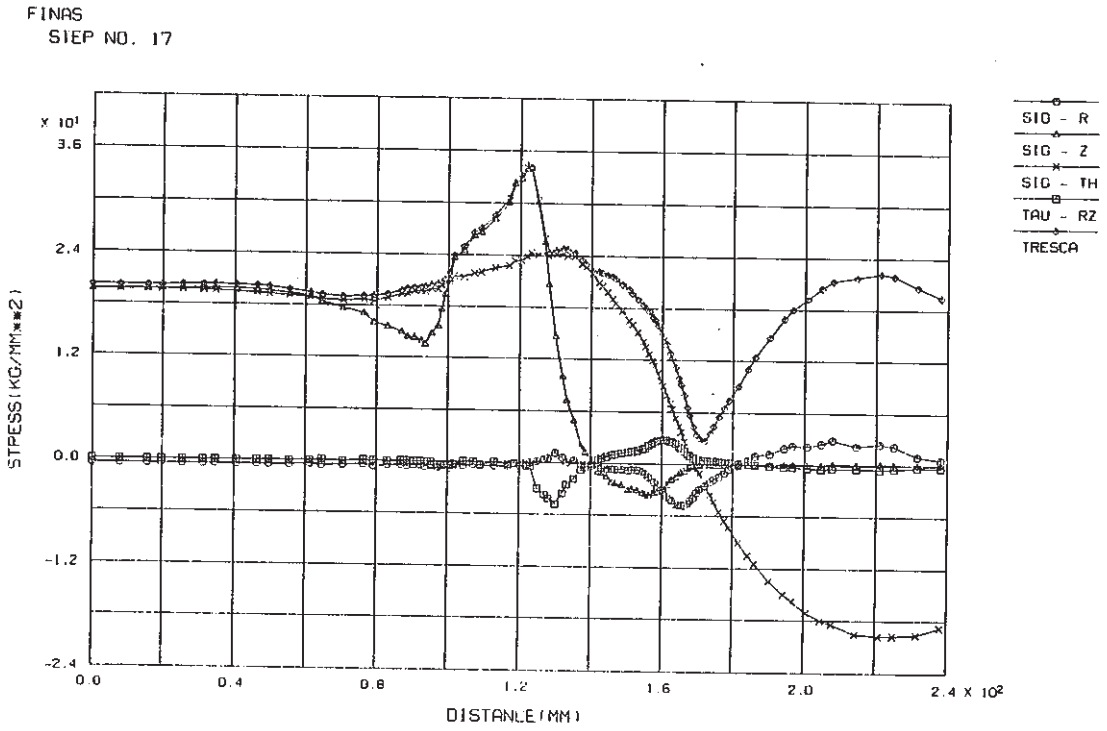


Fig. C.2.13-3 Stress Distribution along Outer Surface at
Hot Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

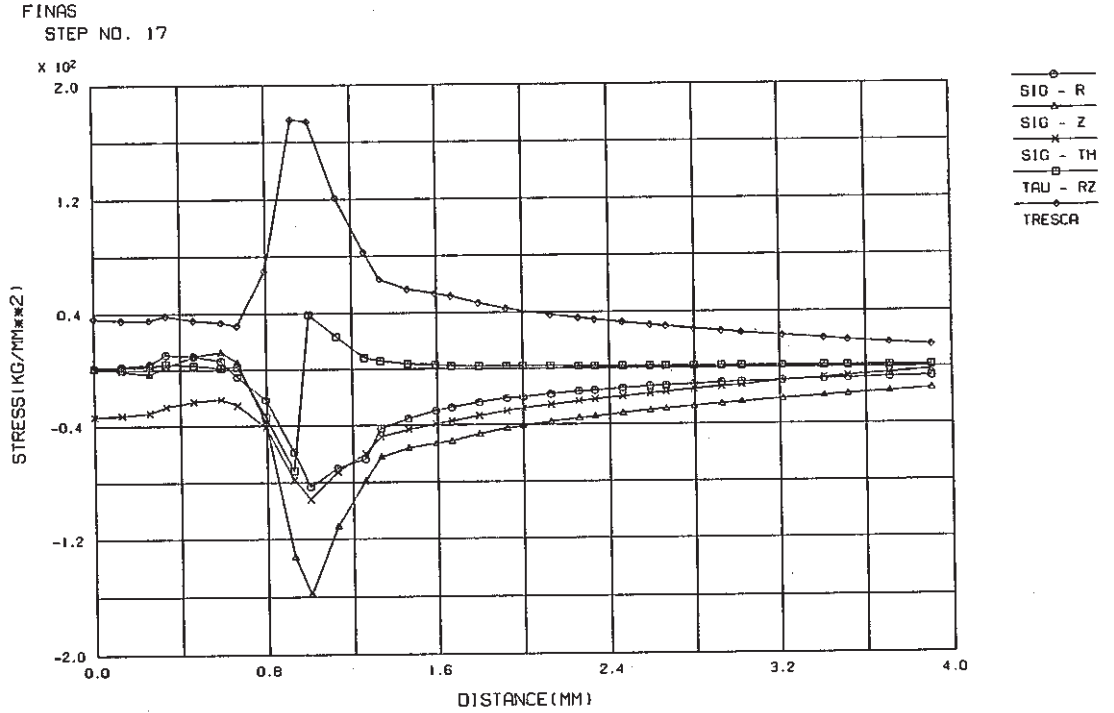


Fig. C.2.14-1 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

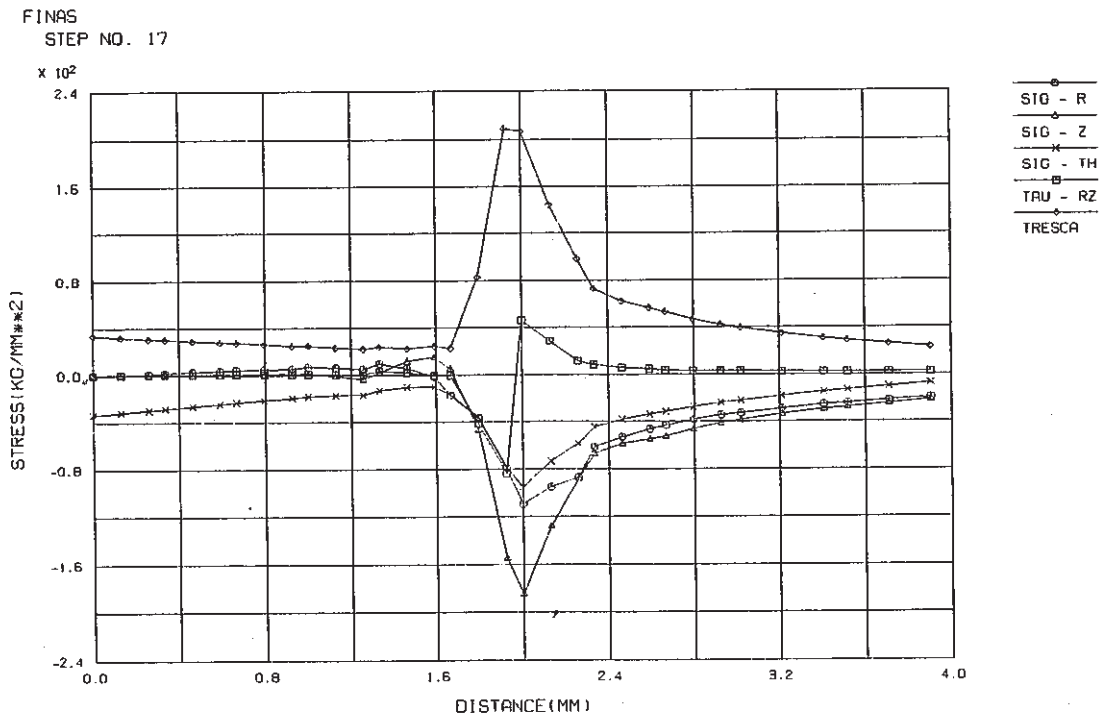


Fig. C.2.14-2 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

FINAS
STEP NO. 17

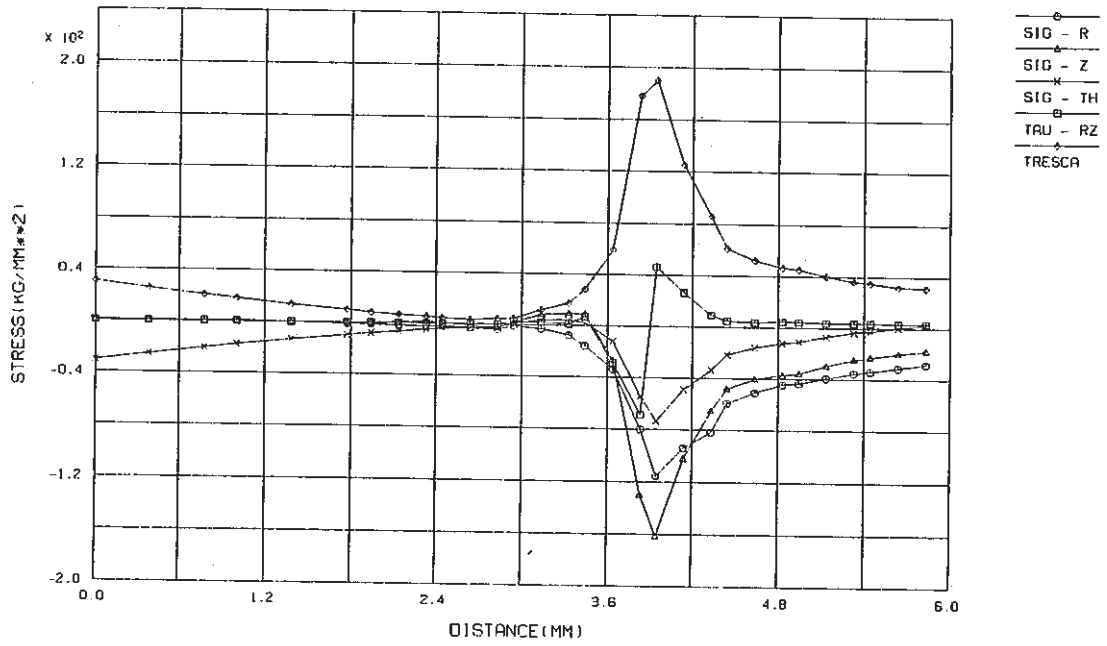


Fig. C.2.14-3 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a_1 (crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

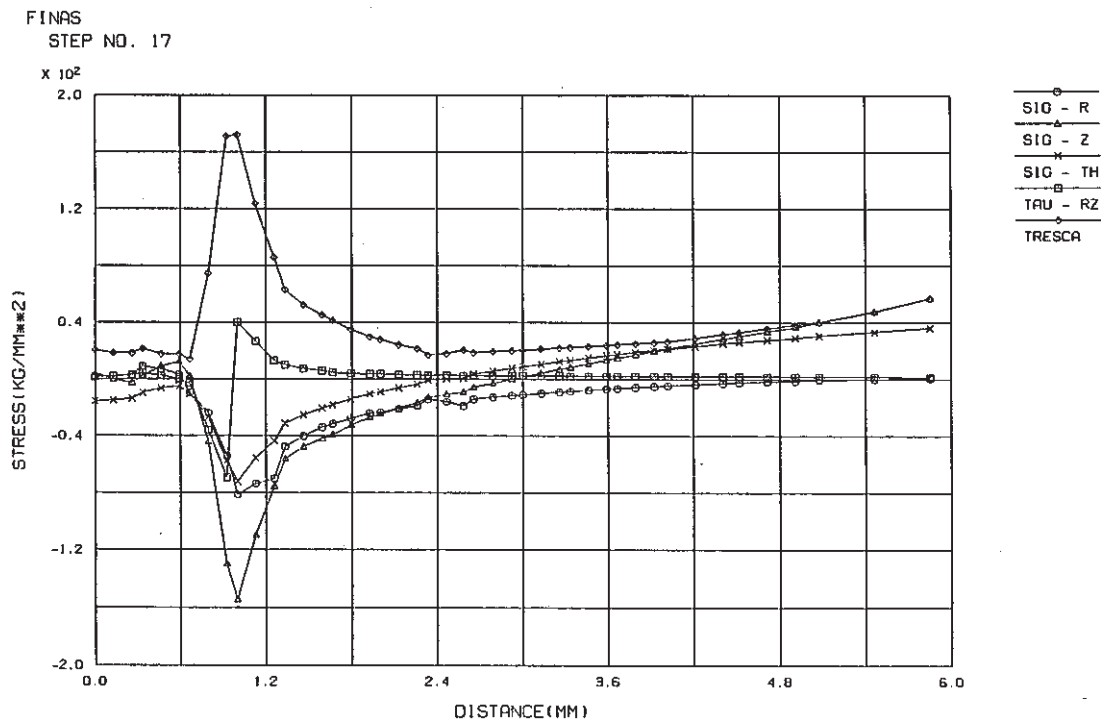


Fig. C.2.15-1 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a₂ (crack depth a₁=1 mm, a₂=1 mm, a₃=1 mm)

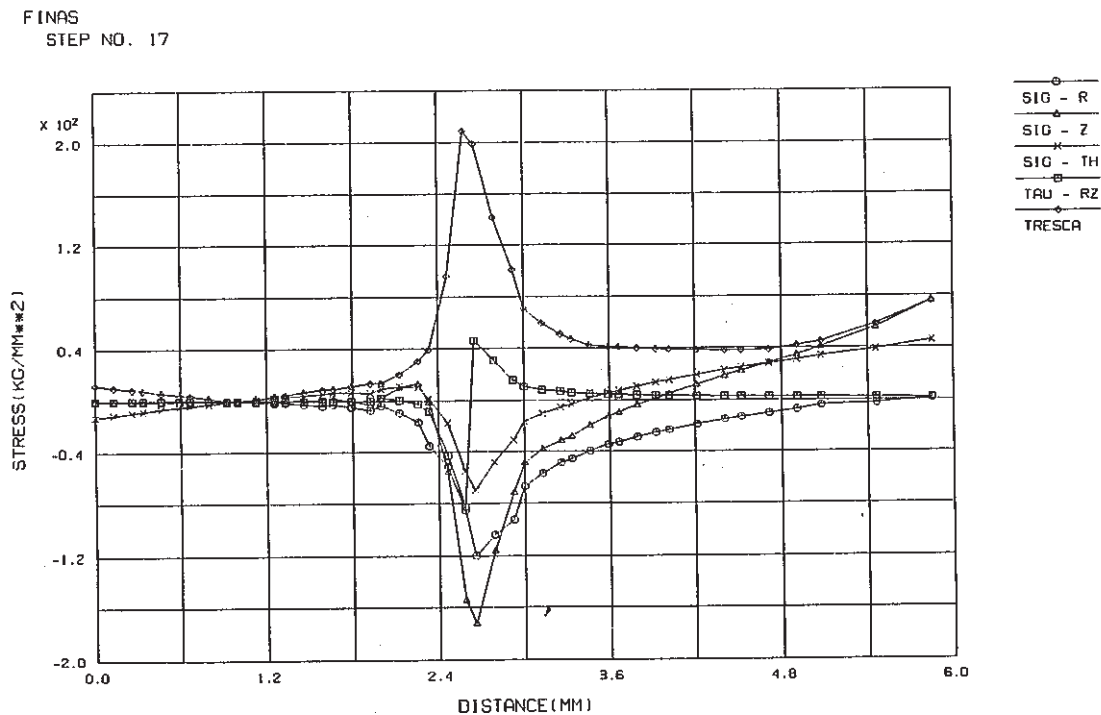


Fig. C.2.15-2 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a₂ (crack depth a₁=2 mm, a₂=2.65 mm, a₃=2 mm)

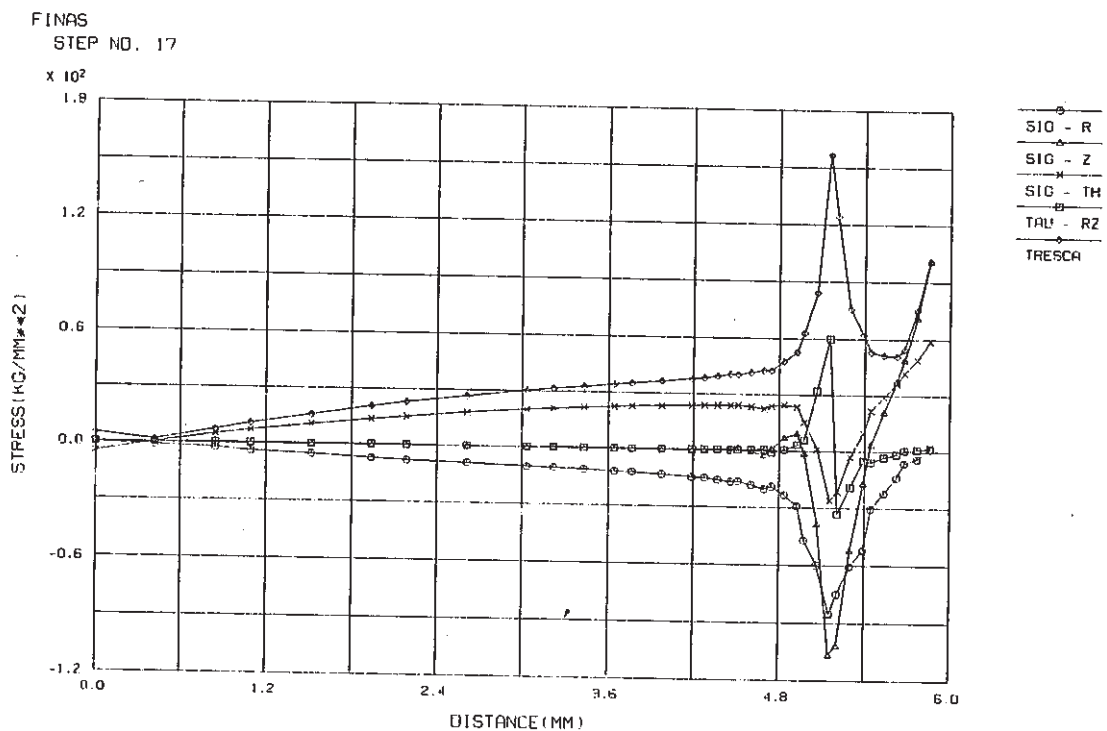


Fig. C.2.15-3 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a₂
(crack depth a₁=4 mm, a₂=5.3 mm, a₃=4 mm)

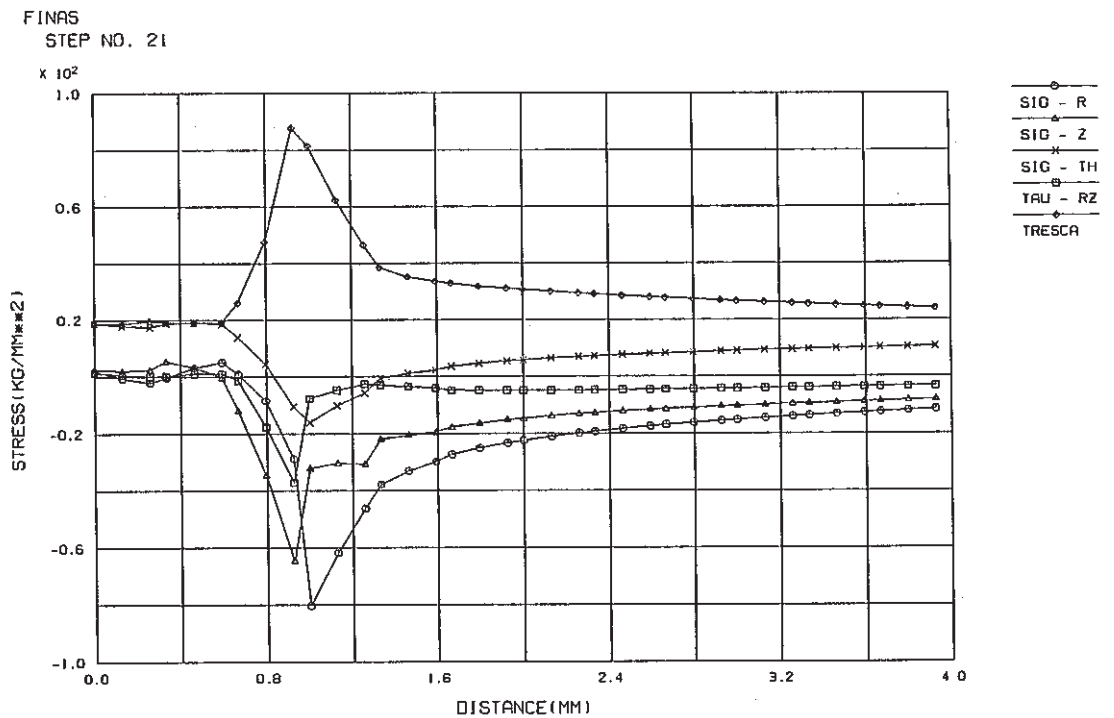


Fig. C.2.16-1 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a₃ (crack depth a₁=1 mm, a₂=1 mm, a₃=1 mm)

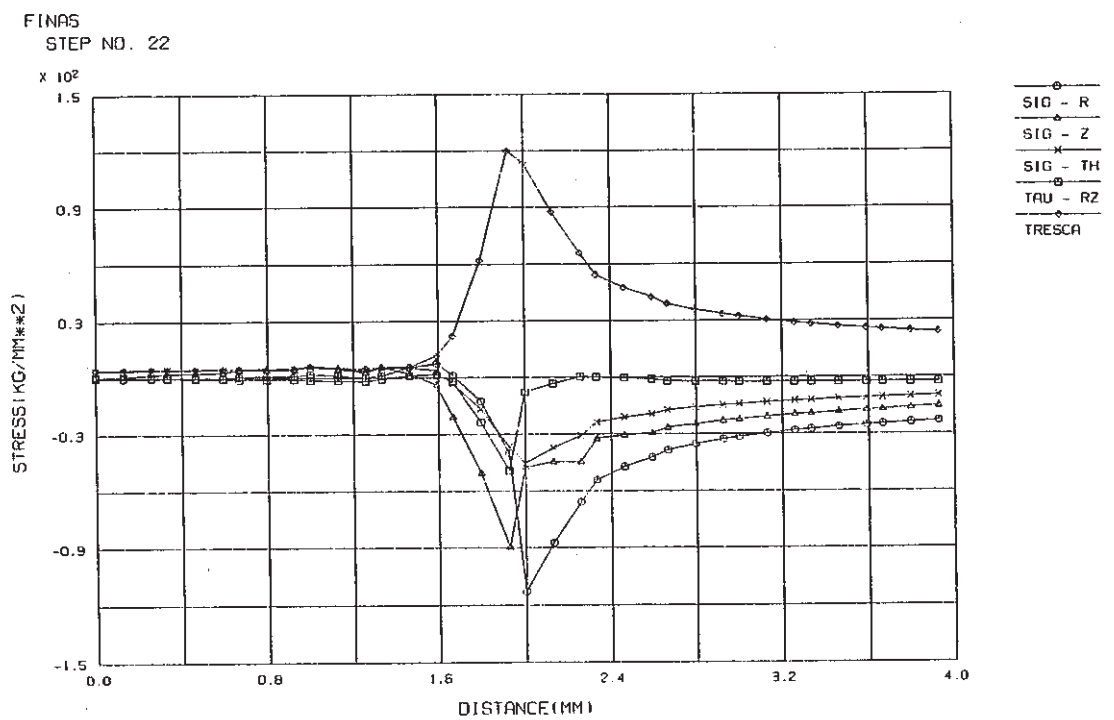


Fig. C.2.16-2 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a₃ (crack depth a₁=2 mm, a₂=2.65 mm, a₃=2 mm)

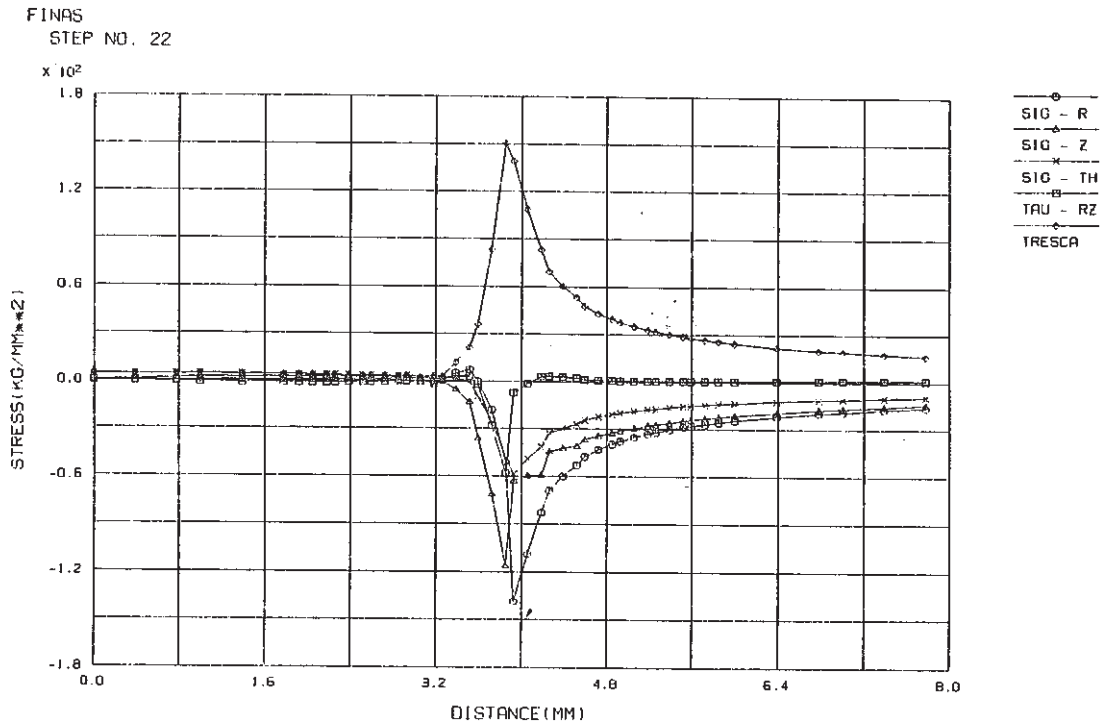


Fig. C.2.16-3 Stress Distribution along Crack Line at Hot Shock of Inlet Nozzle, crack a_3
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-162.000
2	-139.000
3	-116.000
4	-93.0000
5	-70.0000
6	-47.0000
7	-24.0000
8	-1.00000
9	21.99999
10	45.00000

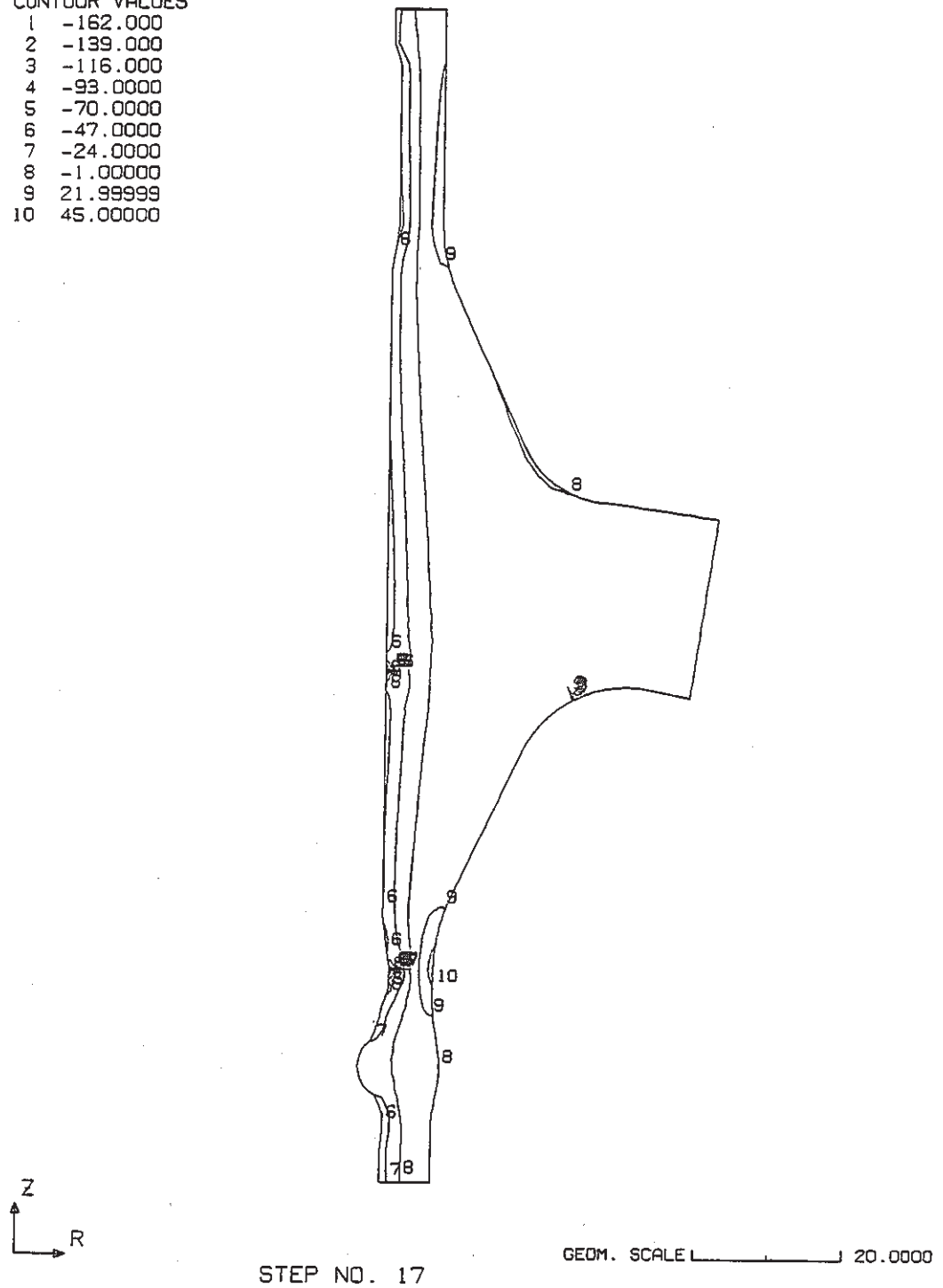
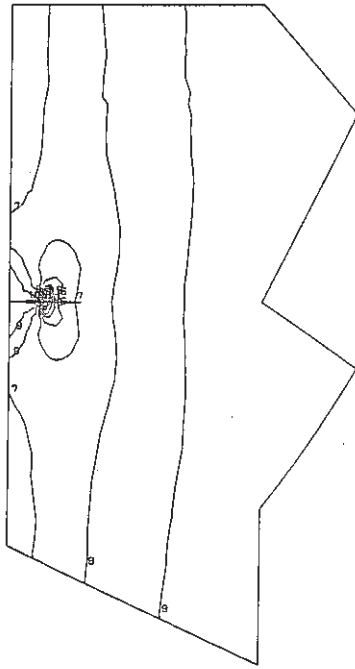


Fig. C.2.17-1 Contour of Axial Stress at Hot Shock of Inlet Nozzle
(crack depth $a_1=1$ mm, $a_2=1$ mm, $a_3=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -160.000
2 -141.000
3 -122.000
4 -103.000
5 -84.0000
6 -65.0000
7 -46.0000
8 -27.0000
9 -8.00000
10 0.99999



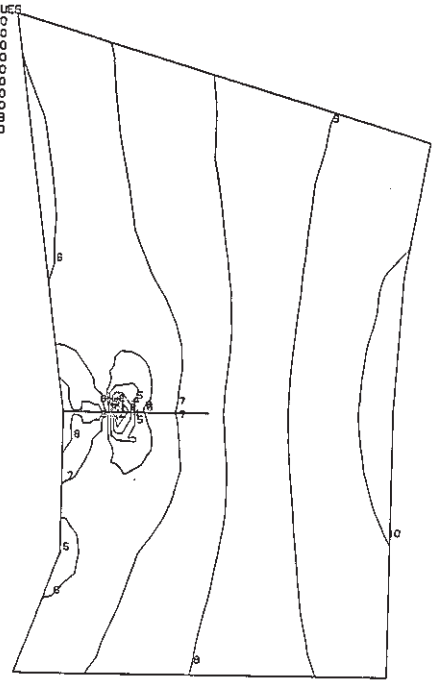
STEP NO. 17

GEOM. SCALE 2.00000

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -162.000
2 -139.000
3 -116.000
4 -93.0000
5 -70.0000
6 -47.0000
7 -24.0000
8 -1.00000
9 21.99999
10 45.00000



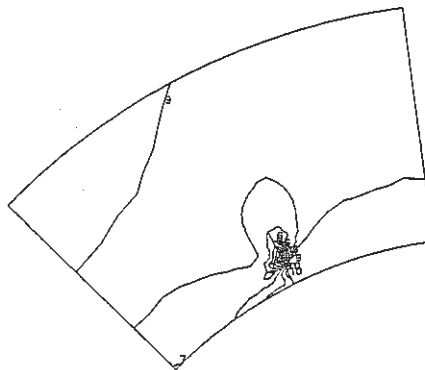
STEP NO. 17

GEOM. SCALE 1.50000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -54.5000
2 -48.0000
3 -41.5000
4 -35.0000
5 -28.5000
6 -21.9999
7 -15.5000
8 -8.99999
9 -2.49999
10 4.000034



STEP NO. 21

GEOM. SCALE 3.00000

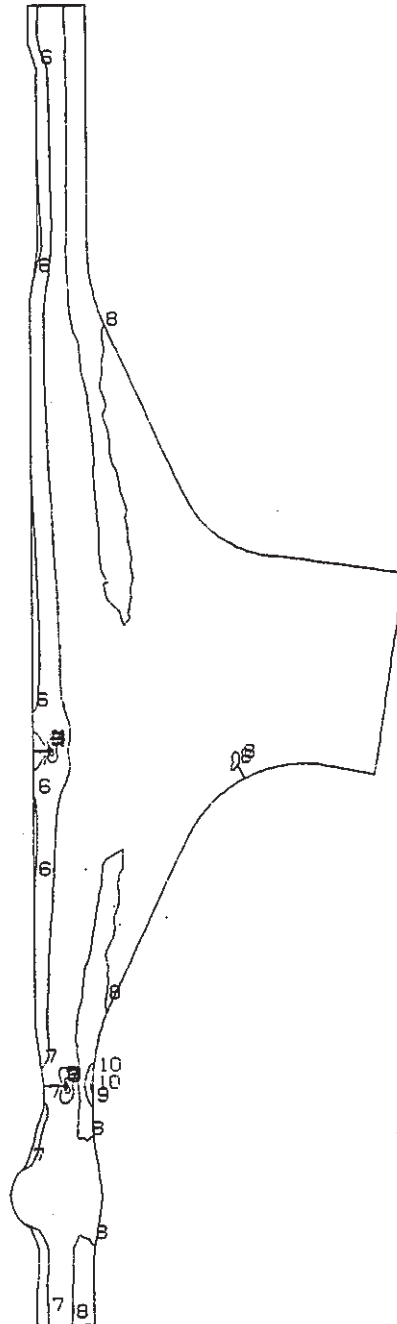
Crack a₃

Fig. C.2.17-1 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-186.000
2	-158.000
3	-130.000
4	-102.000
5	-74.0000
6	-46.0000
7	-18.0000
8	10.00000
9	38.00000
10	66.00001



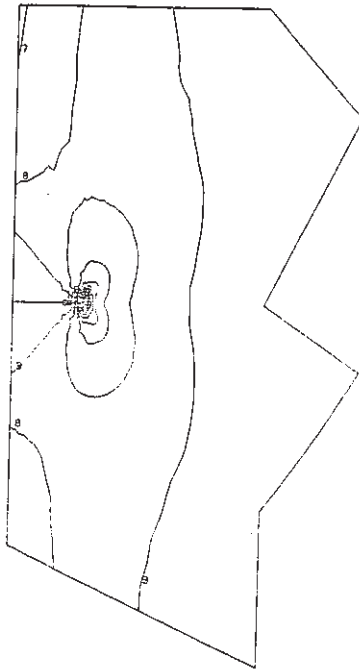
STEP NO. 17

GEOM. SCALE 20.0000

Fig. C.2.17-2 Contour of Axial Stress at Hot Shock of Inlet Nozzle
(crack depth $a_1=2$ mm, $a_2=2.65$ mm, $a_3=2$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -187.000
2 -165.000
3 -143.000
4 -121.000
5 -99.0000
6 -77.0000
7 -55.0000
8 -33.0000
9 -11.0000
10 10.99999



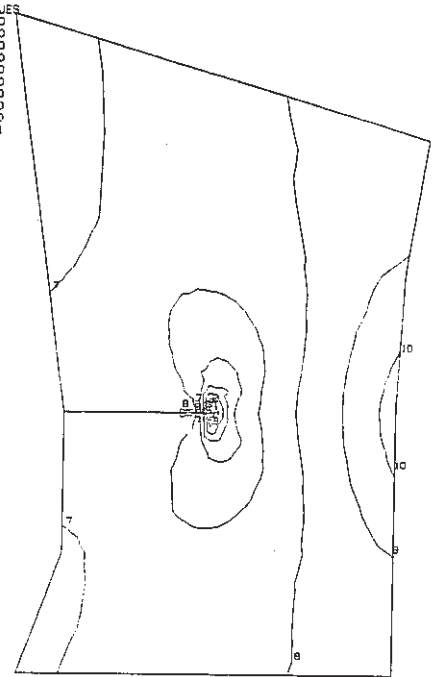
STEP NO. 17

GEOM. SCALE 2.00000

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -165.000
2 -158.000
3 -130.000
4 -102.000
5 -74.0000
6 -46.0000
7 -18.0000
8 10.00000
9 38.00000
10 66.00001



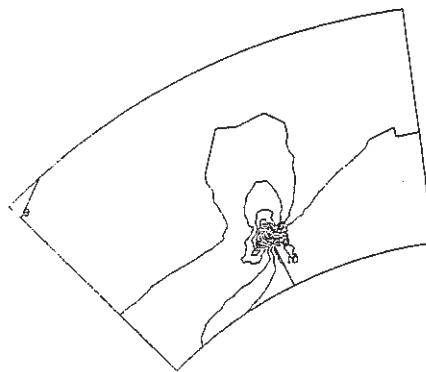
STEP NO. 17

GEOM. SCALE 1.50000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -55.3000
2 -57.4000
3 -49.4999
4 -41.8999
5 -32.6999
6 -25.7999
7 -17.8999
8 -9.99991
9 -2.09991
10 5.900037



STEP NO. 22

GEOM. SCALE 3.00000

Crack a₃

Fig. C.2.17-2 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-161.000
2	-133.000
3	-105.000
4	-77.0000
5	-49.0000
6	-21.0000
7	7.000000
8	35.00000
9	63.00001
10	91.00001

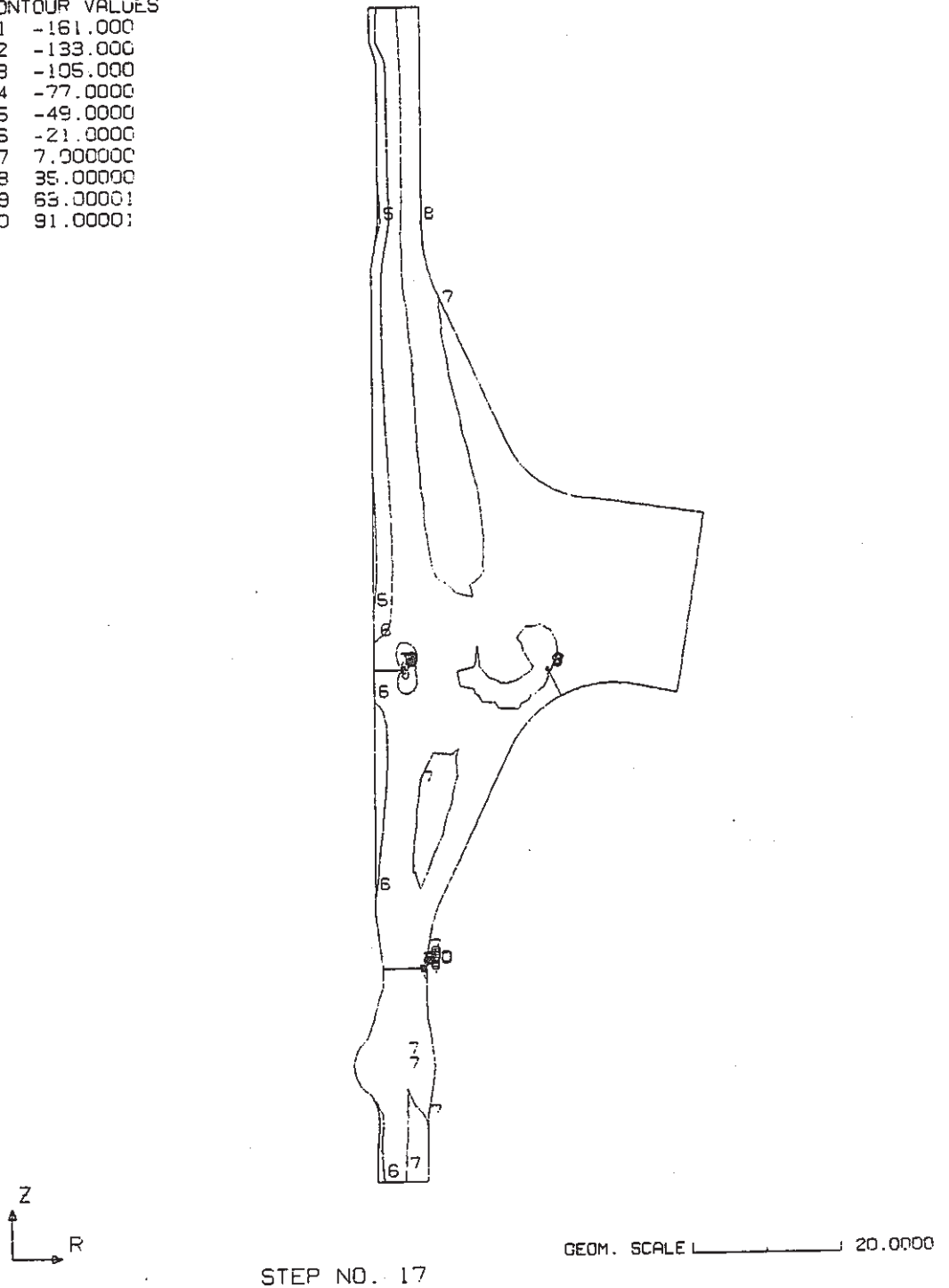
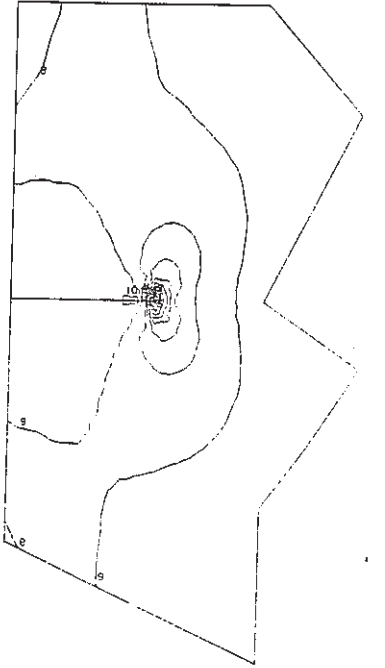


Fig. C.2.17-3 Contour of Axial Stress at Hot Shock of Inlet Nozzle
(crack depth $a_1=4$ mm, $a_2=5.3$ mm, $a_3=4$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -165.000
2 -147.000
3 -129.000
4 -109.000
5 -90.0000
6 -71.0000
7 -52.0000
8 -33.0000
9 -14.0000
10 5.000000



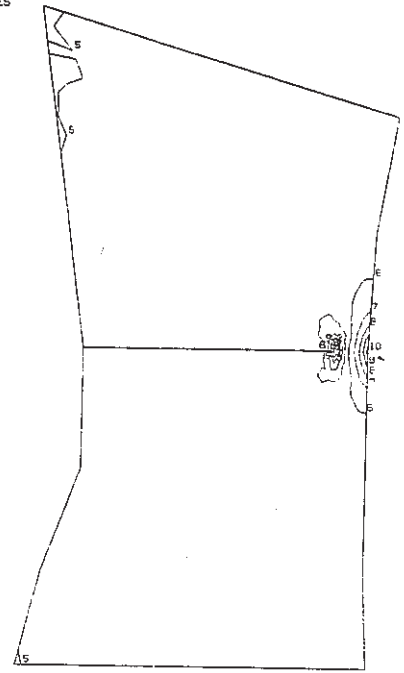
STEP NO. 17

DETM. SCALE 1.0000

Crack a₁

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -105.000
2 -82.0000
3 -59.0000
4 -36.0000
5 -13.0000
6 10.0000
7 33.0000
8 56.0000
9 79.0000
10 101.9999



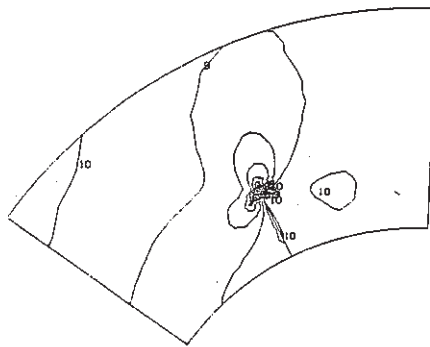
STEP NO. 17

DETM. SCALE 2.0000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -85.6000
2 -75.9000
3 -66.2000
4 -56.5000
5 -46.8000
6 -37.1000
7 -27.4000
8 -17.7000
9 -7.99997
10 1.700025



Z
R

STEP NO. 22

DETM. SCALE 5.00000

Crack a₃

Fig. C.2.17-3 (Cont'd)

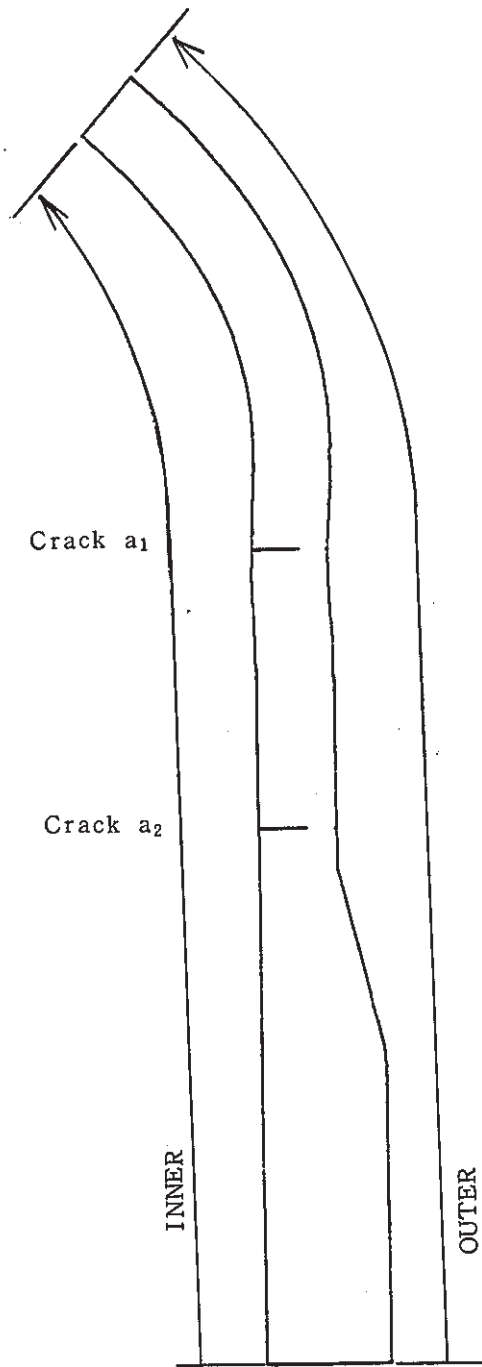


Fig. C.3-1 Evaluation Lines for Surface Stress Distribution of Thinning Portion

FINAS

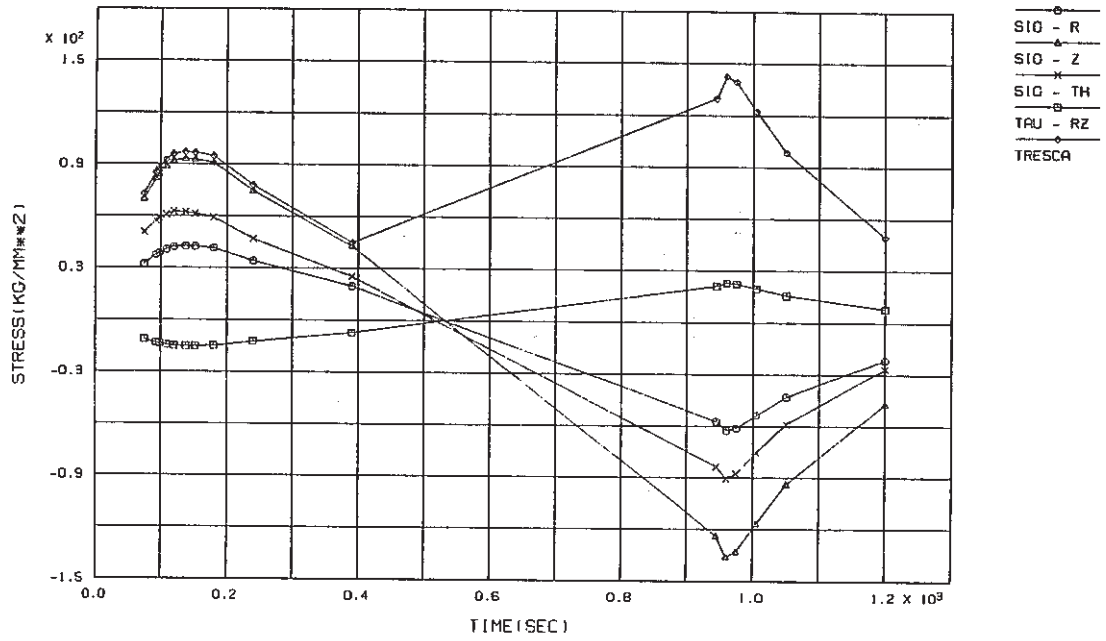


Fig. C.3.1-1 Stress History ahead of Crack Tip of Thinning Portion, crack a_1 (crack depth $a_1=1$ mm, $a_2=1$ mm)

FINAS

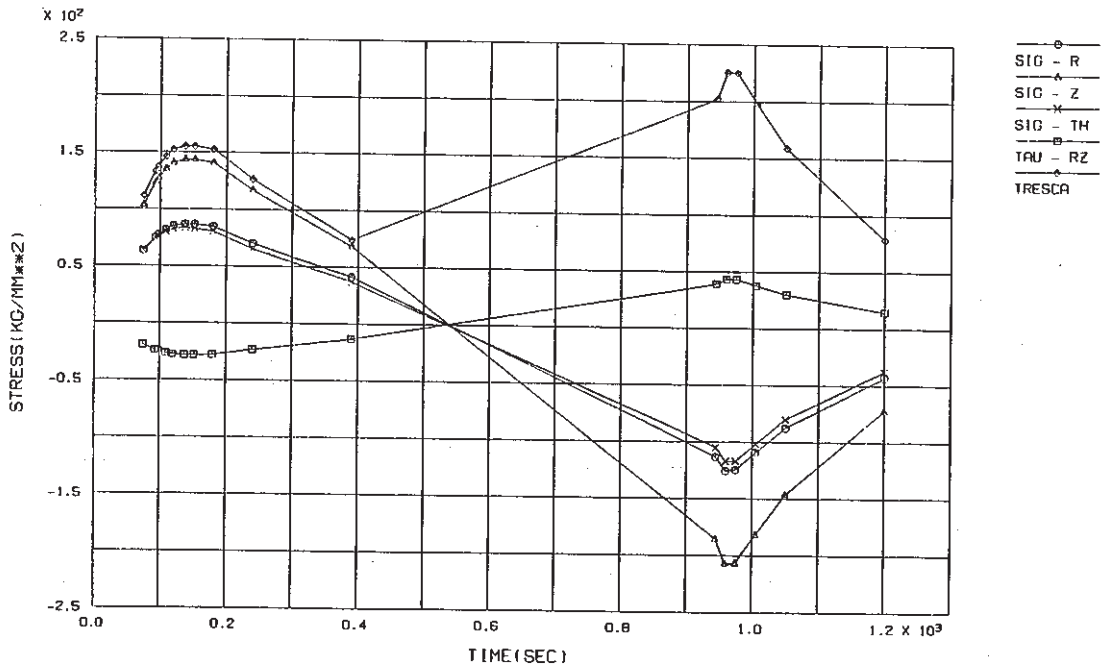


Fig. C.3.1-2 Stress History ahead of Crack Tip of Thinning Portion, crack a_1 (crack depth $a_1=4$ mm, $a_2=5$ mm)

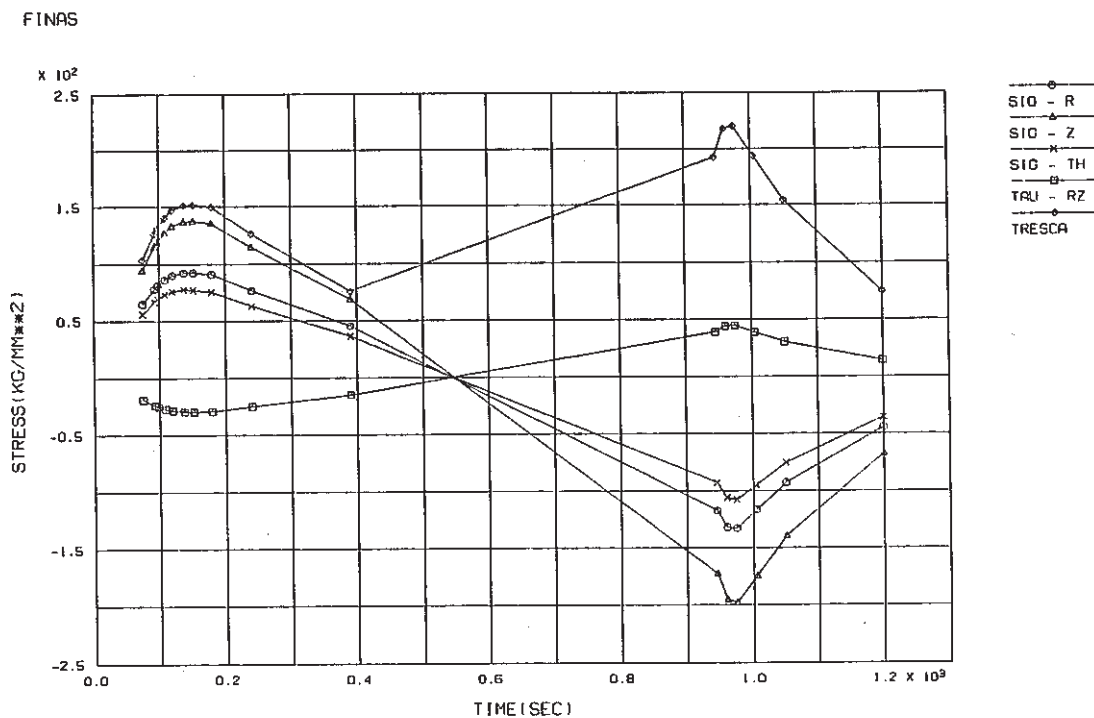


Fig. C.3.1-3 Stress History ahead of Crack Tip of Thinning Portion, crack a_1 (crack depth $a_1=7$ mm, $a_2=10$ mm)

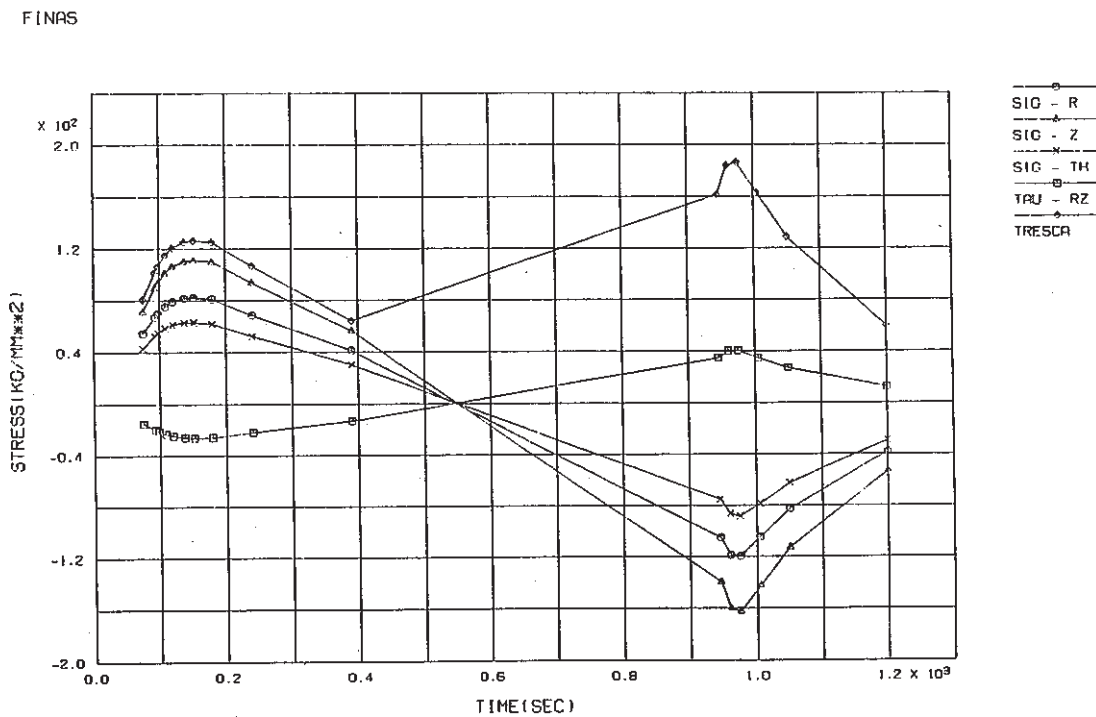


Fig. C.3.1-4 Stress History ahead of Crack Tip of Thinning Portion, crack a_1 (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

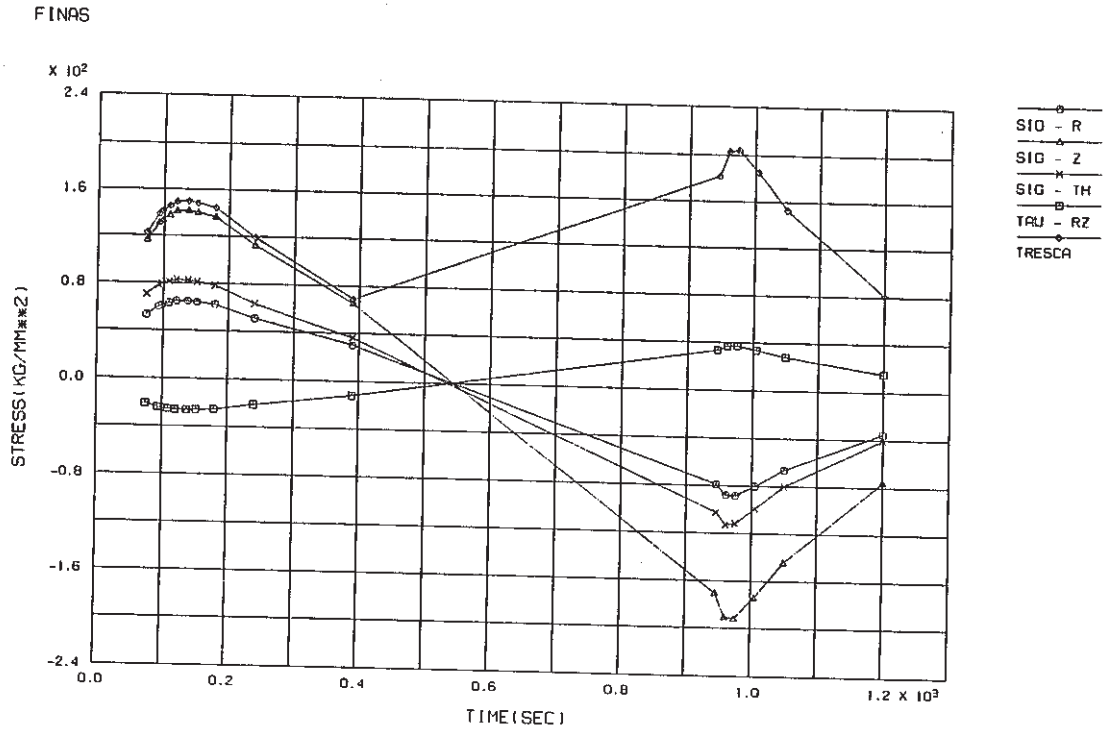


Fig. C.3.2-1 Stress History ahead of Crack Tip of Thinning Portion, crack a_2 (crack depth $a_1=1$ mm, $a_2=1$ mm)

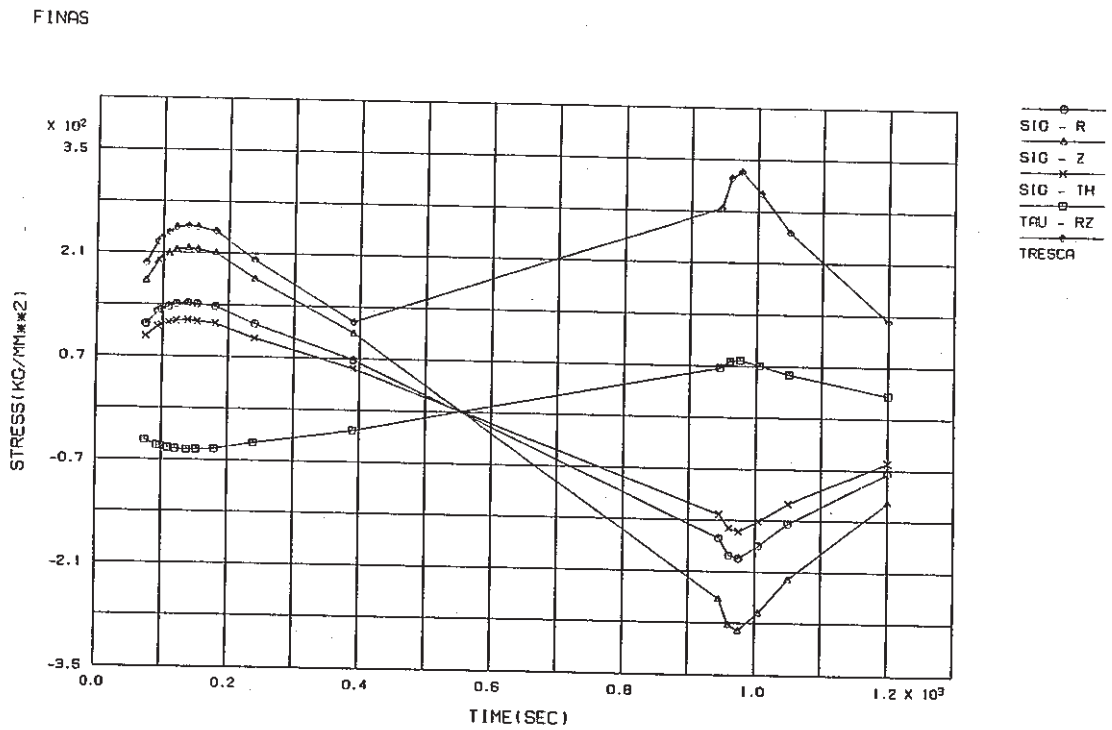


Fig. C.3.2-2 Stress History ahead of Crack Tip of Thinning Portion, crack a_2 (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS

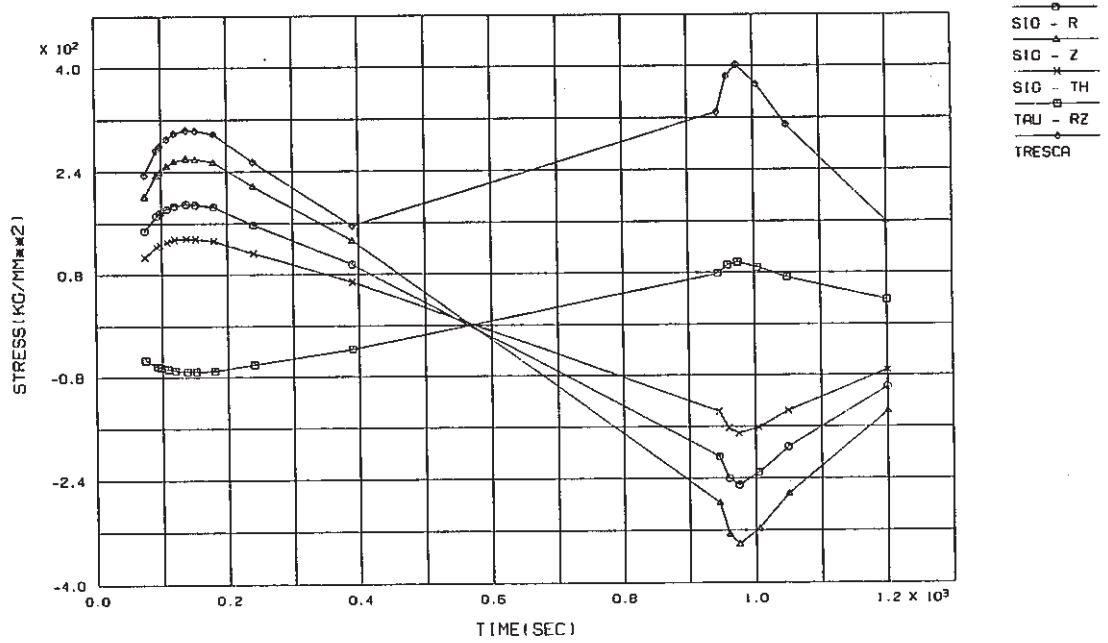


Fig. C.3.2-3 Stress History ahead of Crack Tip of Thinning Portion, crack a₂ (crack depth a₁=7 mm, a₂= 10 mm)

FINAS

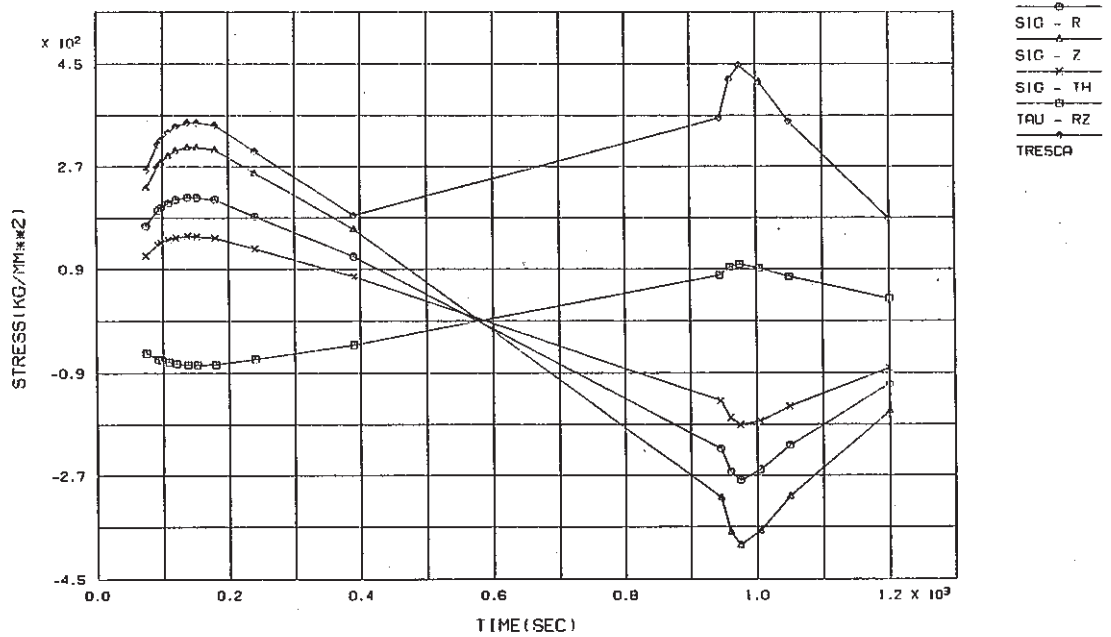


Fig. C.3.2-4 Stress History ahead of Crack Tip of Thinning Portion, crack a₂ (crack depth a₁=9.4 mm, a₂=15 mm)

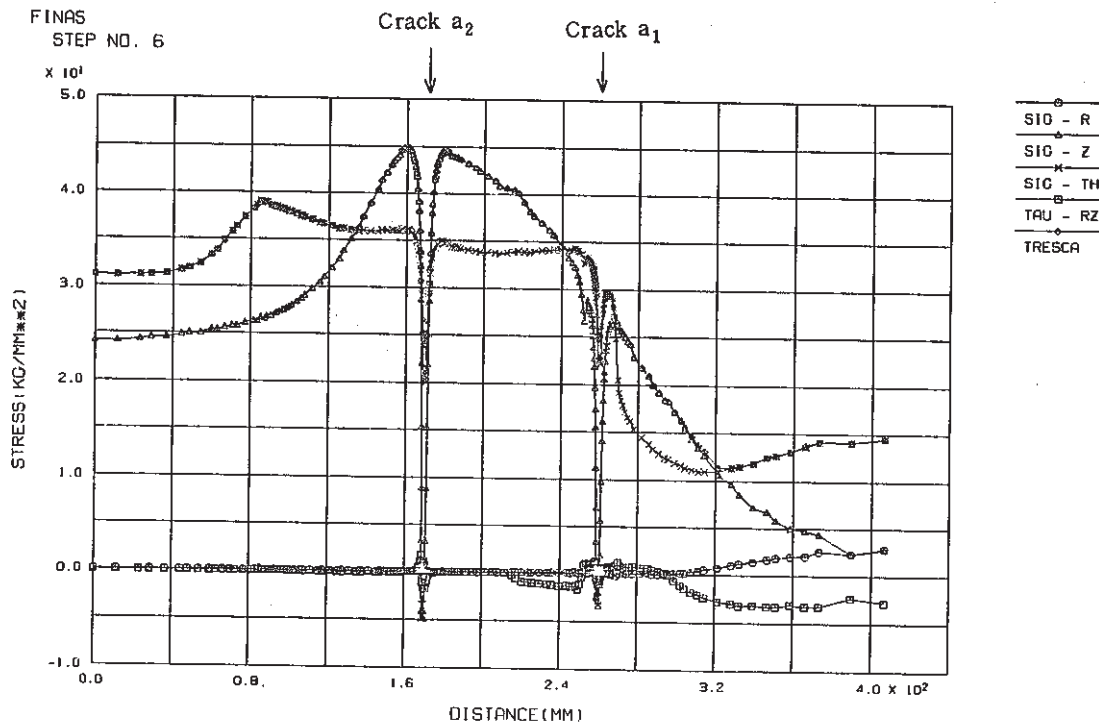


Fig. C.3.3-1 Stress Distribution along Inner Surface at Cold Shock of Thinning Portion (crack depth $a_1=1$ mm, $a_2=1$ mm)

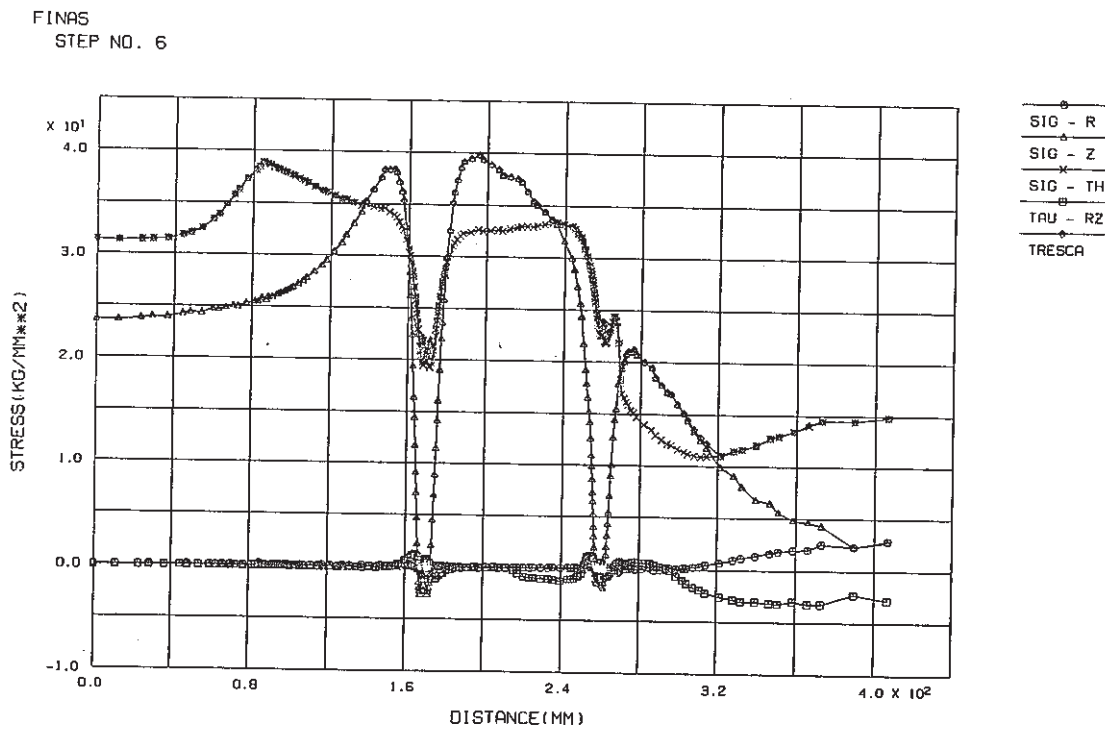


Fig. C.3.3-2 Stress Distribution along Inner Surface at Cold Shock of Thinning Portion (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS
STEP NO. 6

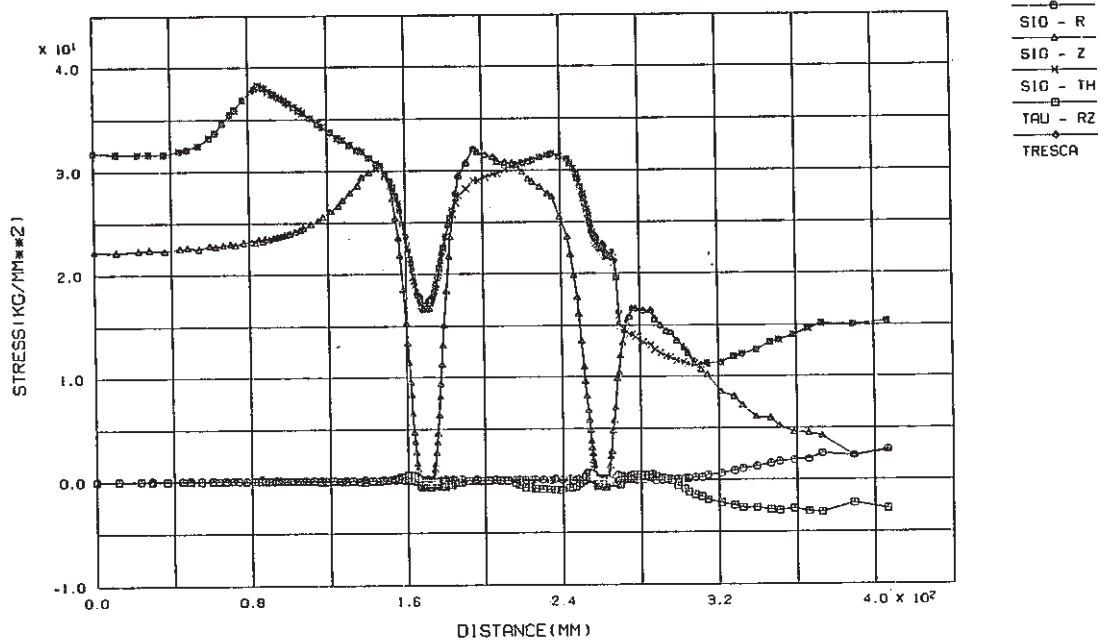


Fig. C.3.3-3 Stress Distribution along Inner Surface at Cold Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

FINAS
STEP NO. 6

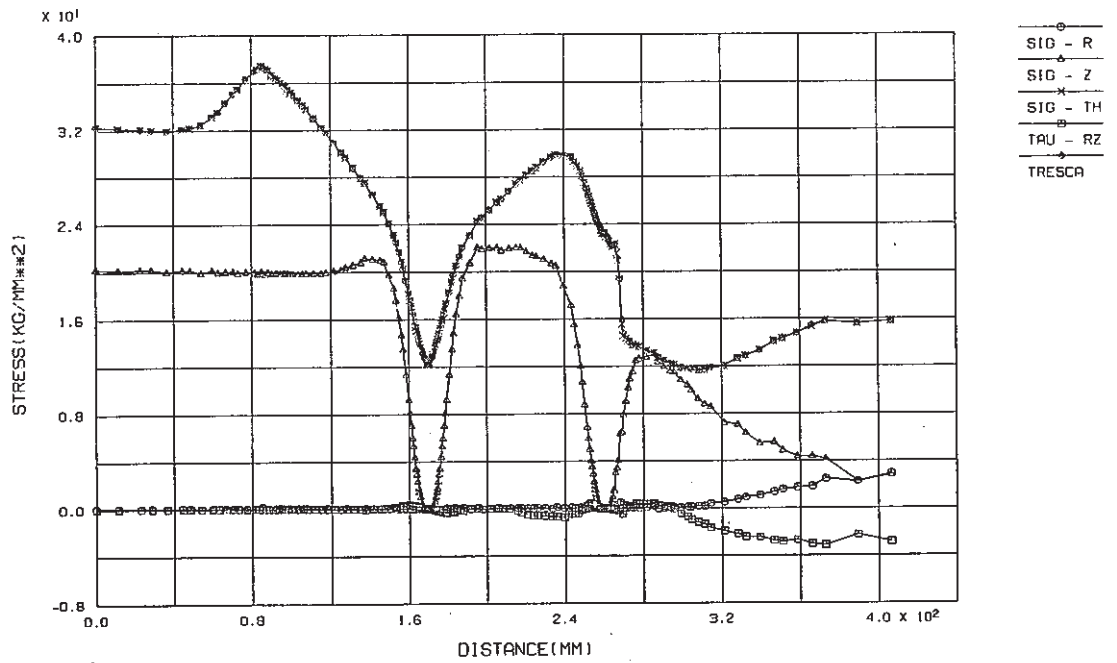


Fig. C.3.3-4 Stress Distribution along Inner Surface at Cold Shock of Thinning Portion (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

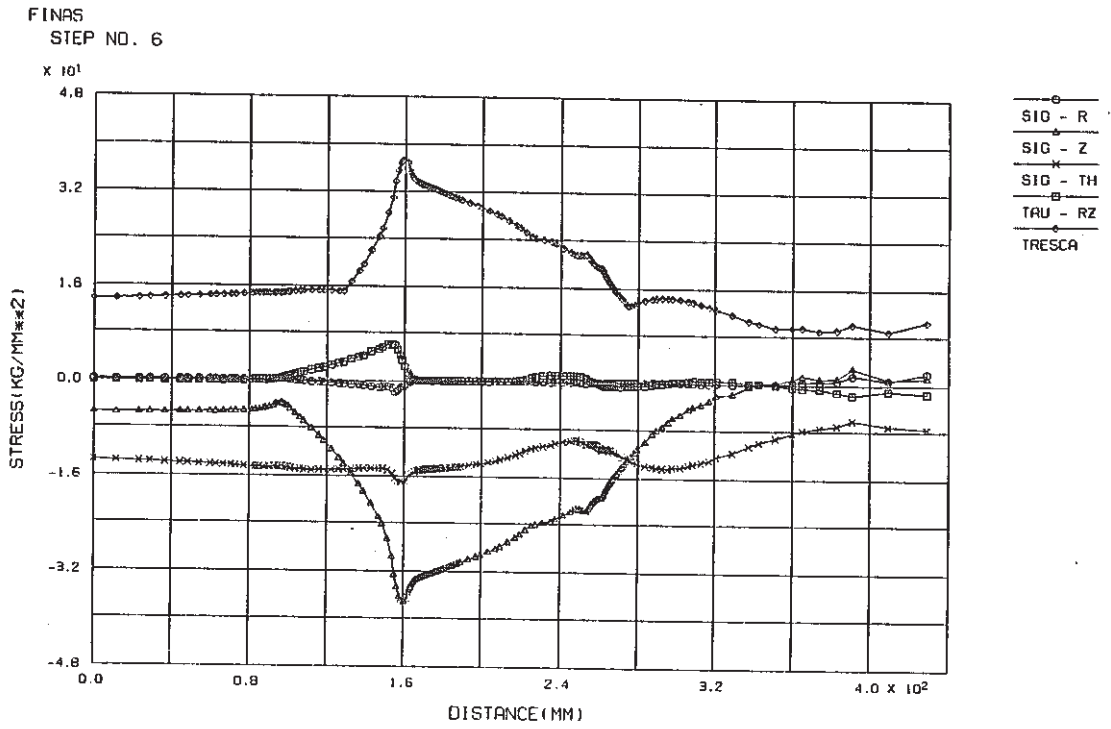


Fig. C.3.4-1 Stress Distribution along Outer Surface at Cold Shock of Thinning Portion (crack depth $a_1=1$ mm, $a_2=1$ mm)

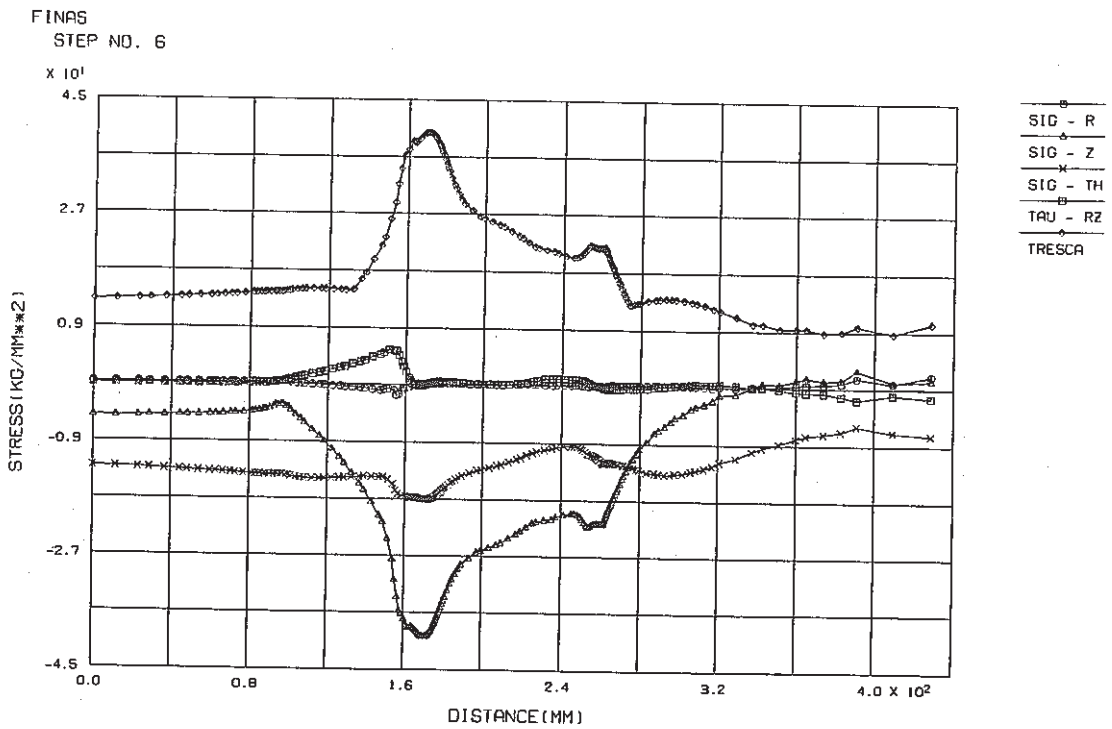


Fig. C.3.4-2 Stress Distribution along Outer Surface at Cold Shock of Thinning Portion (crack depth $a_1=4$ mm, $a_2=5$ mm)

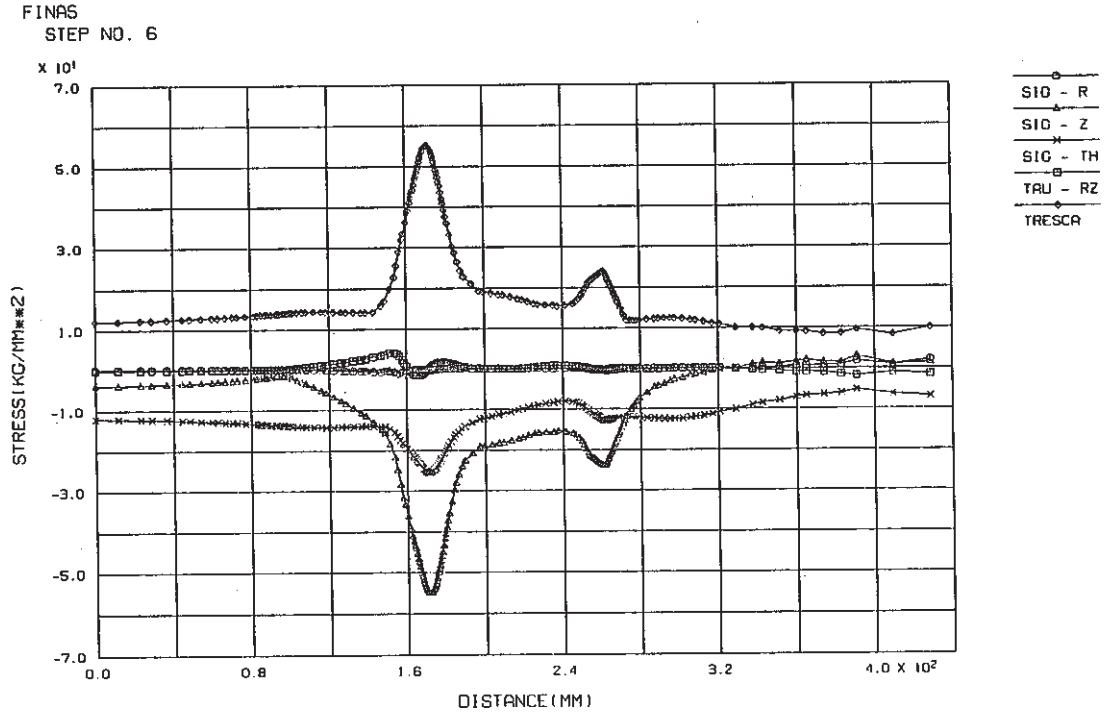


Fig. C.3.4-3 Stress Distribution along Outer Surface at Cold Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

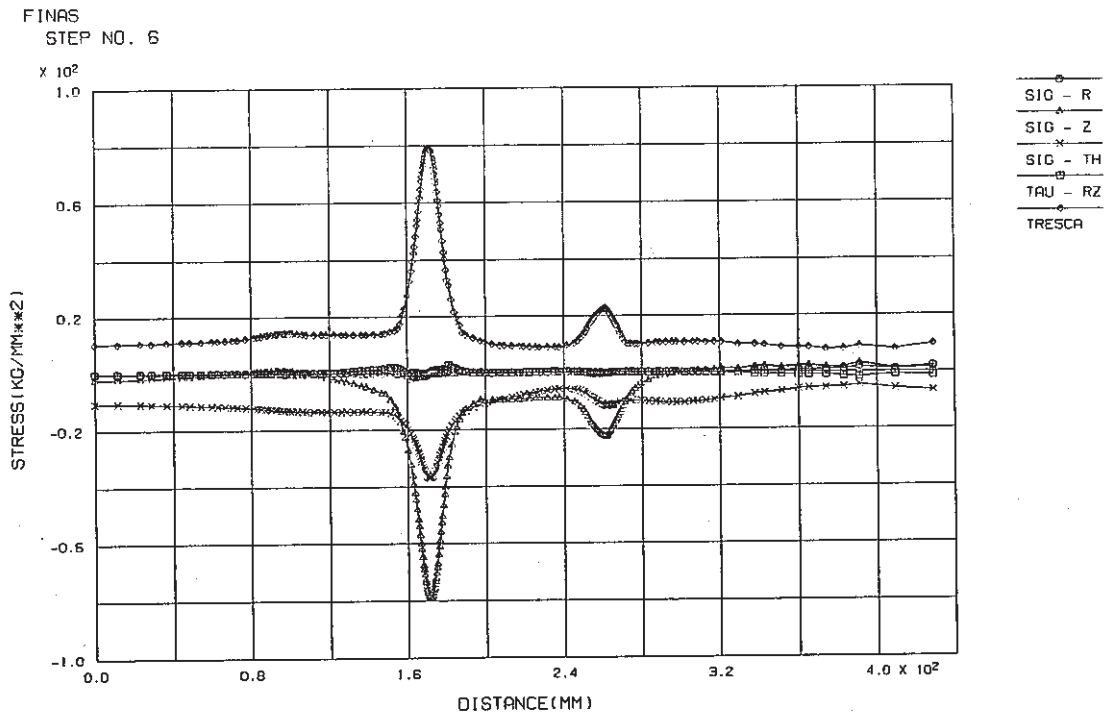


Fig. C.3.4-4 Stress Distribution along Outer Surface at Cold Shock of Thinning Portion (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

FINAS
STEP NO. 6

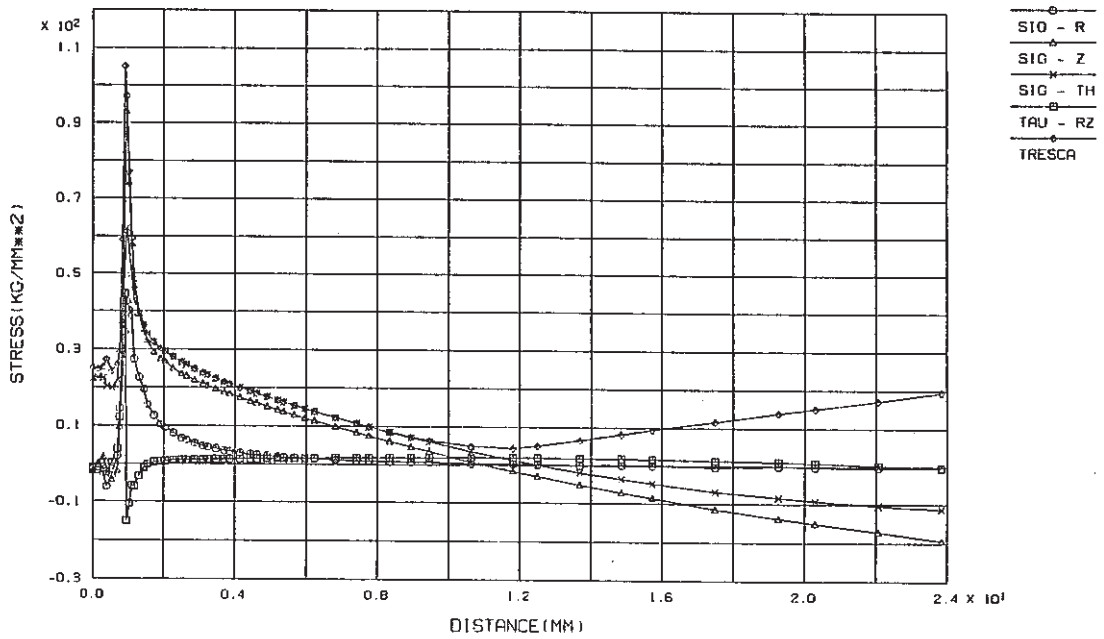


Fig. C.3.5-1 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_1 (crack depth $a_1=1$ mm, $a_2=1$ mm)

FINAS
STEP NO. 6

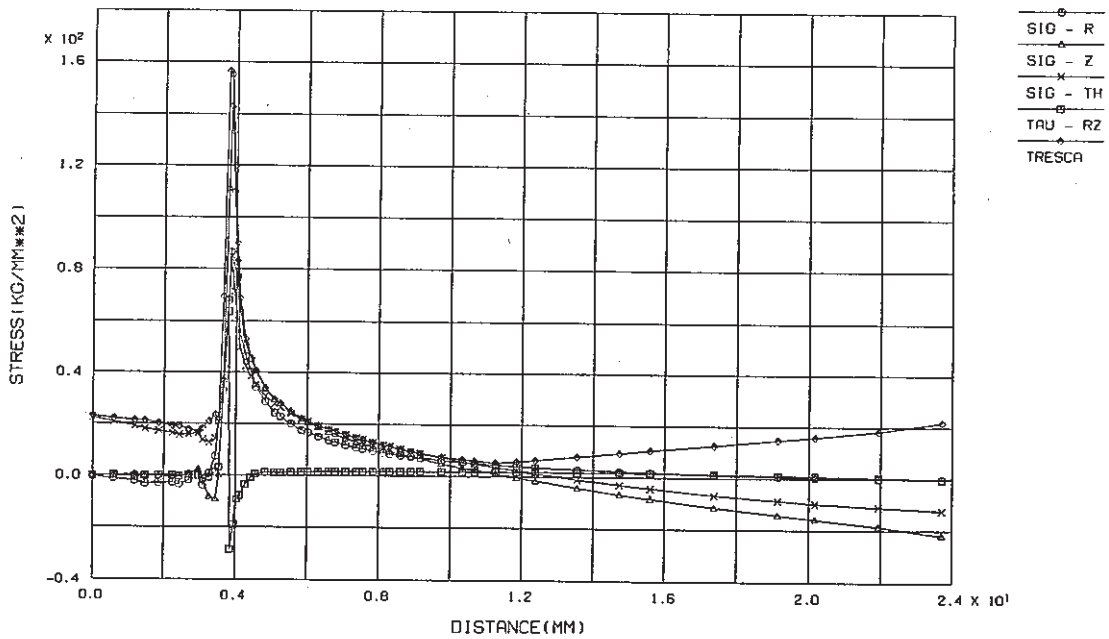


Fig. C.3.5-2 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_1 (crack depth $a_1=4$ mm, $a_2=5$ mm)

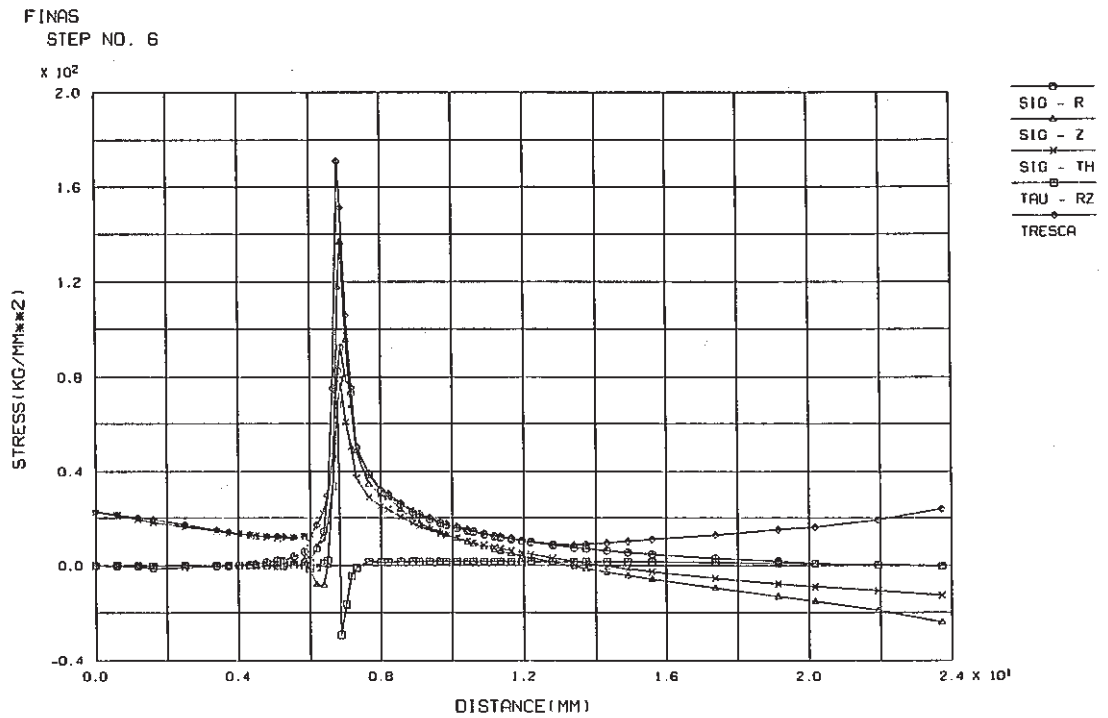


Fig. C.3.5-3 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_1 (crack depth $a_1=7$ mm, $a_2=10$ mm)

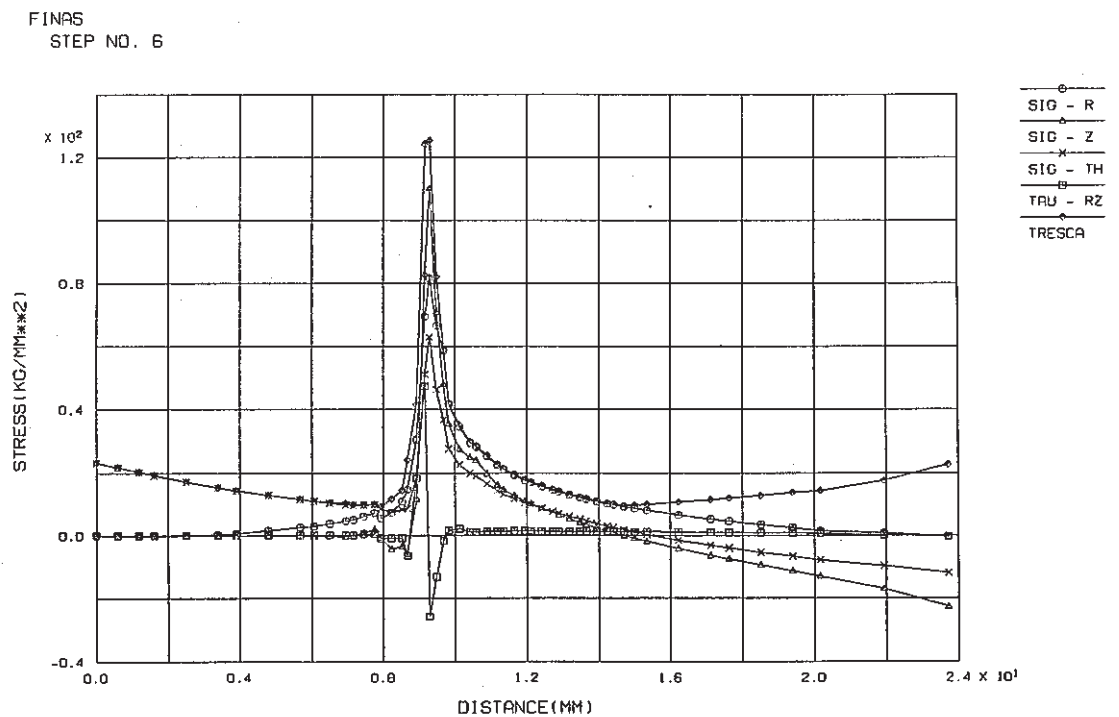


Fig. C.3.5-4 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_1 (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

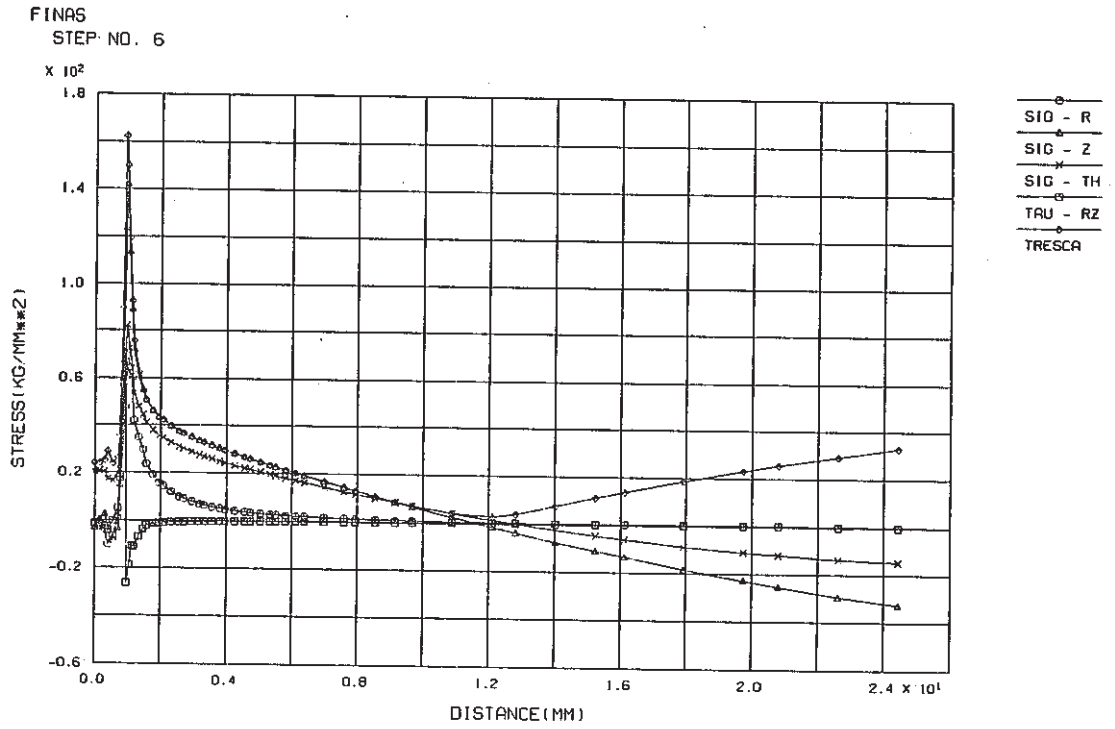


Fig. C.3.6-1 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_2 (crack depth $a_1=1$ mm, $a_2=1$ mm)

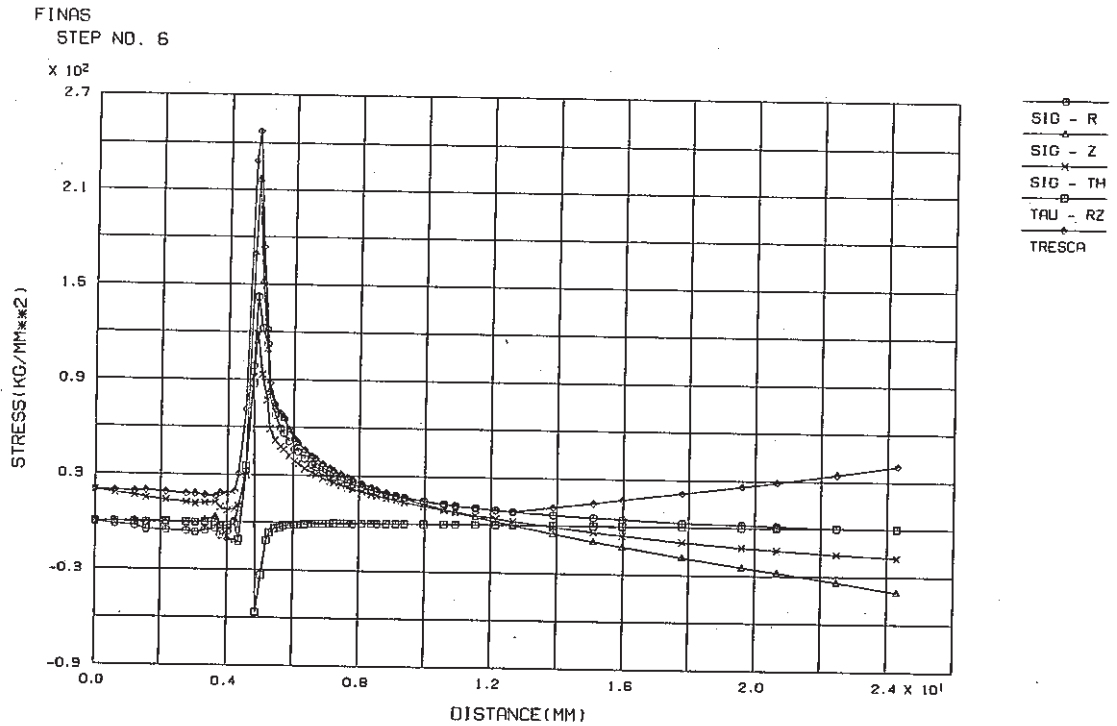


Fig. C.3.6-2 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a_2 (crack depth $a_1=4$ mm, $a_2=5$ mm)

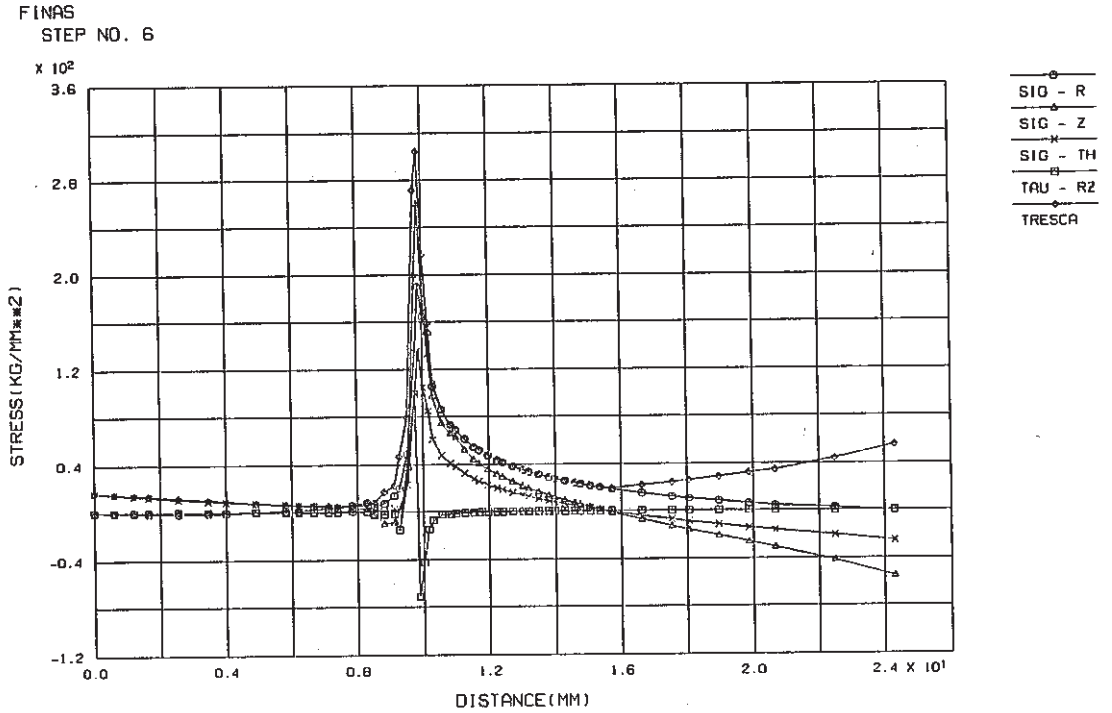


Fig. C.3.6-3 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a₂ (crack depth a₁=7 mm, a₂=10 mm)

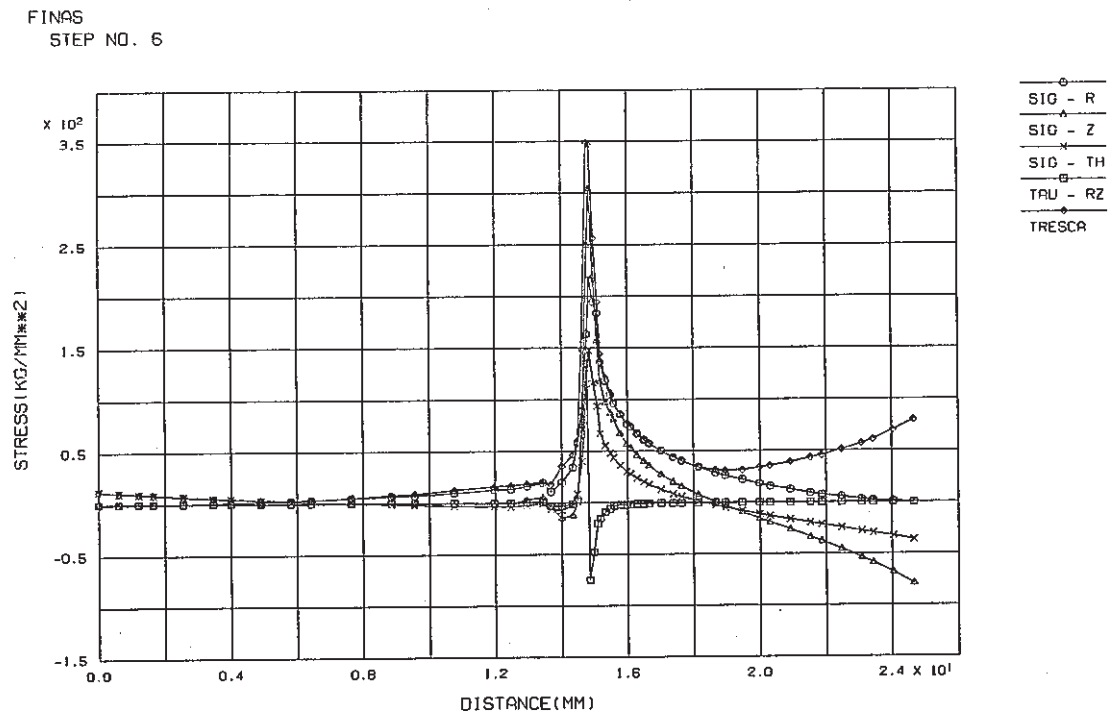


Fig. C.3.6-4 Stress Distribution along Crack Line at Cold Shock of Thinning Portion, crack a₂ (crack depth a₁=9.4 mm, a₂=15 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-30.0000
2	-11.0000
3	8.000000
4	26.99999
5	46.00000
6	65.00000
7	84.00001
8	102.9999
9	121.9999
10	140.9999

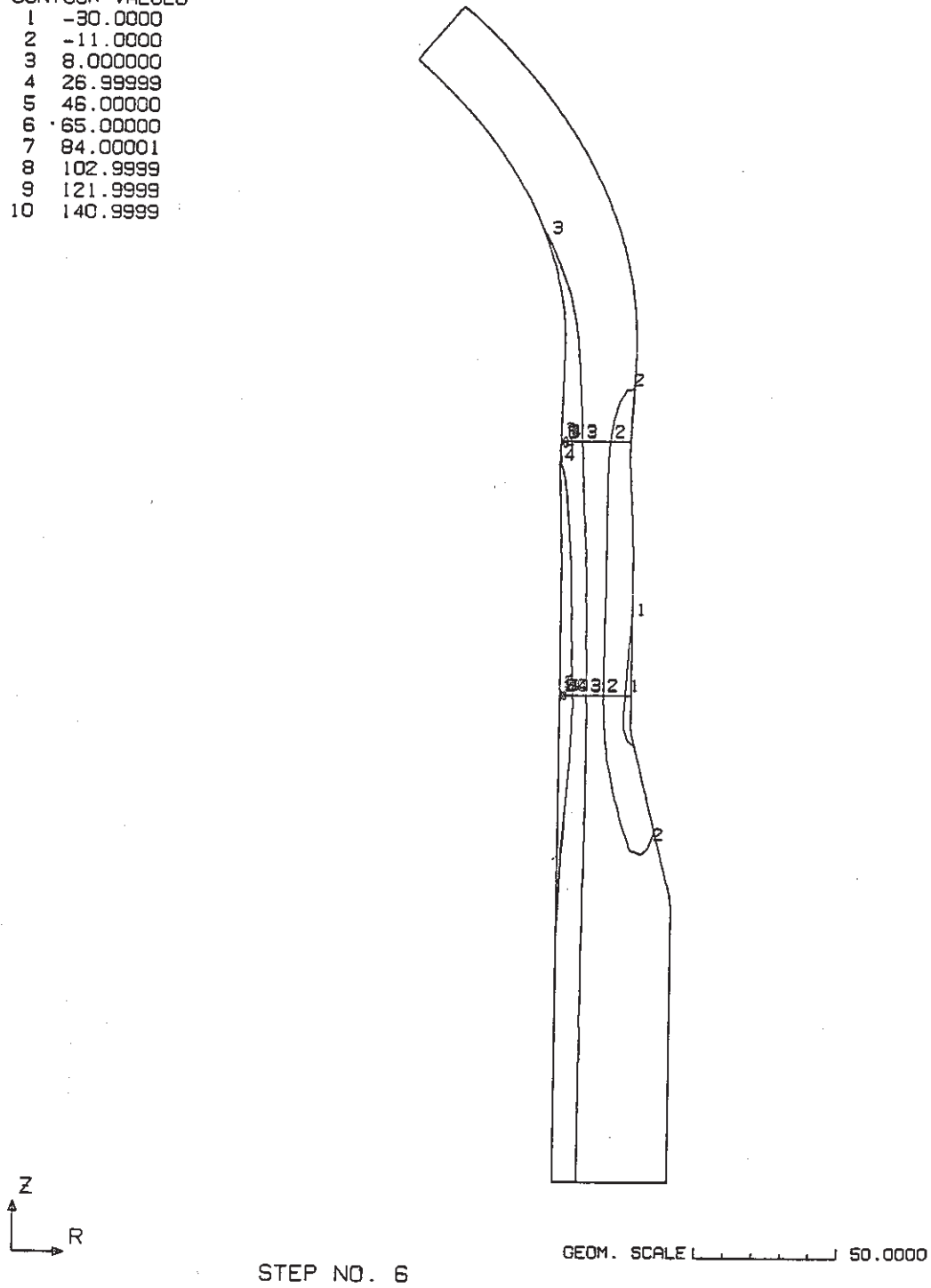
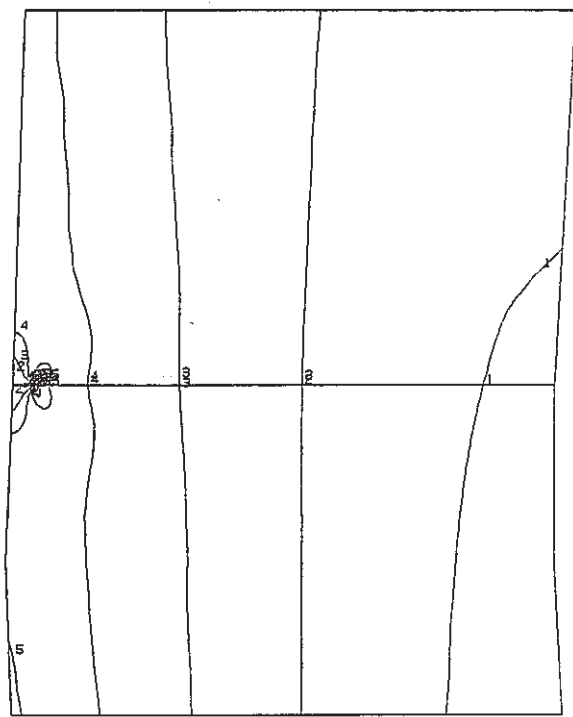


Fig. C.3.7-1 Contour of Axial Stress at Cold Shock of Thinning Portion
(crack depth $a_1=1$ mm, $a_2=1$ mm)

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -16.0000
 - 2 -4.00000
 - 3 8.000000
 - 4 20.00000
 - 5 32.00000
 - 6 44.00000
 - 7 56.00001
 - 8 68.00001
 - 9 80.00001
 - 10 92.00001



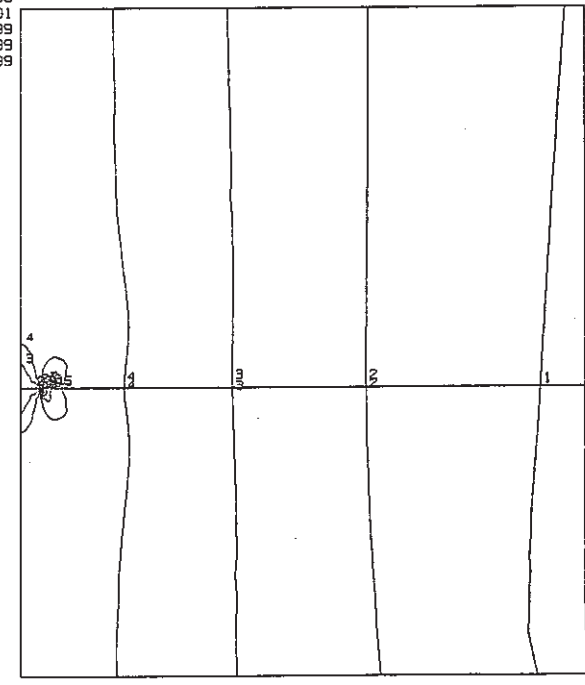
STEP NO. 6

GEOM. SCALE 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -30.0000
 - 2 -11.0000
 - 3 8.000000
 - 4 26.99999
 - 5 46.00000
 - 6 65.00000
 - 7 84.00001
 - 8 102.9999
 - 9 121.9999
 - 10 140.9999



STEP NO. 6

GEOM. SCALE 5.00000

Crack a₁

Fig. C.3.7-1 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-28.0000
2	-1.00000
3	26.00000
4	53.00001
5	80.00001
6	106.9999
7	134.0000
8	160.9999
9	188.0000
10	214.9999

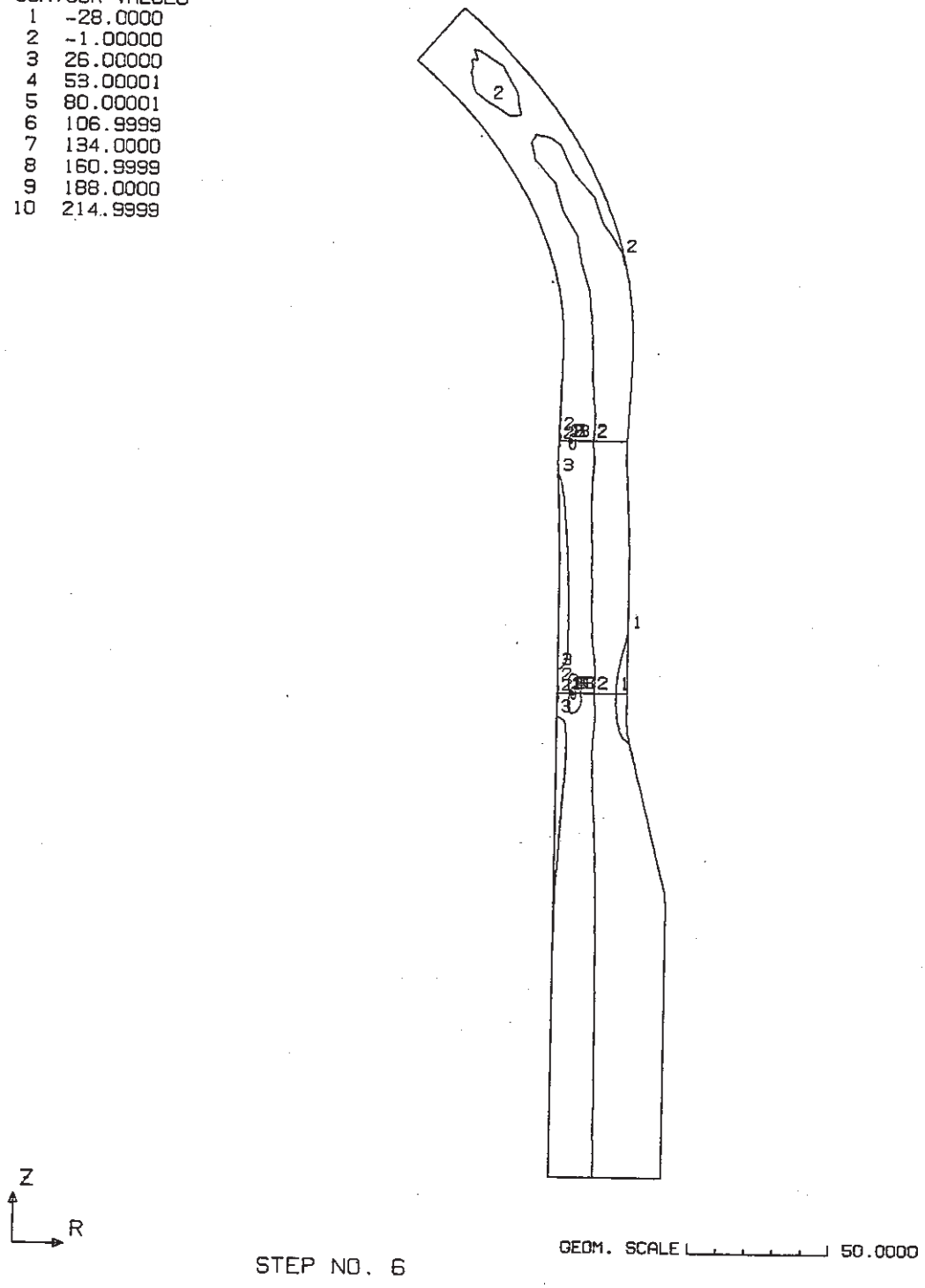
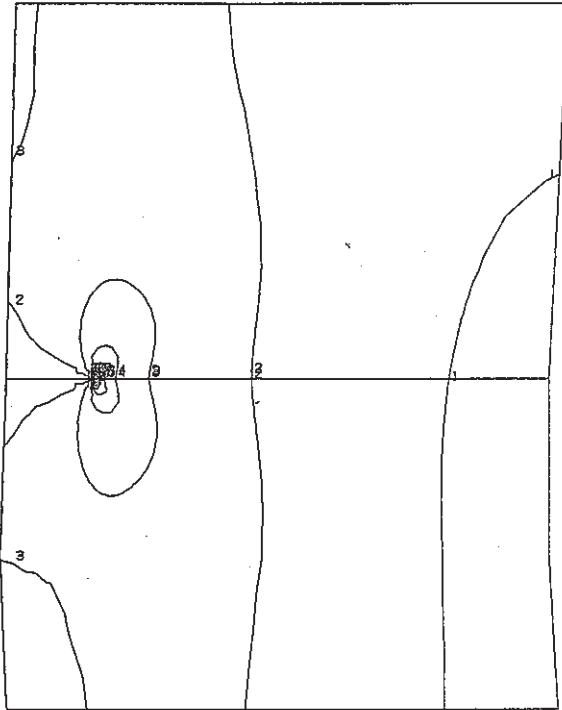


Fig. C.3.7-2 Contour of Axial Stress at Cold Shock of Thinning Portion (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-15.0000
2	2.000000
3	18.999999
4	36.000000
5	53.000001
6	70.000000
7	87.000001
8	103.999999
9	121.000000
10	138.000000



STEP NO. 6

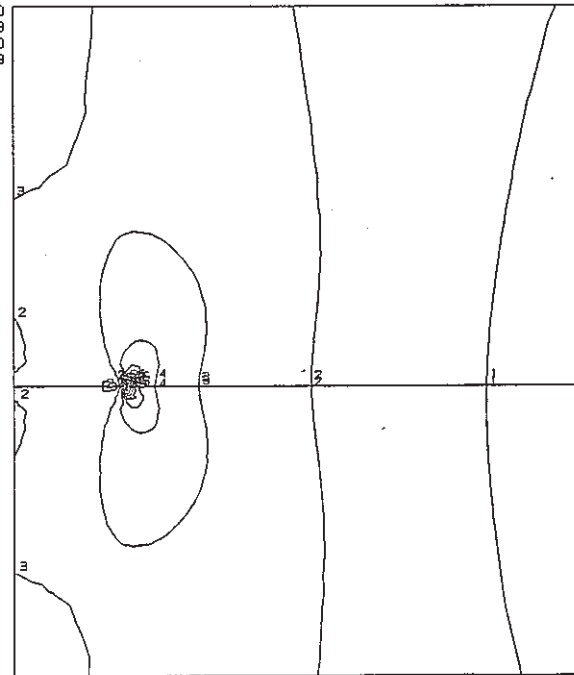
GEOM. SCALE 1 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-28.0000
2	-1.000000
3	26.000000
4	53.000001
5	80.000001
6	106.999999
7	134.000000
8	160.999999
9	188.000000
10	214.999999



STEP NO. 6

GEOM. SCALE 1 5.00000

Crack a₁

Fig. C.3.7-2 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-42.0000
2	-9.00000
3	24.00000
4	57.00000
5	90.00001
6	122.9999
7	155.9999
8	186.9999
9	222.0000
10	255.0000

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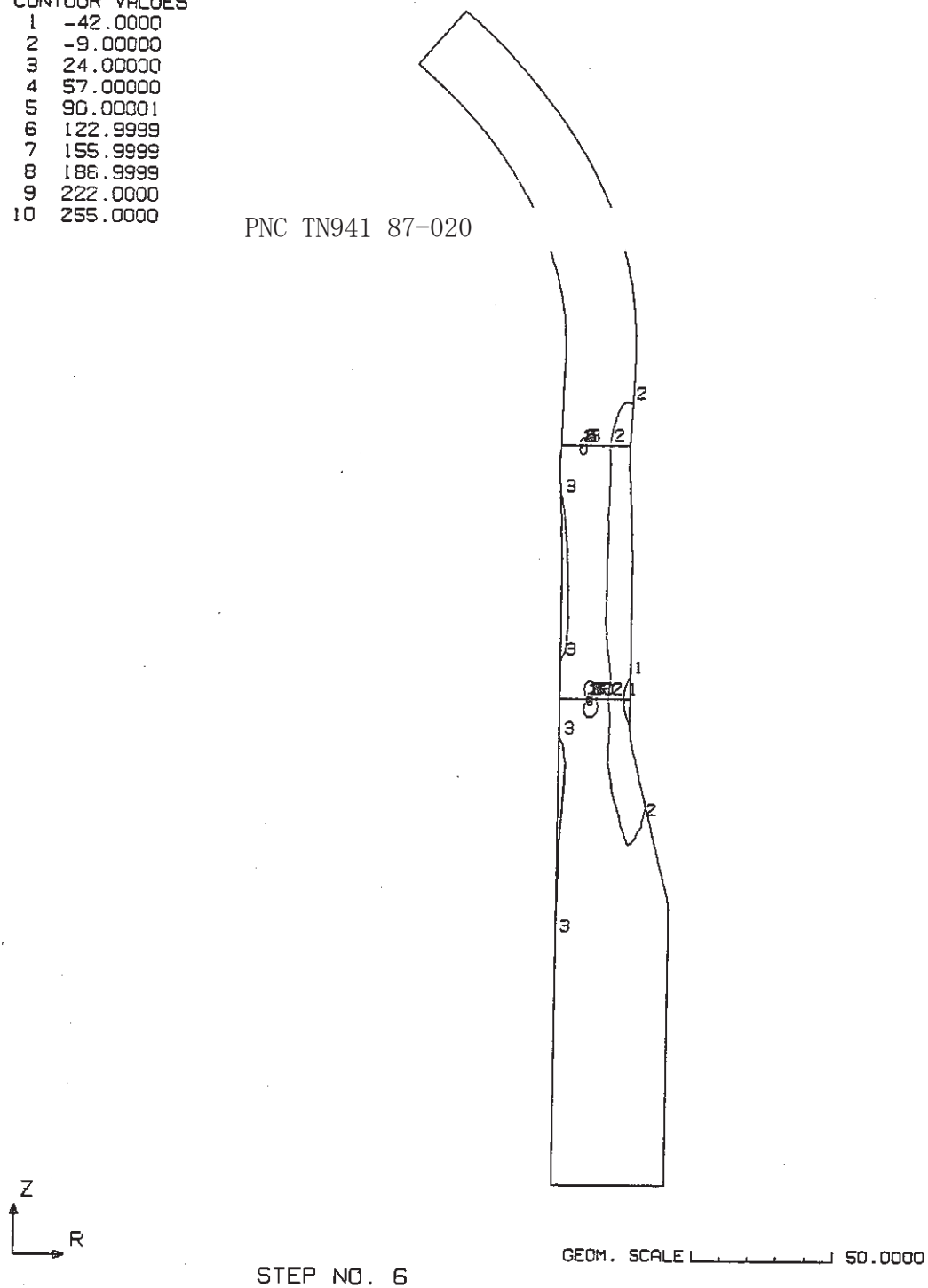
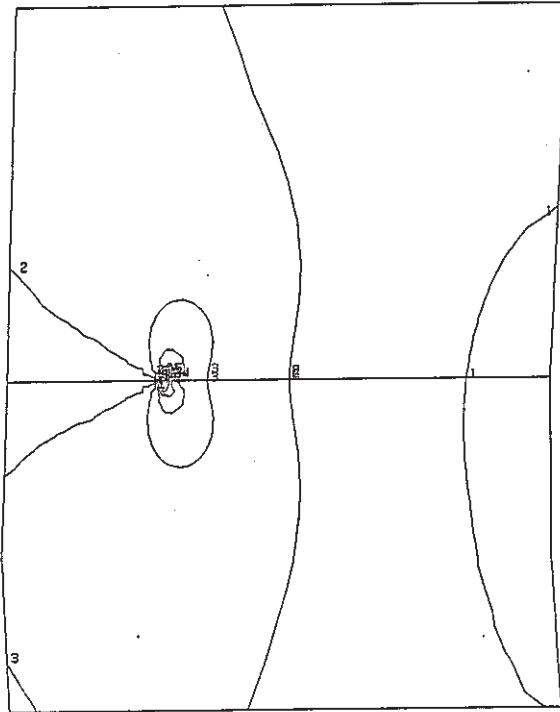


Fig. C.3.7-3 Contour of Axial Stress at Cold Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-16.0000
2	2.00000
3	20.00000
4	38.00000
5	56.00001
6	74.00001
7	92.00001
8	109.9999
9	127.9999
10	146.0000



STEP NO. 6

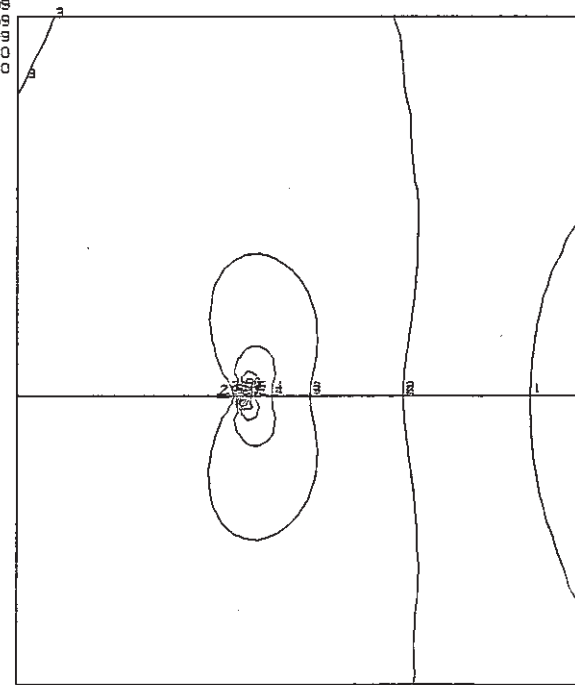
GEOM. SCALE 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-42.0000
2	-9.00000
3	24.00000
4	57.00000
5	90.00001
6	122.9999
7	155.9999
8	188.9999
9	222.0000
10	255.0000



STEP NO. 6

GEOM. SCALE 5.00000

Crack a₁

Fig. C.3.7-3 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-62.0000
2	-21.0000
3	20.00000
4	61.00001
5	101.9999
6	142.9999
7	184.0000
8	225.0000
9	265.9999
10	306.9999

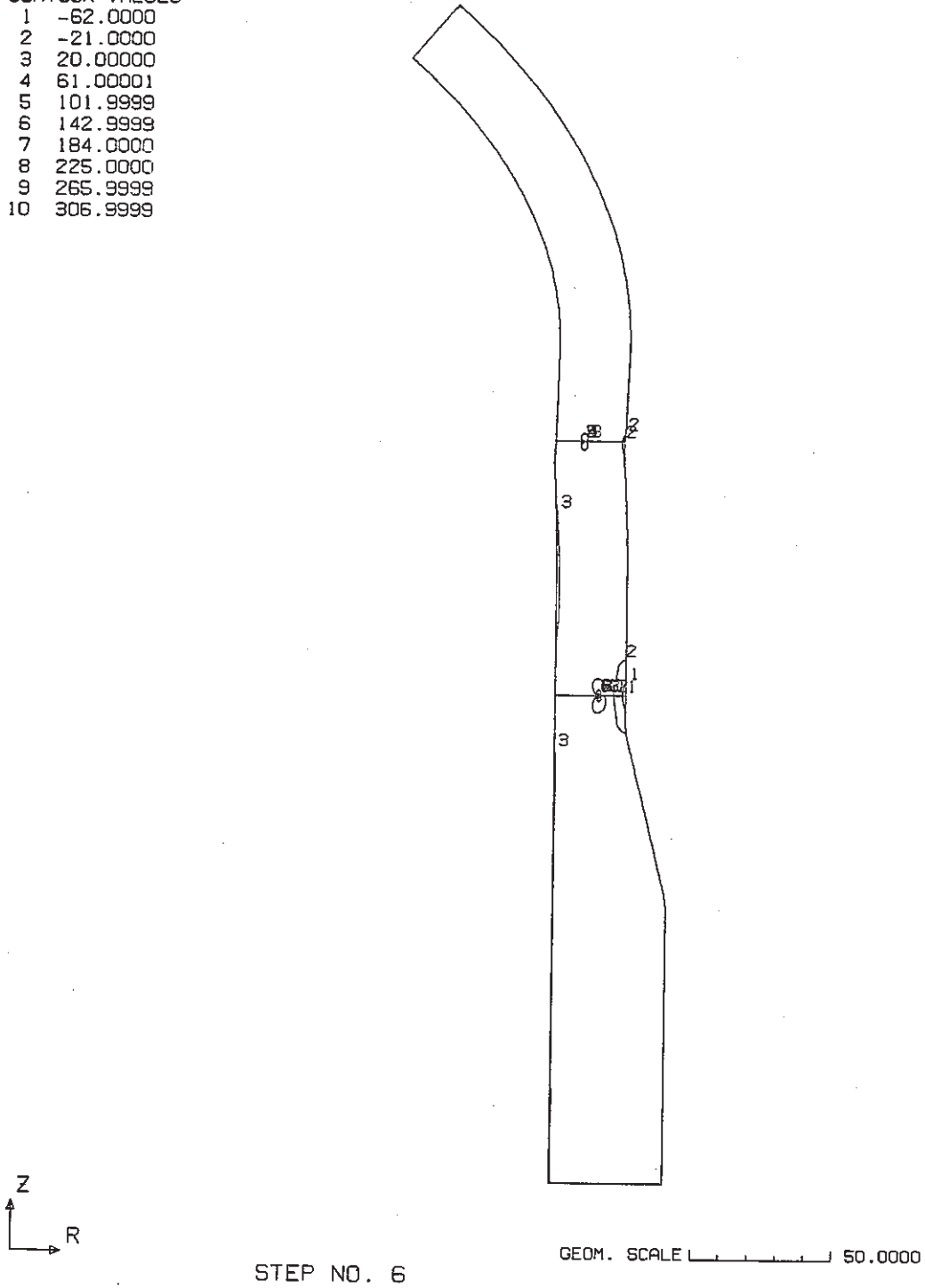
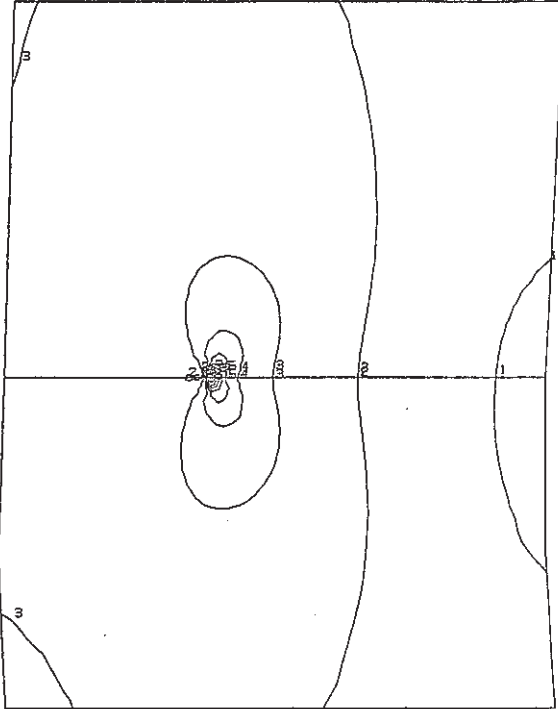


Fig. C.3.7-4 Contour of Axial Stress at Cold Shock of Thinning Portion
(crack depth $a_1=9.4$ mm, $a_2=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-17.0000
2	-3.00000
3	10.99999
4	25.00000
5	39.00000
6	53.00001
7	67.00000
8	81.00001
9	95.00001
10	109.0000



STEP NO. 6

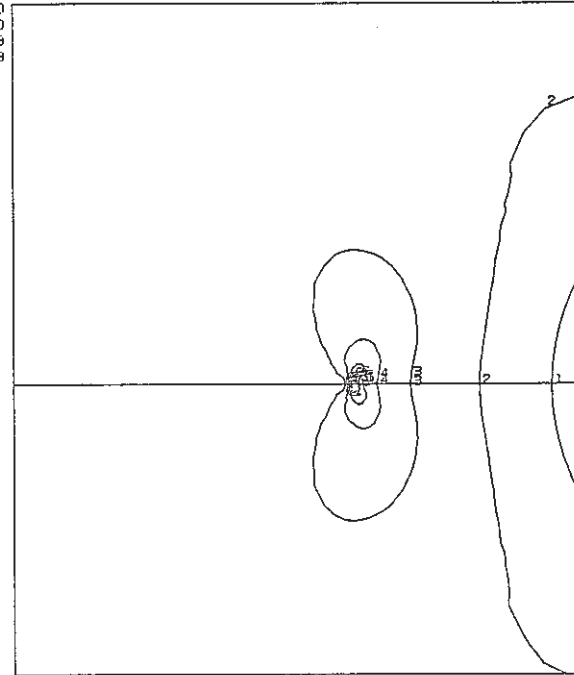
GEOM. SCALE 1 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-62.0000
2	-21.0000
3	20.00000
4	61.00001
5	101.9999
6	142.9999
7	184.0000
8	225.0000
9	265.9999
10	306.9999



STEP NO. 6

GEOM. SCALE 1 5.00000

Crack a₁

Fig. C.3.7-4 (Cont'd)

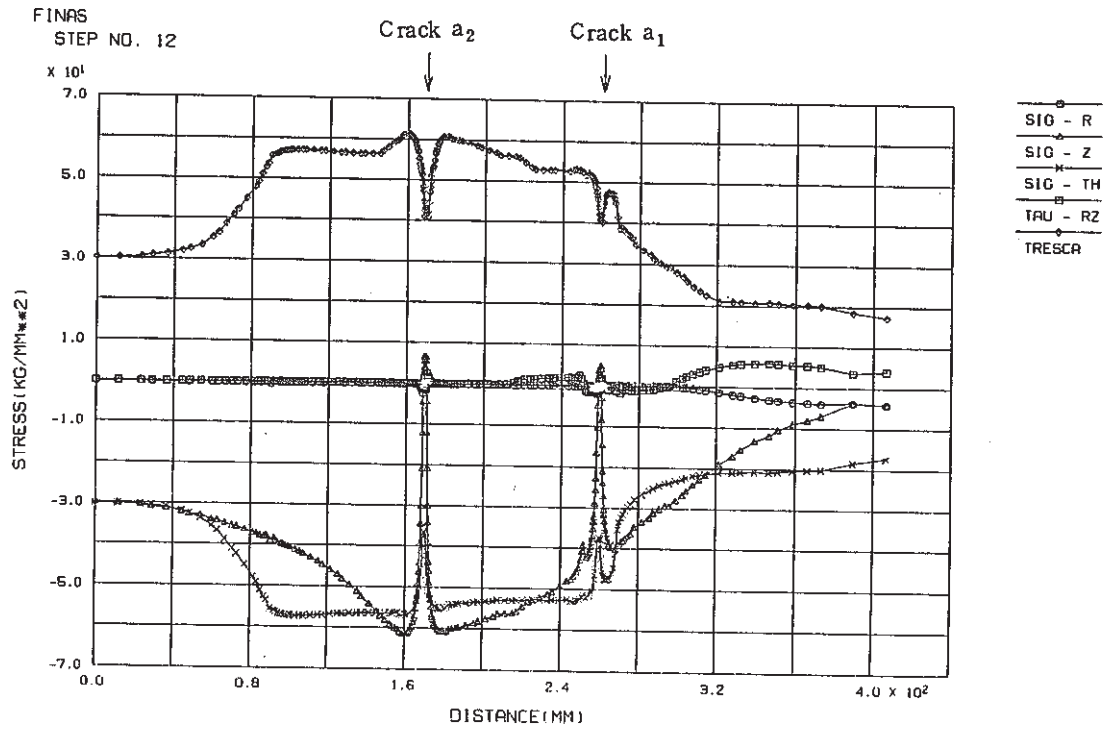


Fig. C.3.8-1 Stress Distribution along Inner Surface at Hot Shock of Thinning Portion (crack depth $a_1=1$ mm, $a_2=1$ mm)

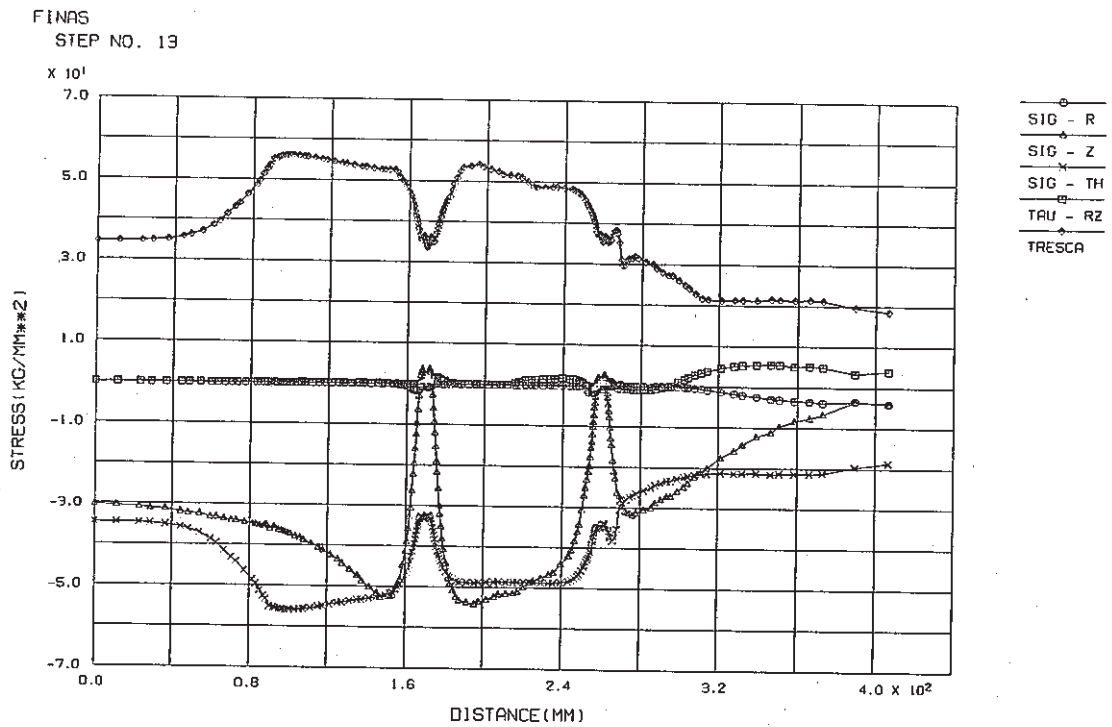


Fig. C.3.8-2 Stress Distribution along Inner Surface at Hot Shock of Thinning Portion (crack depth $a_1=4$ mm, $a_2=5$ mm)

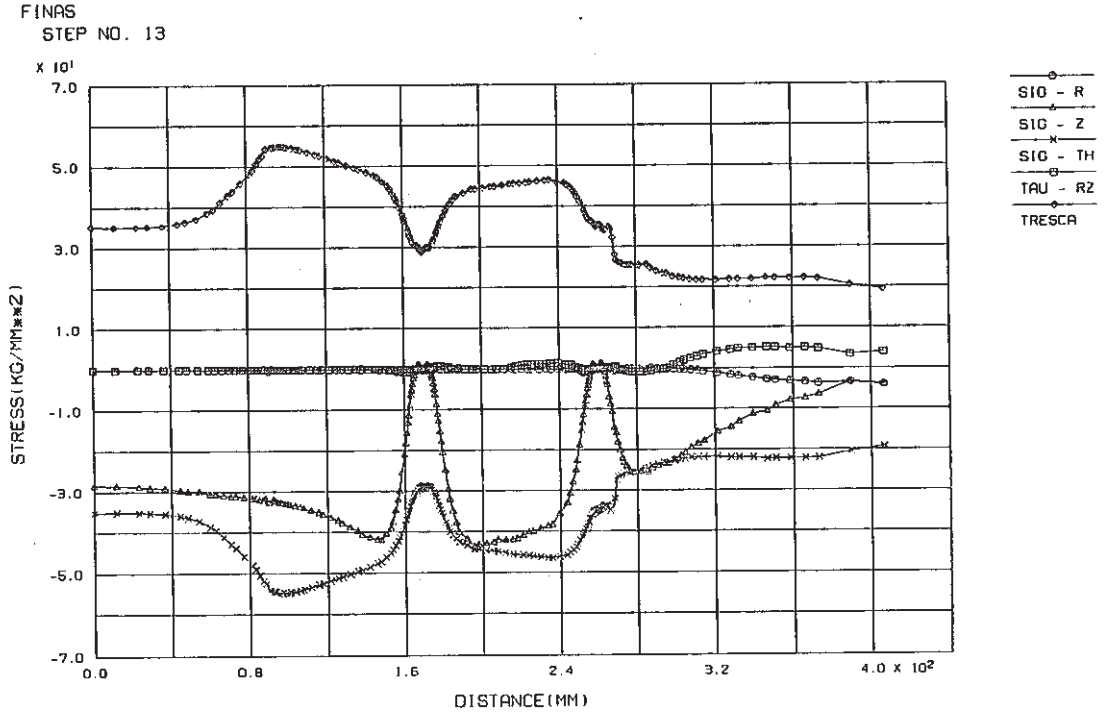


Fig. C.3.8-3 Stress Distribution along Inner Surface at Hot Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

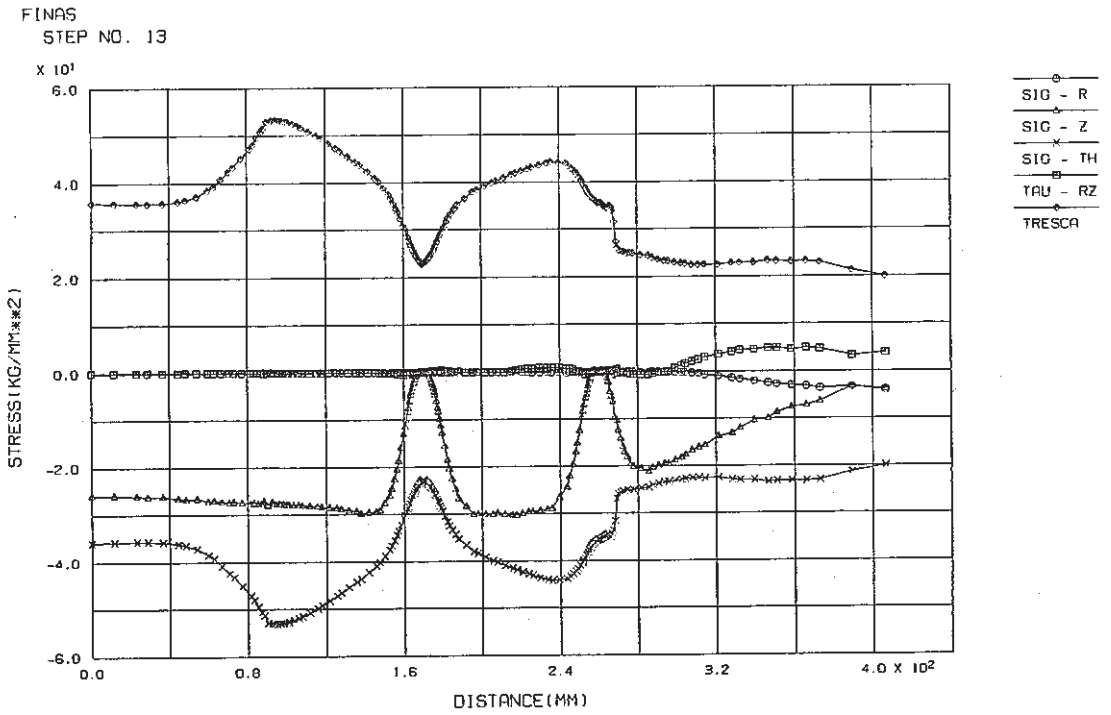


Fig. C.3.8-4 Stress Distribution along Inner Surface at Hot Shock of Thinning Portion (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

FINAS
STEP NO. 12

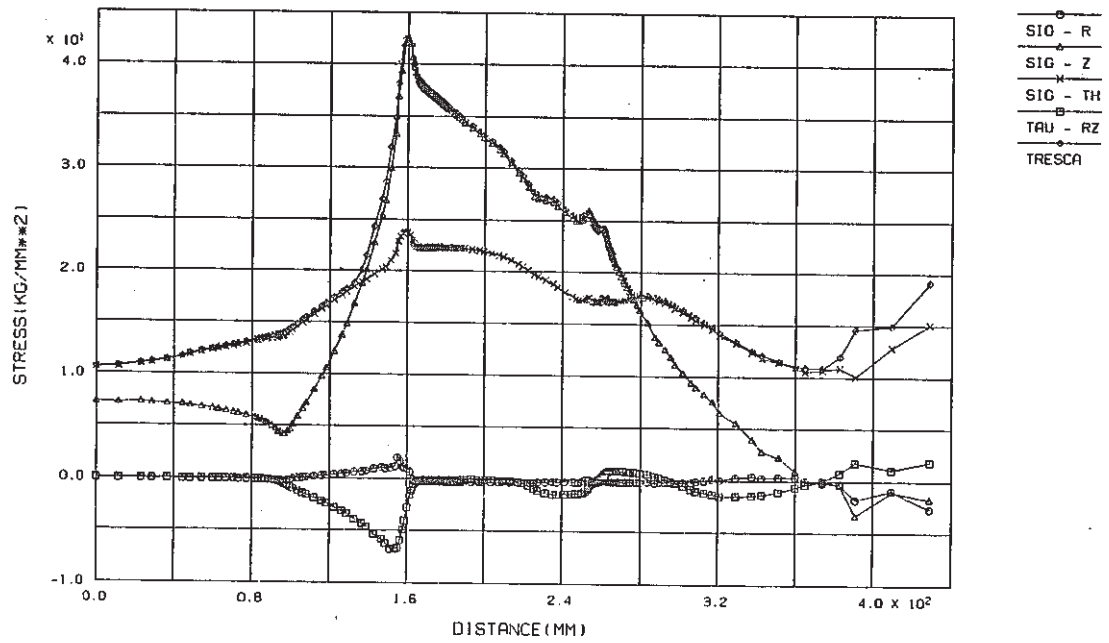


Fig. C.3.9-1 Stress Distribution along Outer Surface at Hot Shock of Thinning Portion (crack depth $a_1 = 1$ mm, $a_2 = 1$ mm)

FINAS
STEP NO. 13

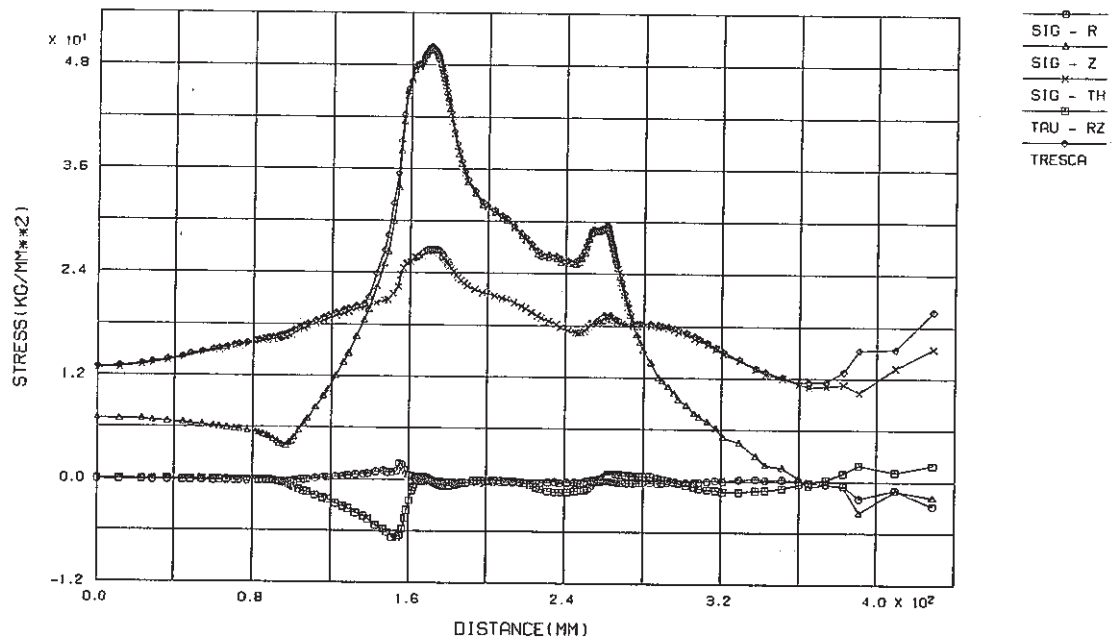


Fig. C.3.9-2 Stress Distribution along Outer Surface at Hot Shock of Thinning Portion (crack depth $a_1 = 4$ mm, $a_2 = 5$ mm)

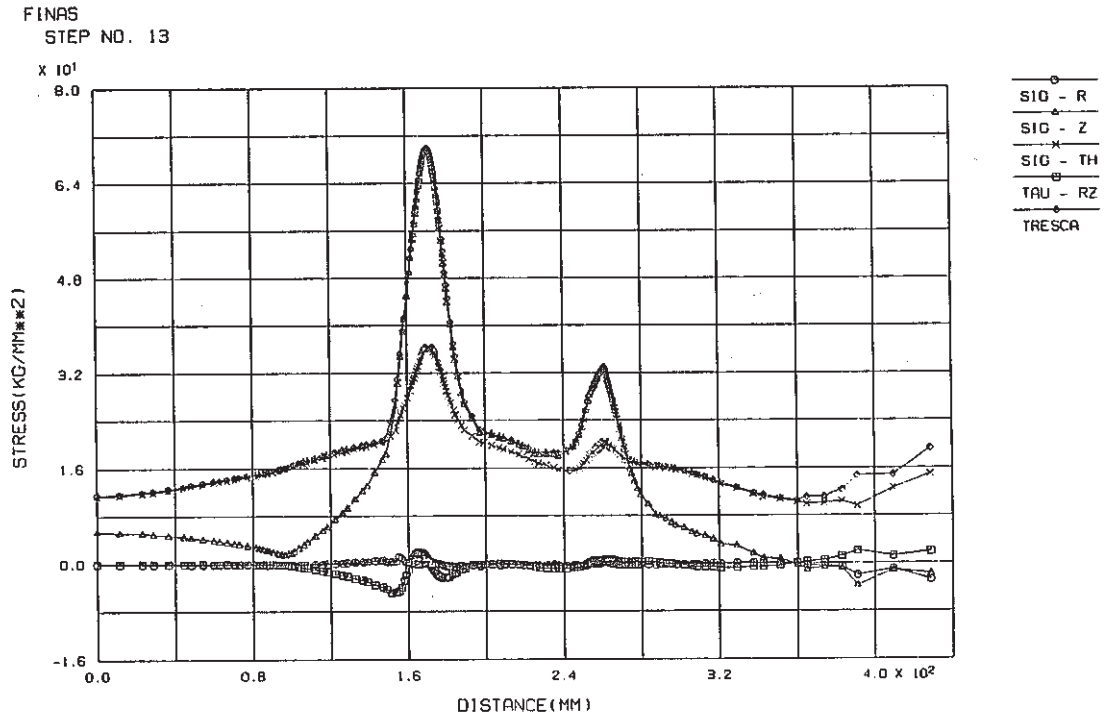


Fig. C.3.9-3 Stress Distribution along Outer Surface at Hot Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

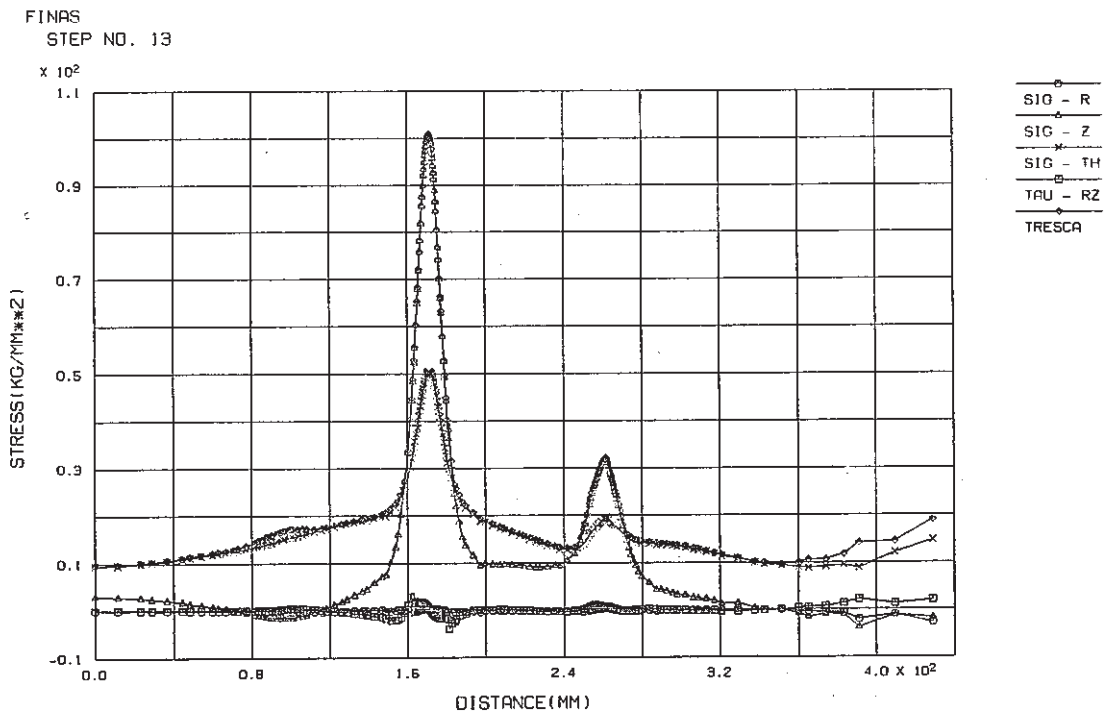


Fig. C.3.9-4 Stress Distribution along Outer Surface at Hot Shock of Thinning Portion (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

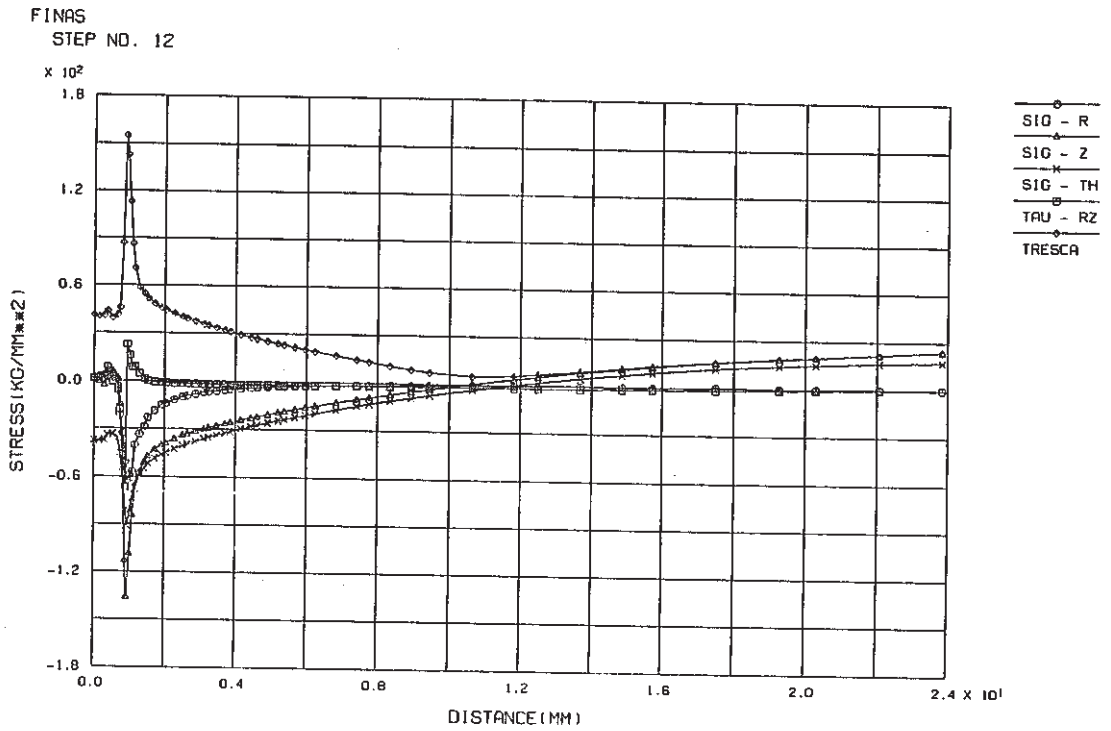


Fig. C.3.10-1 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_1 (crack depth $a_1=1$ mm, $a_2=1$ mm)

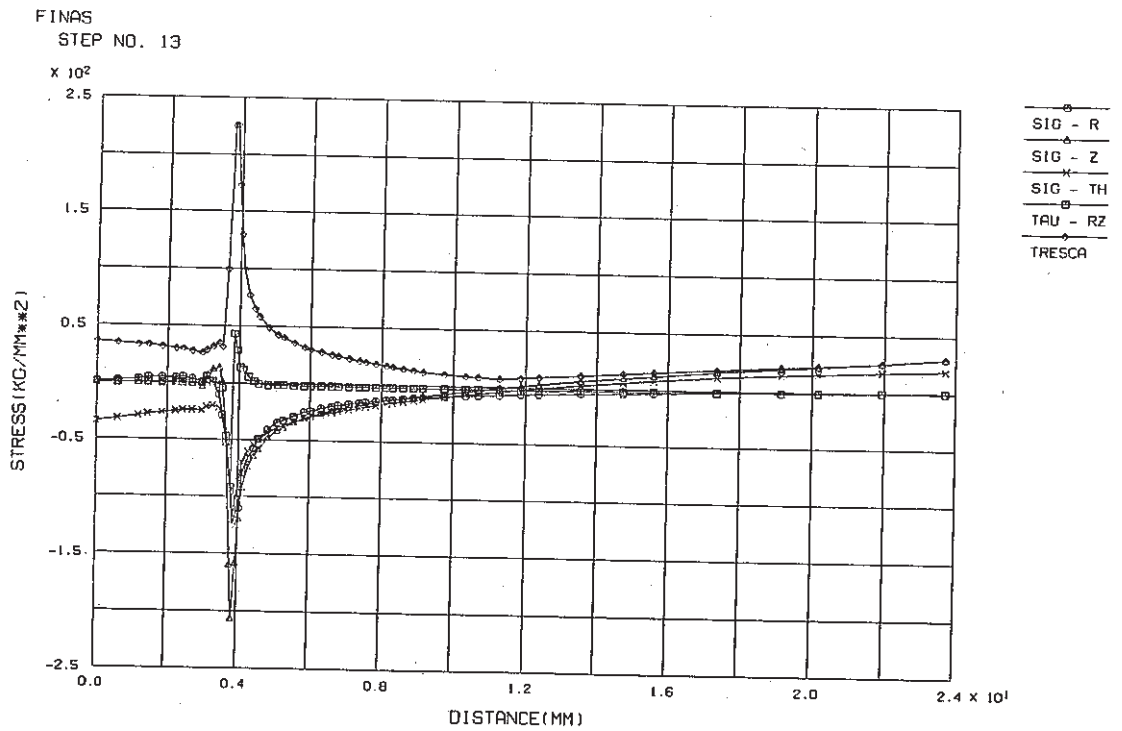


Fig. C.3.10-2 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_1 (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS
STEP NO. 13

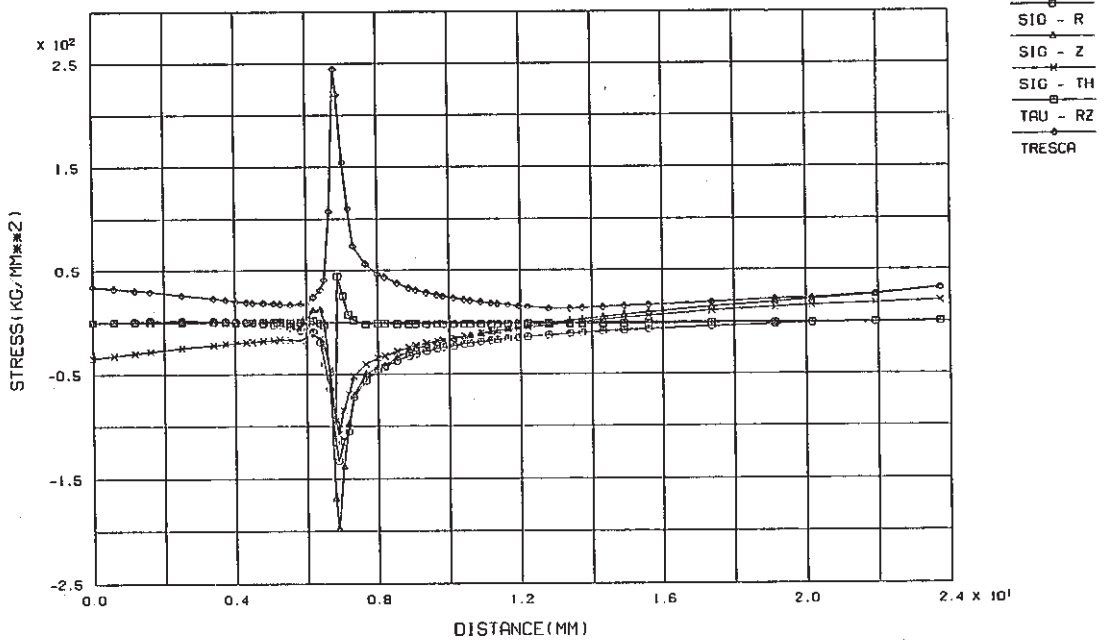


Fig. C.3.10-3 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_1 (crack depth $a_1=7$ mm, $a_2=10$ mm)

FINAS
STEP NO. 13

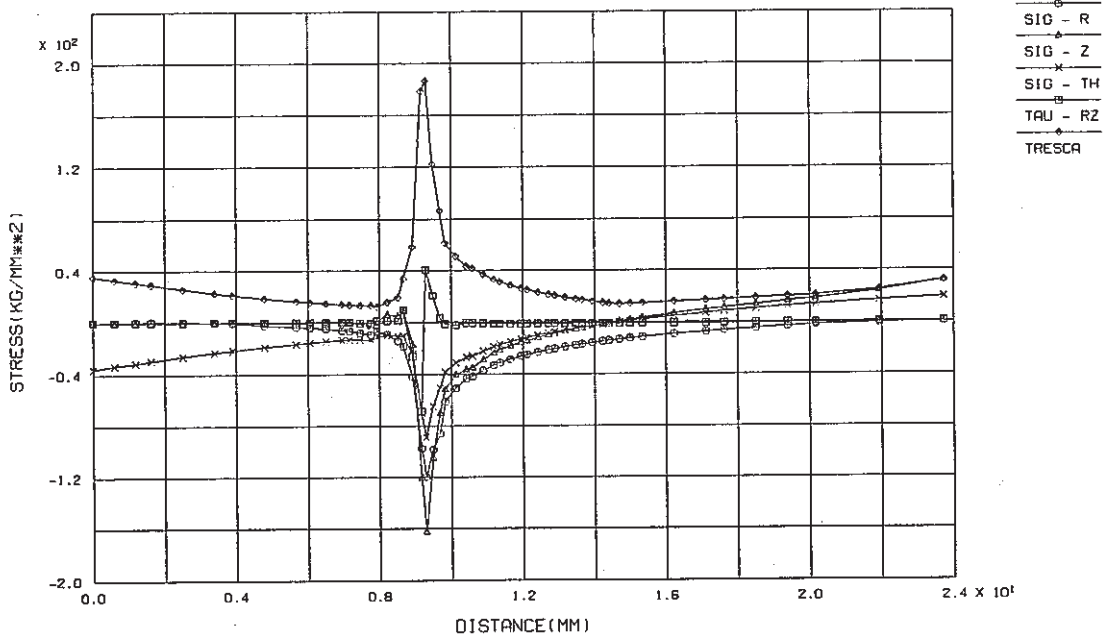


Fig. C.3.10-4 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_1 (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

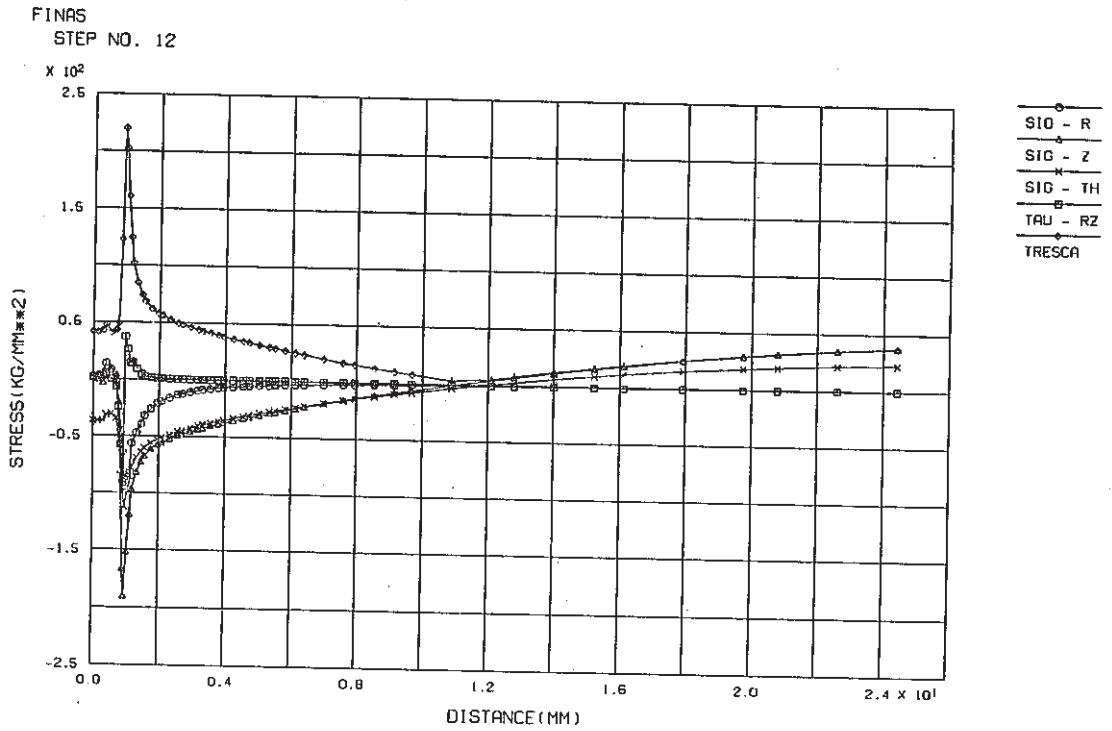


Fig. C.3.11-1 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_2 (crack depth $a_1=1$ mm, $a_2=1$ mm)

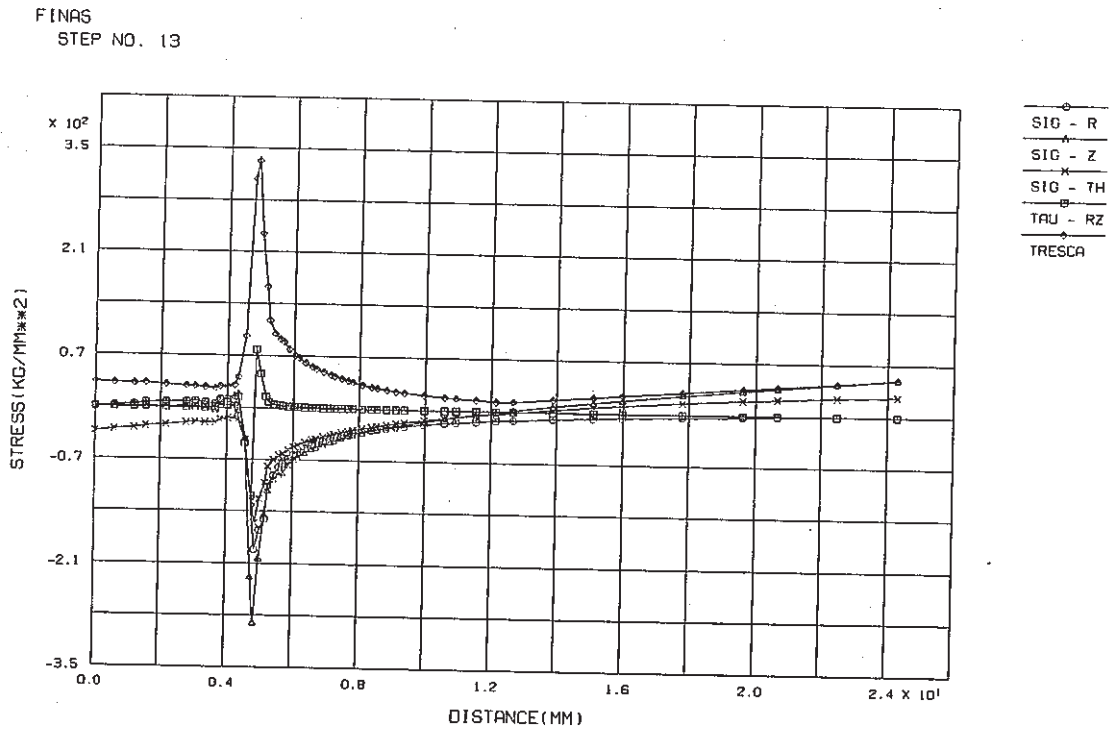


Fig. C.3.11-2 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_2 (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS
STEP NO. 13

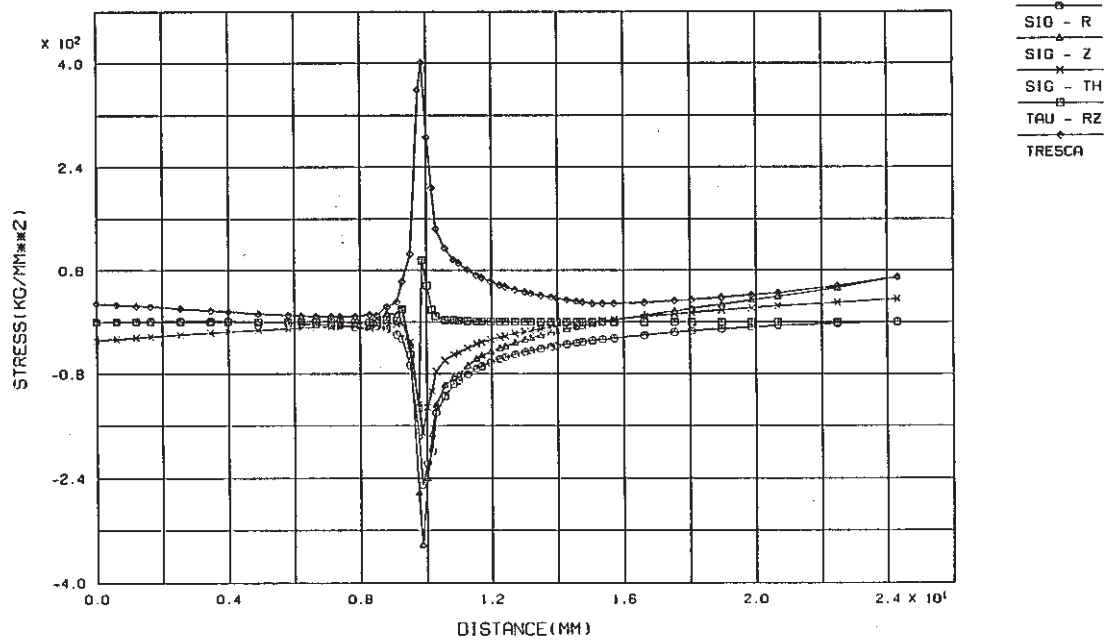


Fig. C.3.11-3 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_2 (crack depth $a_1=7$ mm, $a_2=10$ mm)

FINAS
STEP NO. 13

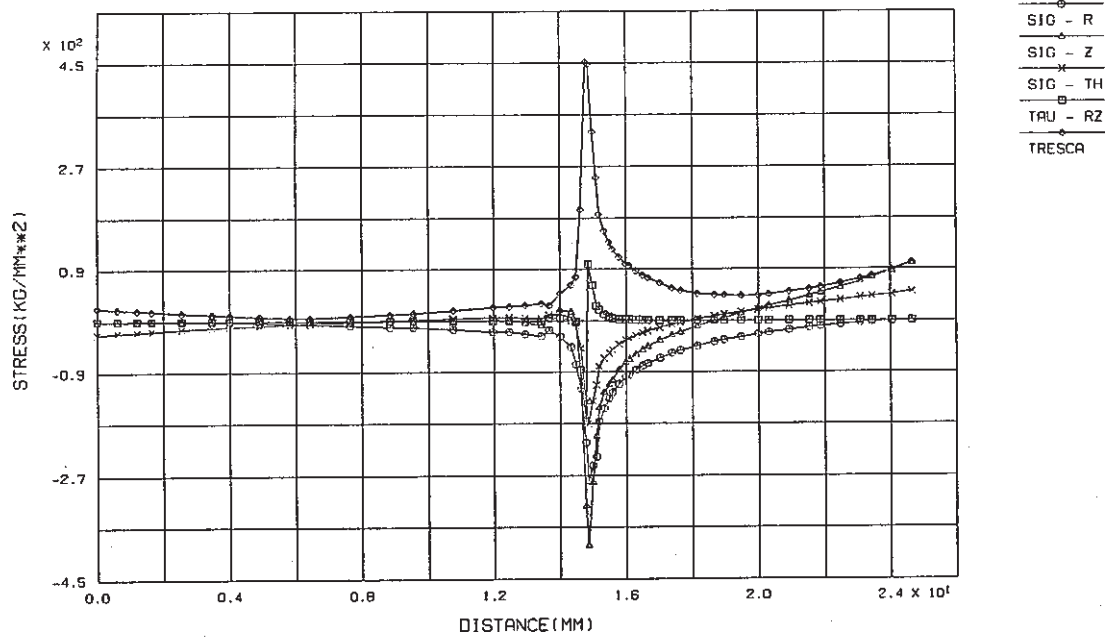


Fig. C.3.11-4 Stress Distribution along Crack Line at Hot Shock of Thinning Portion, crack a_2 (crack depth $a_1=9.4$ mm, $a_2=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-193.000
2	-168.000
3	-143.000
4	-118.000
5	-93.0000
6	-68.0000
7	-43.0000
8	-18.0000
9	7.000000
10	32.00000

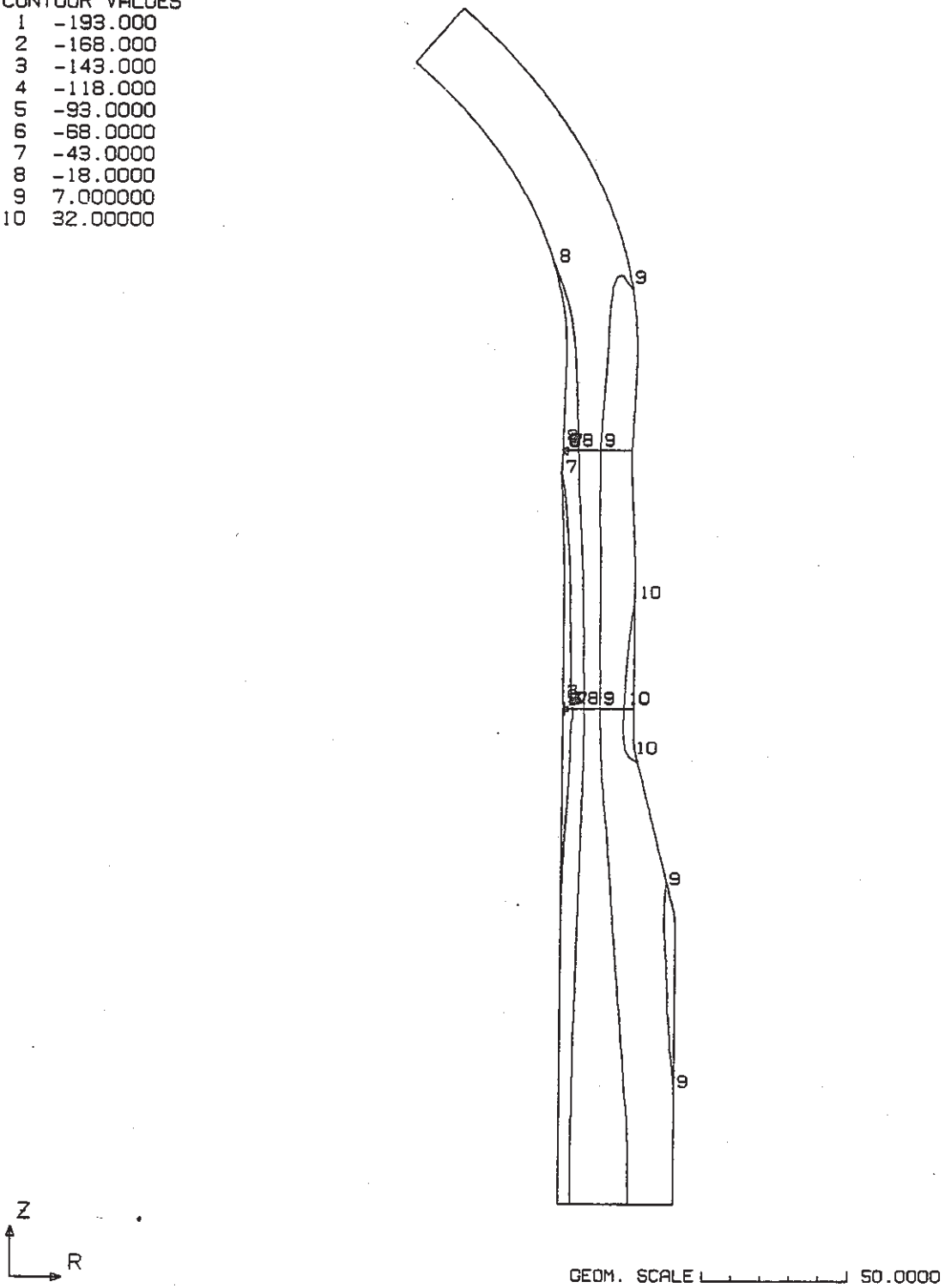
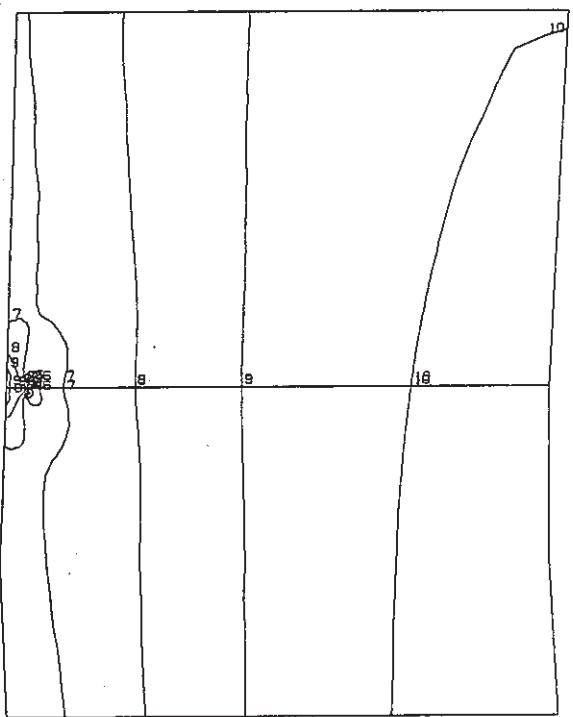


Fig. C.3.12-1 Contour of Axial Stress at Hot Shock of Thinning Portion (crack depth $a_1=1$ mm, $a_2=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-196.000
2	-119.000
3	-102.000
4	-65.0000
5	-58.0000
6	-51.0000
7	-34.0000
8	-17.0000
9	0.0
10	16.99999



STEP NO. 12

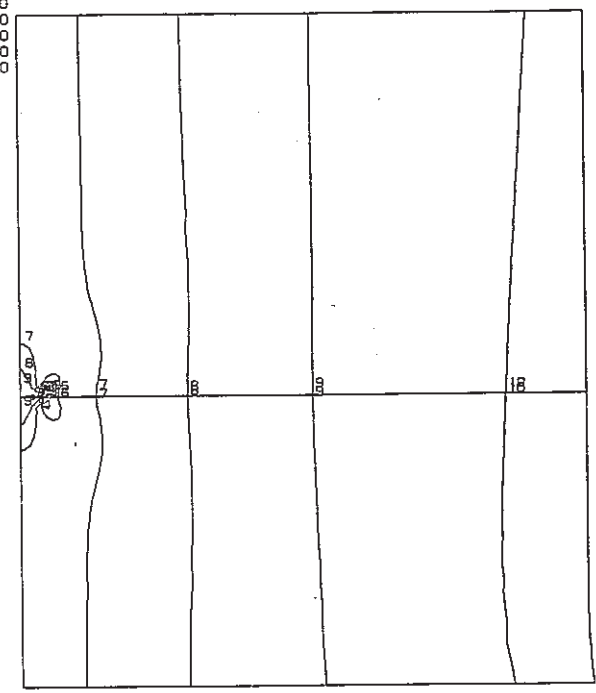
GEOM. SCALE 1 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-193.000
2	-168.000
3	-143.000
4	-118.000
5	-93.0000
6	-68.0000
7	-43.0000
8	-18.0000
9	7.000000
10	32.00000



STEP NO. 12

GEOM. SCALE 1 5.00000

Crack a₁

Fig. C.3.12-1 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-288.000
2	-252.000
3	-216.000
4	-180.000
5	-144.000
6	-108.000
7	-72.0000
8	-36.0000
9	0.0
10	36.00000

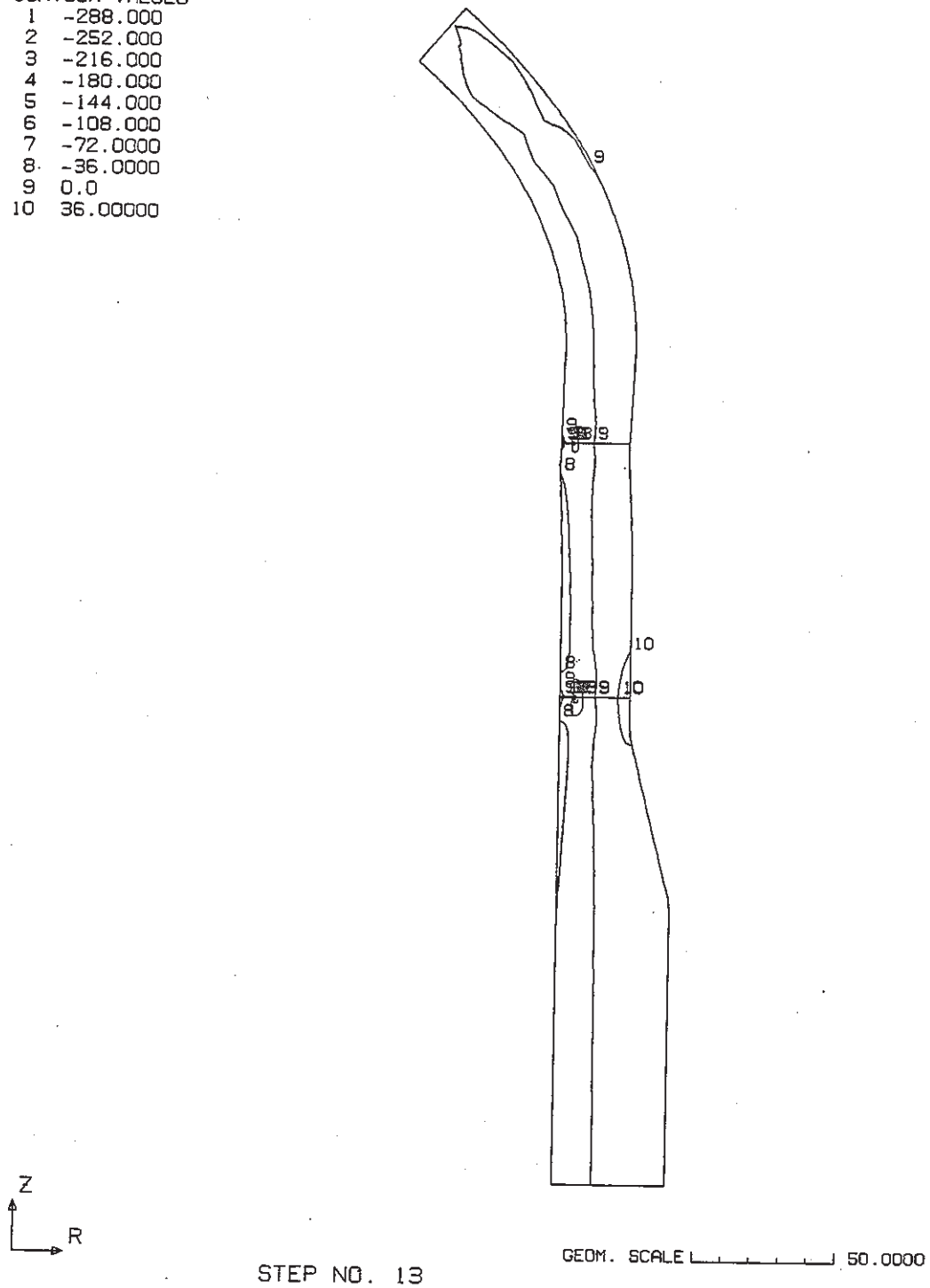
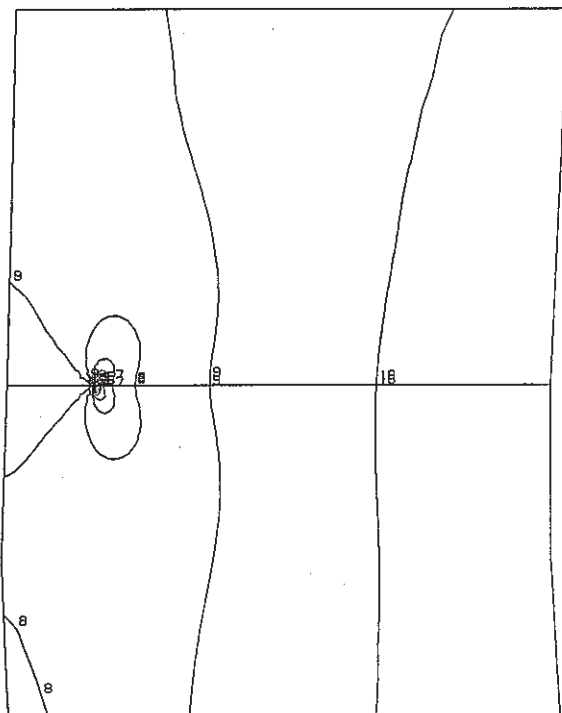


Fig. C.3.12-2 Contour of Axial Stress at Hot Shock of Thinning Portion (crack depth $a_1=4$ mm, $a_2=5$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-202.000
2	-178.000
3	-154.000
4	-130.000
5	-106.000
6	-82.0000
7	-58.0000
8	-34.0000
9	-10.0000
10	13.99999



STEP NO. 13

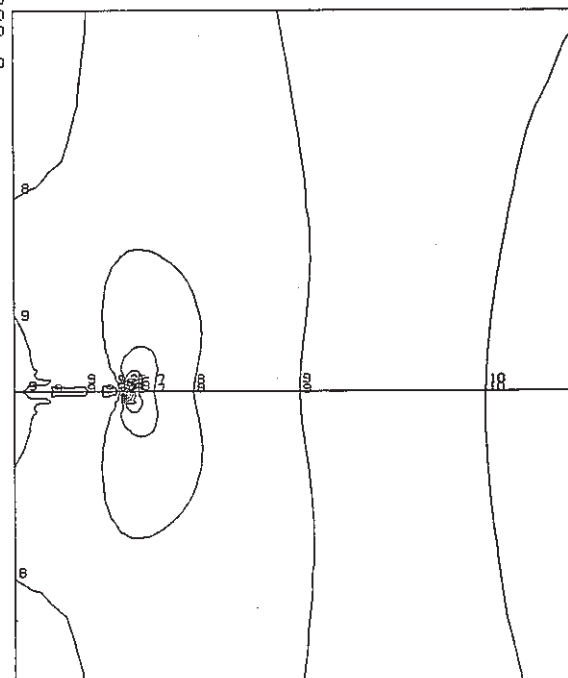
GEOM. SCALE 1 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-288.000
2	-252.000
3	-216.000
4	-180.000
5	-144.000
6	-108.000
7	-72.0000
8	-36.0000
9	0.0
10	36.00000



STEP NO. 13

GEOM. SCALE 1 5.00000

Crack a₁

Fig. C.3.12-2 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-336.000
2	-293.000
3	-250.000
4	-207.000
5	-164.000
6	-121.000
7	-78.0000
8	-35.0000
9	8.000000
10	51.00000

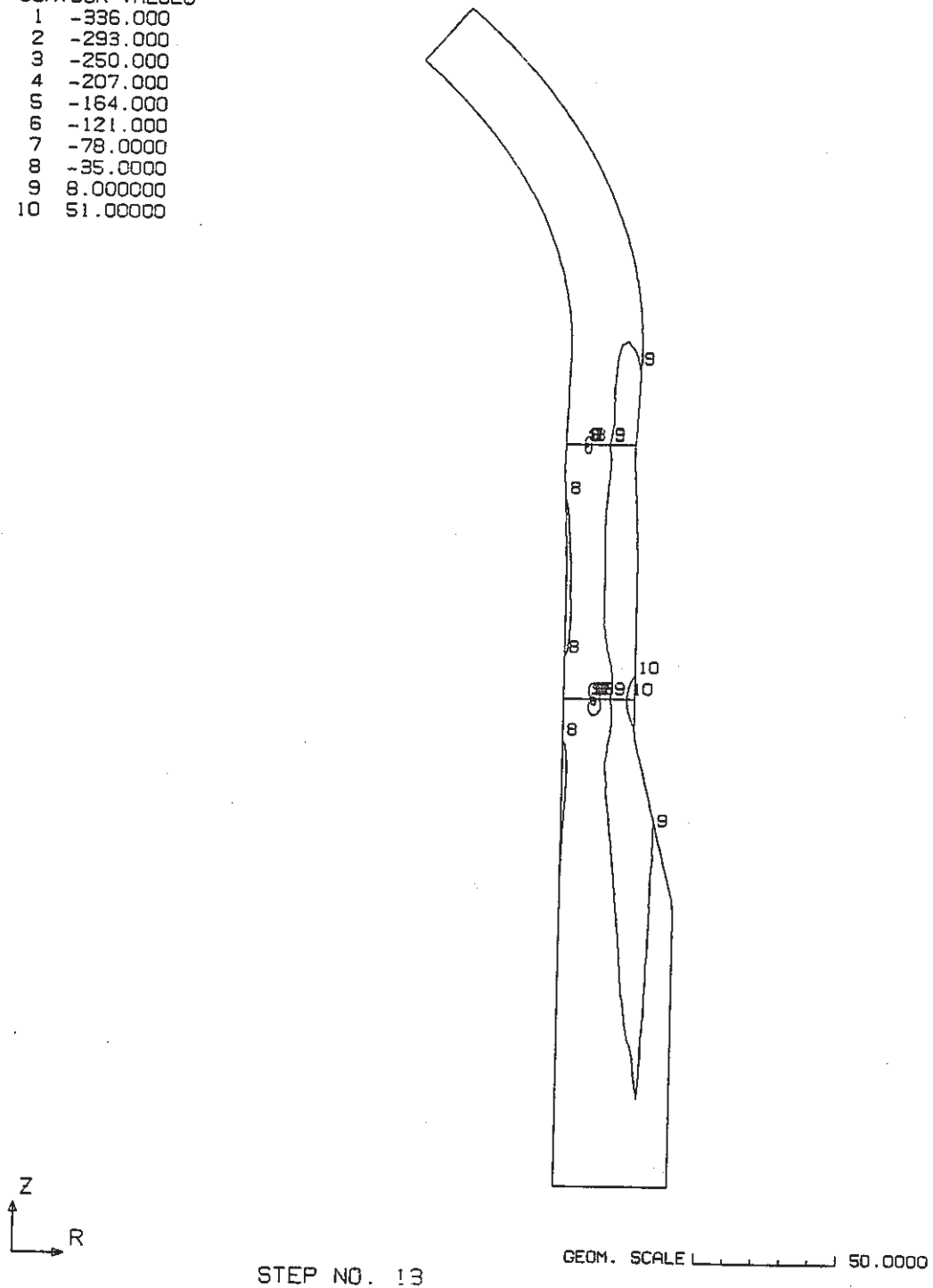
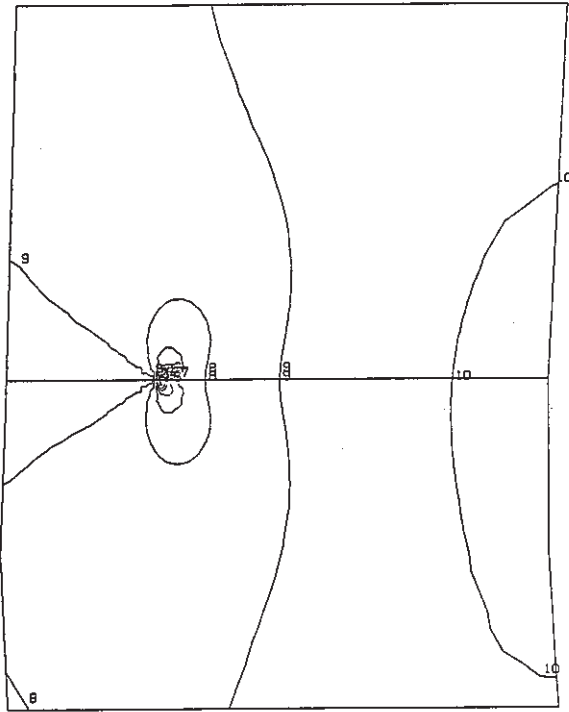


Fig. C.3.12-3 Contour of Axial Stress at Hot Shock of Thinning Portion (crack depth $a_1=7$ mm, $a_2=10$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -204.000
 2 -179.000
 3 -154.000
 4 -129.000
 5 -104.000
 6 -79.0000
 7 -54.0000
 8 -29.0000
 9 -4.00000
 10 21.00000



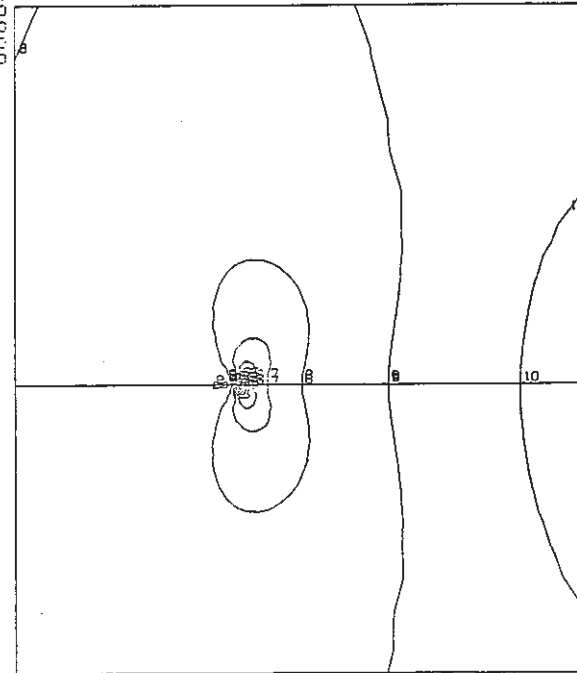
STEP NO. 13

GEOM. SCALE 5.00000

Crack a₂

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -336.000
 2 -293.000
 3 -250.000
 4 -207.000
 5 -164.000
 6 -121.000
 7 -78.0000
 8 -35.0000
 9 8.00000
 10 51.00000



STEP NO. 13

GEOM. SCALE 5.00000

Crack a₁

Fig. C.3.12-3 (Cont'd)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-392.000
2	-340.000
3	-288.000
4	-236.000
5	-184.000
6	-132.000
7	-80.0000
8	-28.0000
9	24.00000
10	76.00001

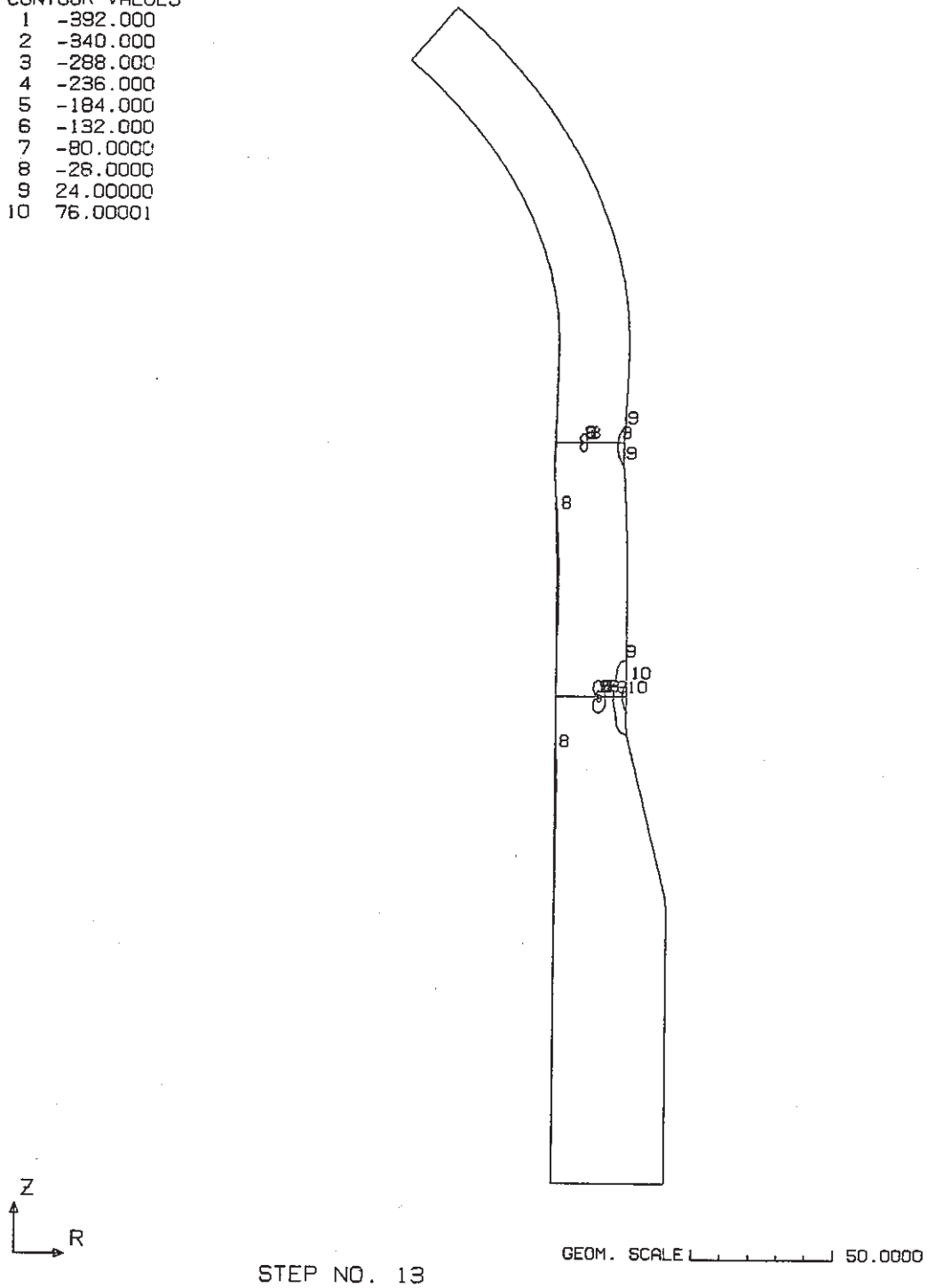
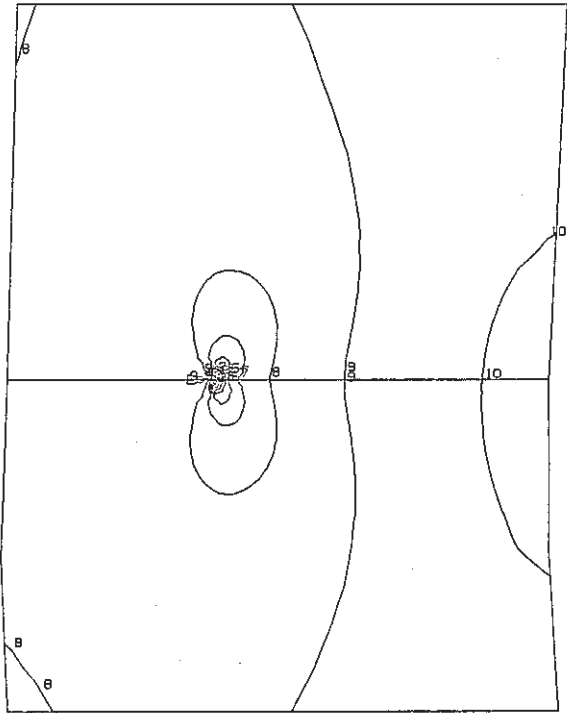


Fig. C.3.12-4 Contour of Axial Stress at Hot Shock of Thinning Portion
(crack depth $a_1=9.4$ mm, $a_2=15$ mm)

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -158.000
 - 2 -138.000
 - 3 -118.000
 - 4 -98.0000
 - 5 -78.0000
 - 6 -58.0000
 - 7 -38.0000
 - 8 -18.0000
 - 9 2.00000
 - 10 21.99999

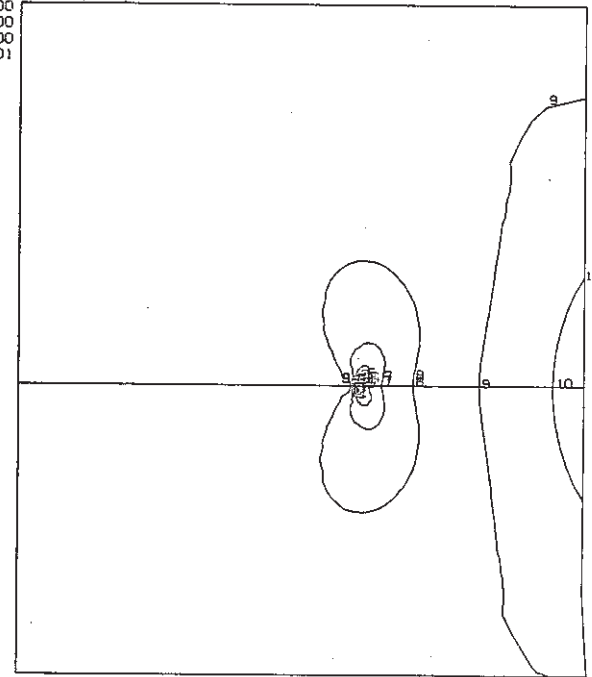


STEP NO. 13

Crack a₂

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -392.000
 - 2 -340.000
 - 3 -288.000
 - 4 -236.000
 - 5 -184.000
 - 6 -132.000
 - 7 -80.0000
 - 8 -28.0000
 - 9 24.00000
 - 10 76.00001



STEP NO. 13

Crack a₁

Fig. C.3.12-4 (Cont'd)

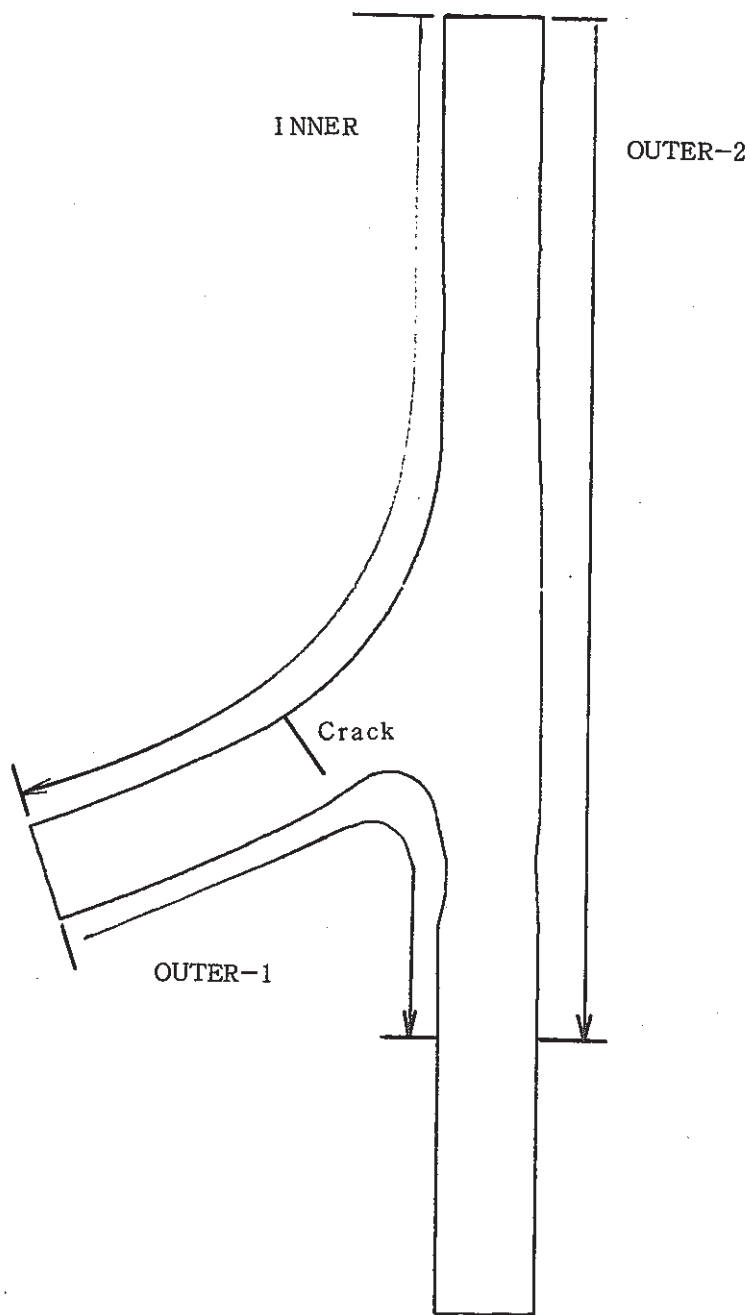


Fig. C.4-1 Evaluation Lines for Surface Stress Distribution of Conical-Bottom Head

FINAS

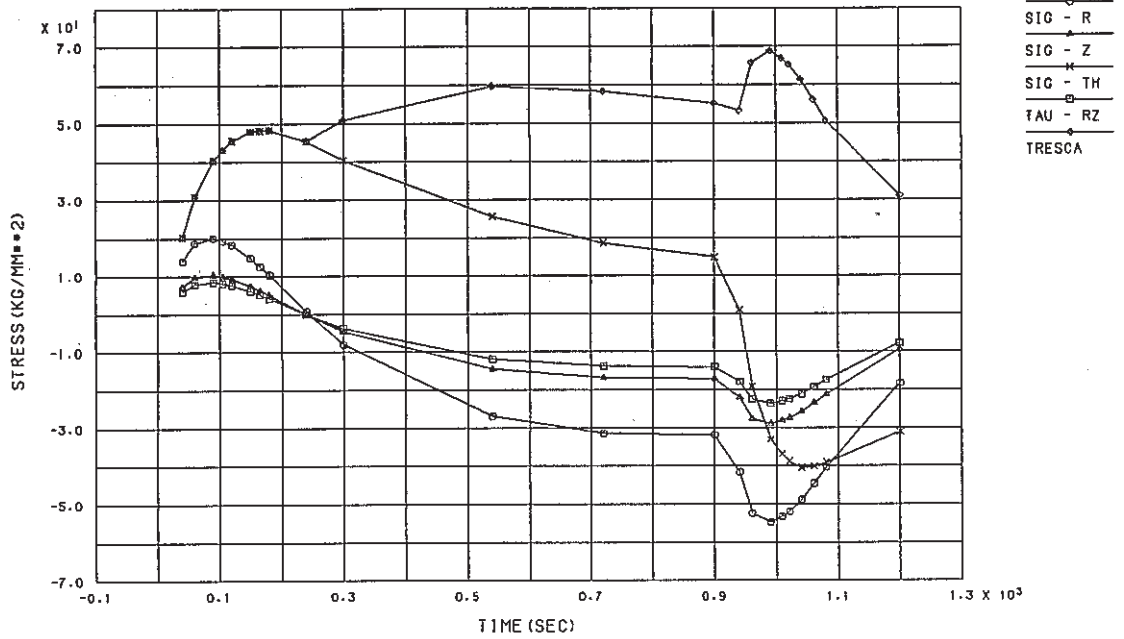


Fig. C.4.1-1 Stress History of ahead Crack Tip of Conical-Bottom Head
(crack depth a=1 mm)

FINAS

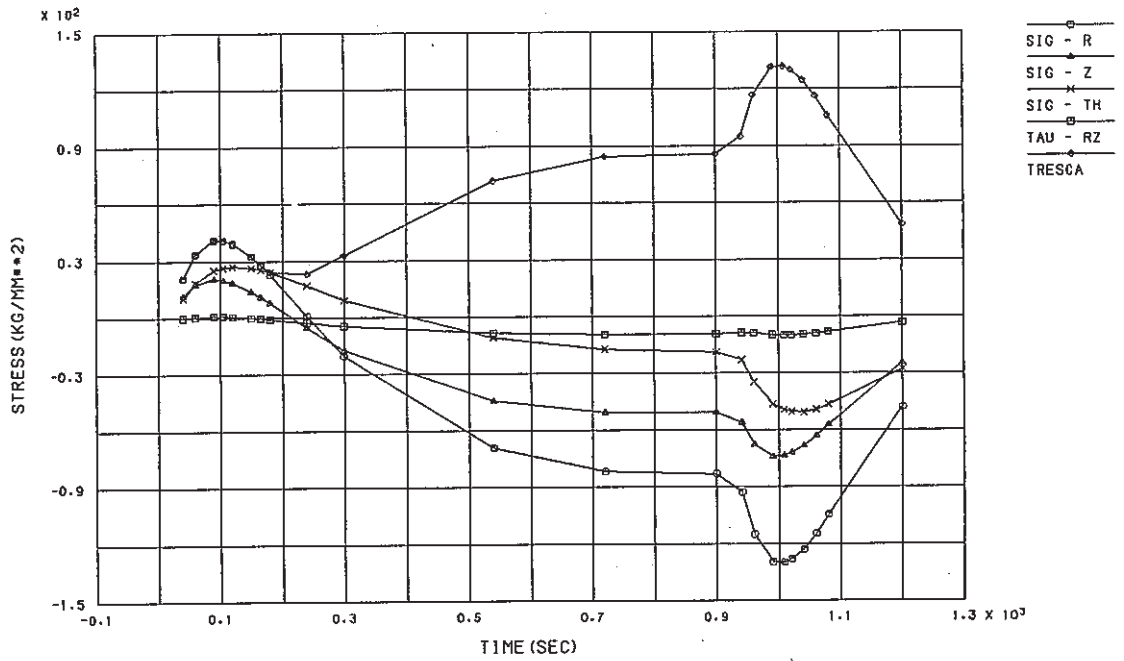


Fig. C.4.1-2 Stress History ahead of Crack Tip of Conical-Bottom Head
(crack depth a=15 mm)

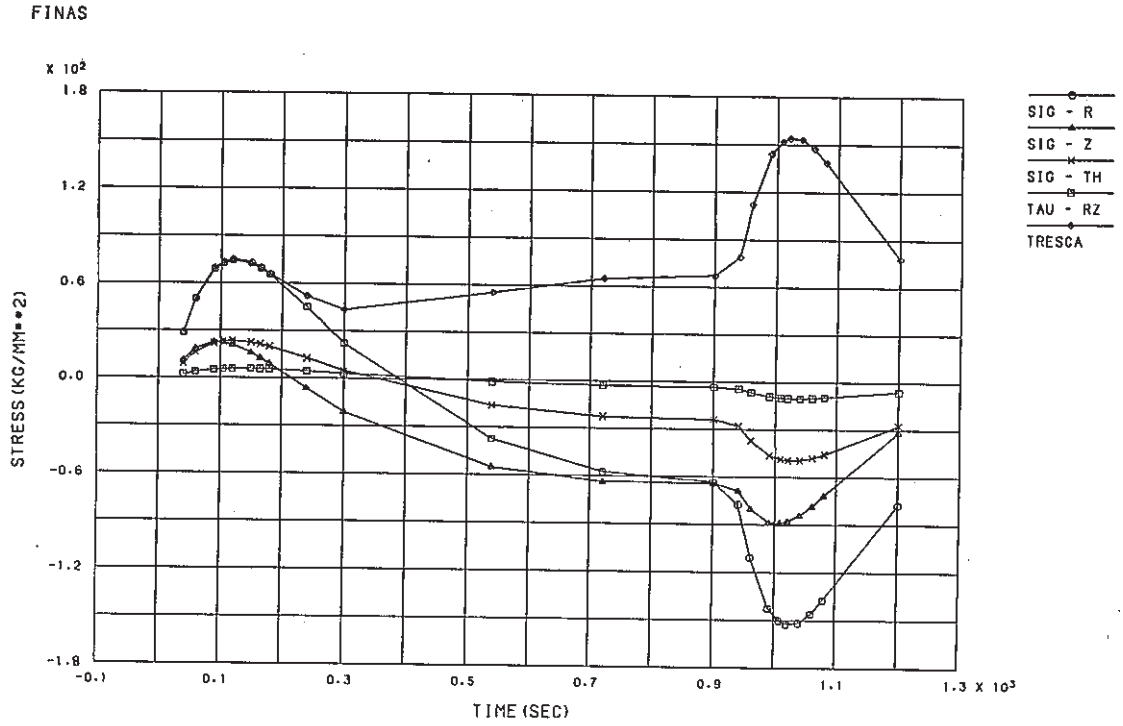


Fig. C.4.1-3 Stress History ahead of Crack Tip of Conical-Bottom Head
(crack depth $a=32$ mm)

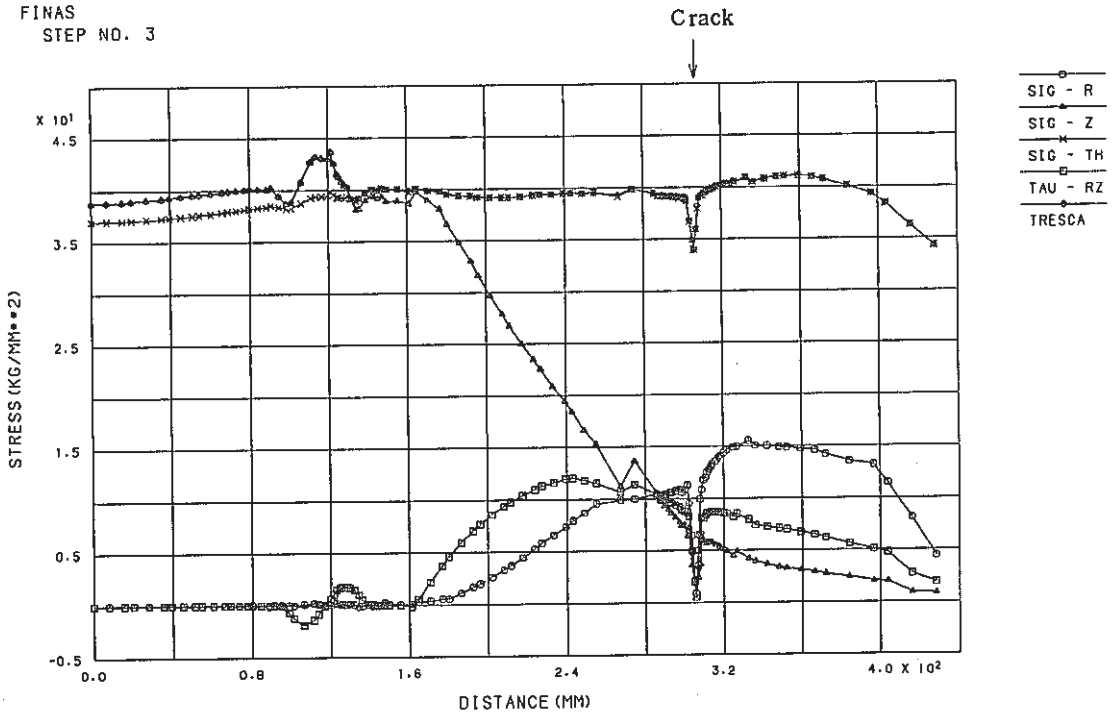


Fig. C.4.2-1 Stress Distribution along Inner Surface at Cold Shock of Conical-Bottom Head (crack depth a=1 mm)

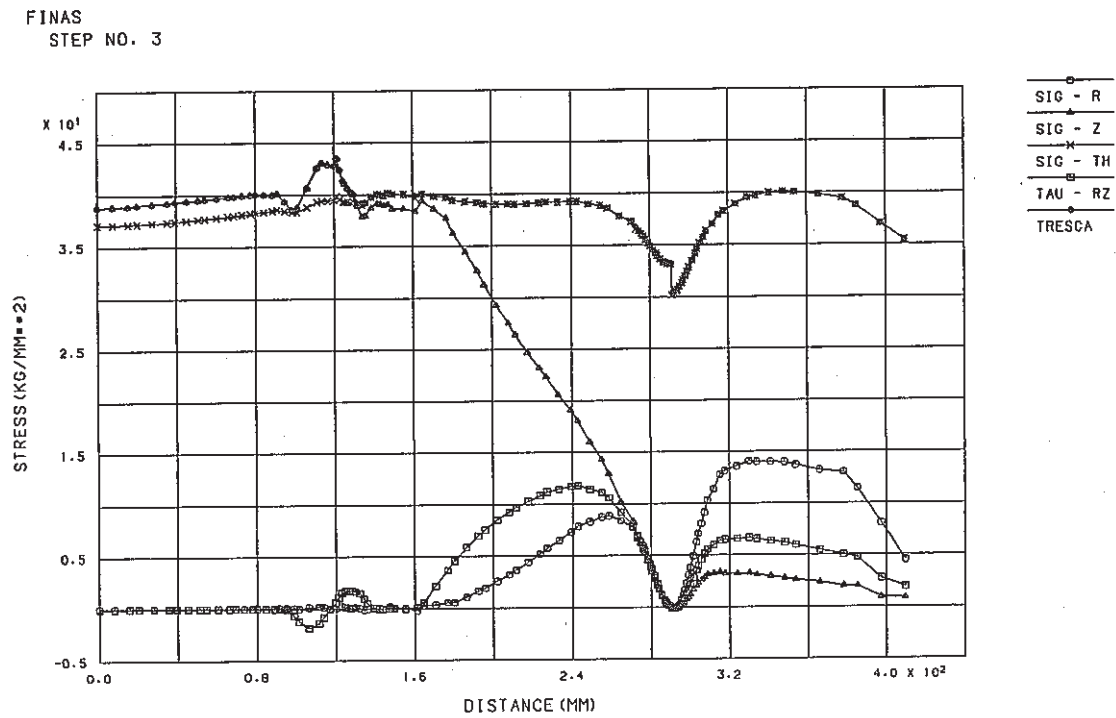


Fig. C.4.2-2 Stress Distribution along Inner Surface at Cold Shock of Conical-Bottom Head (crack depth a=15 mm)

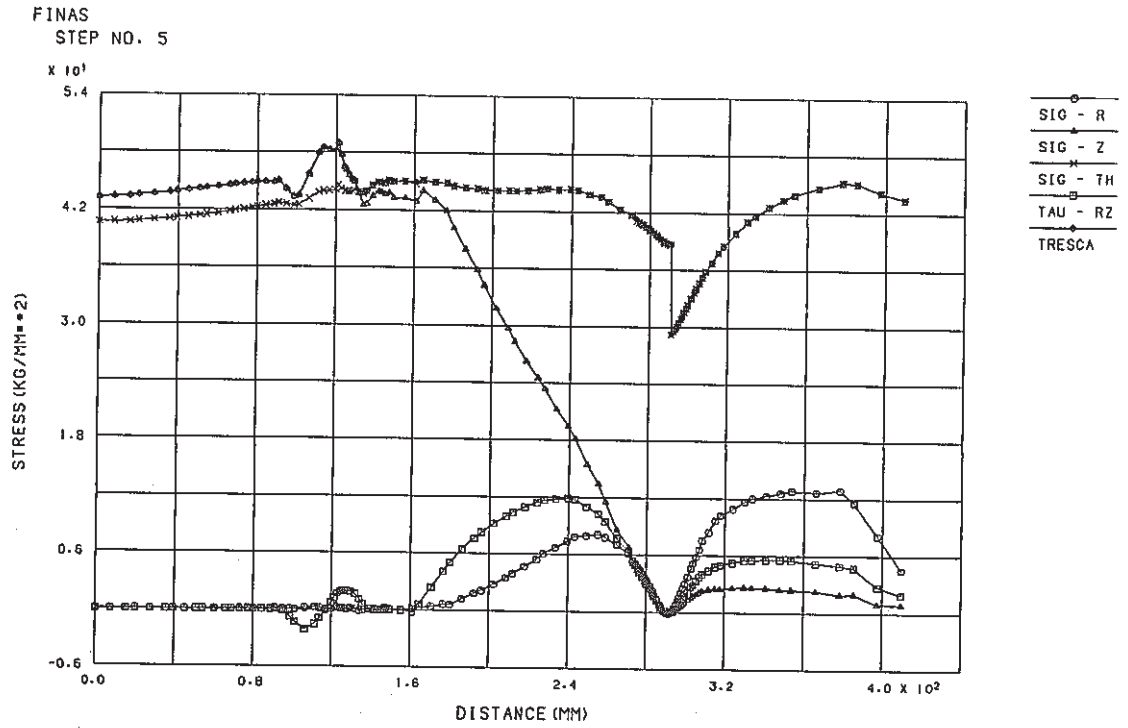


Fig. C.4.2-3 Stress Distribution along Inner Surface at Cold Shock of Conical-Bottom Head (crack depth $a=32$ mm)

FINAS
STEP NO. 3

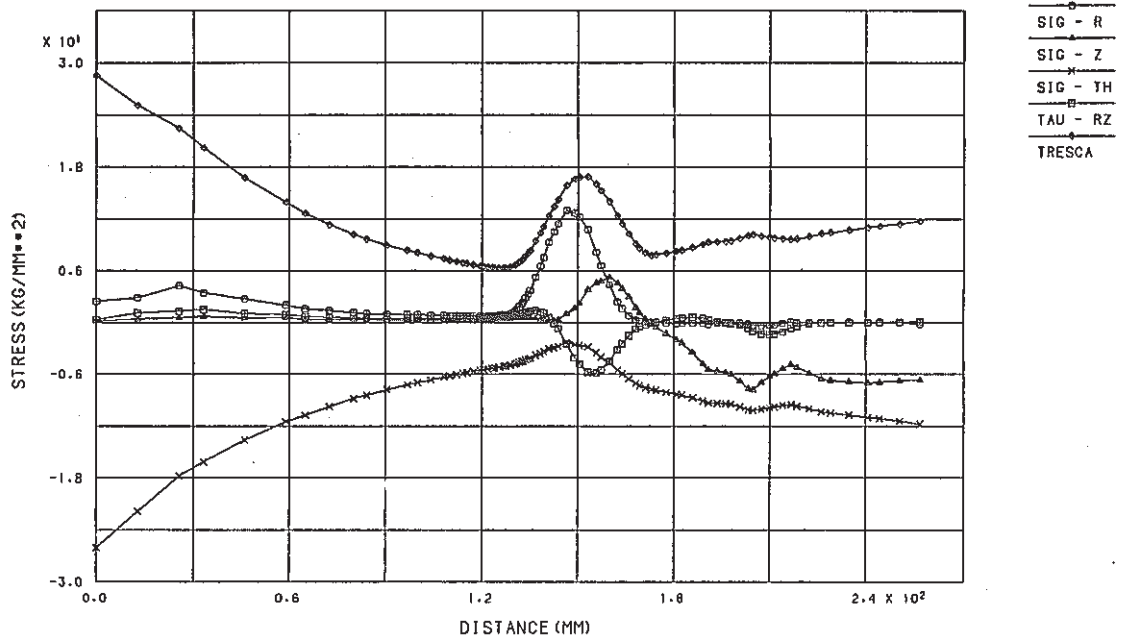


Fig. C.4.3-1 Stress Distribution along Outer-1 Surface at Cold Shock of Conical-Bottom Head (crack depth a=1 mm)

FINAS
STEP NO. 3

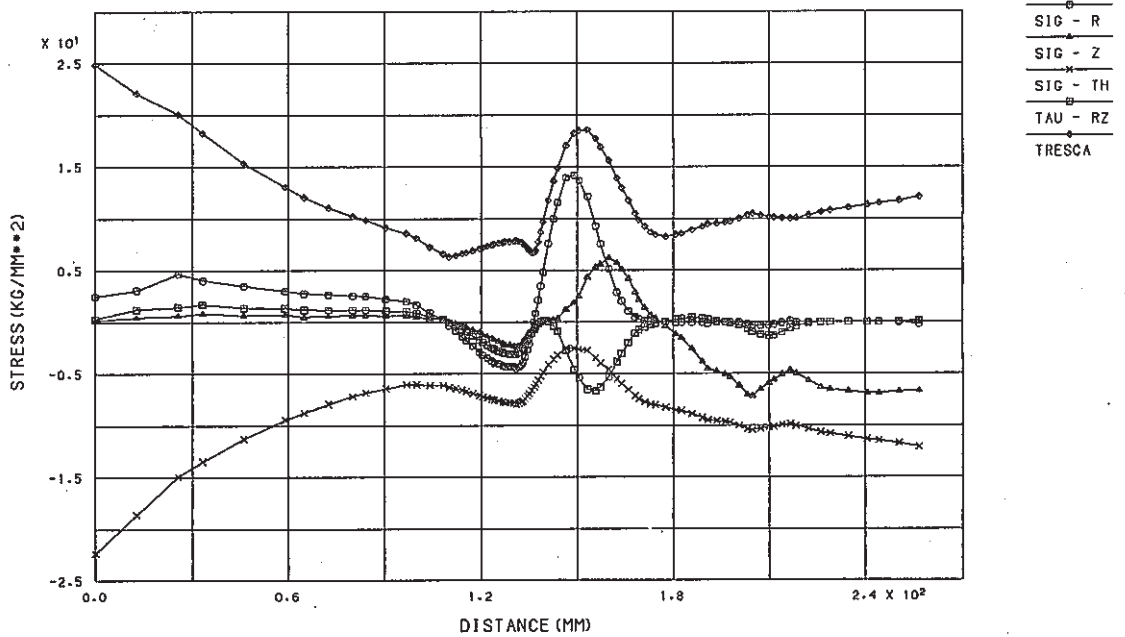


Fig. C.4.3-2 Stress Distribution along Outer-1 Surface at Cold Shock of Conical-Bottom Head (crack depth a=15 mm)

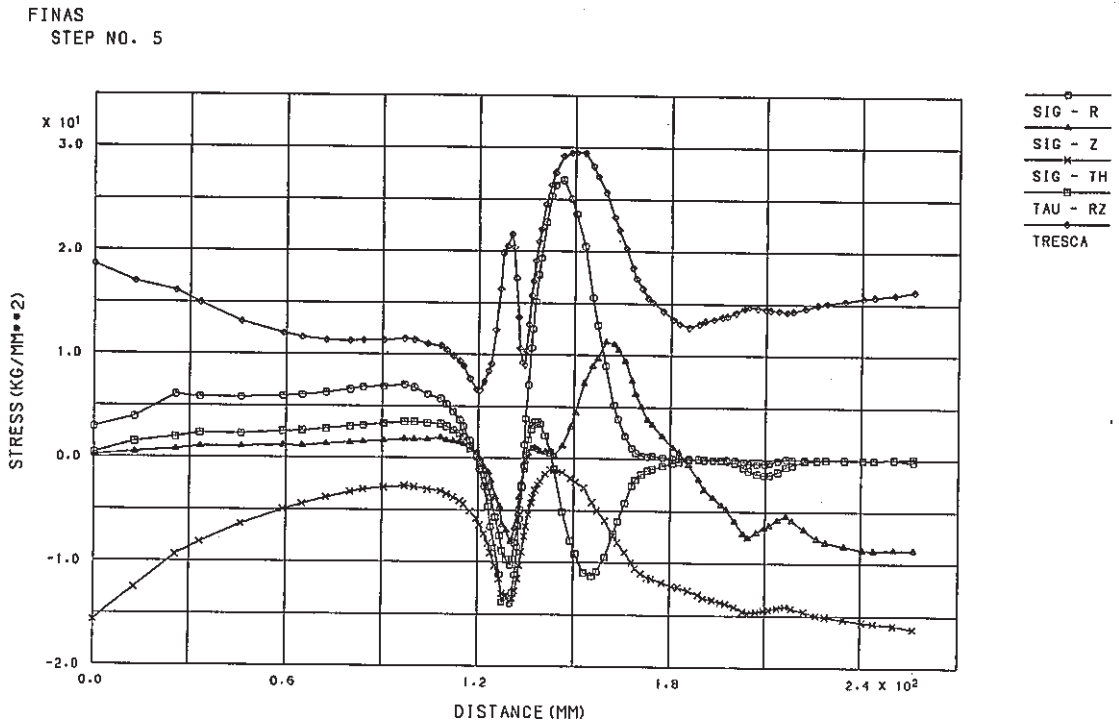


Fig. C.4.3-3 Stress Distribution along Outer-l Surface at Cold Shock of Conical-Bottom Head (crack depth a=32 mm)

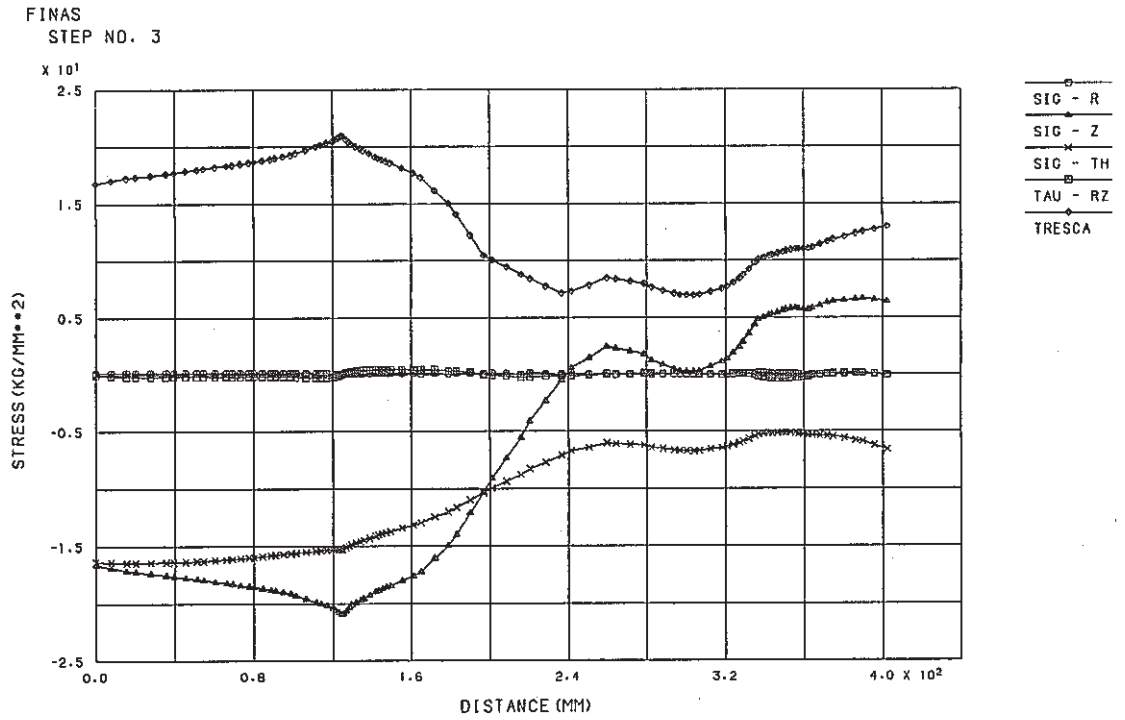


Fig. C.4.4-1 Stress Distribution along Outer-2 Surface at Cold Shock of Conical-Bottom Head (crack depth a=1 mm)

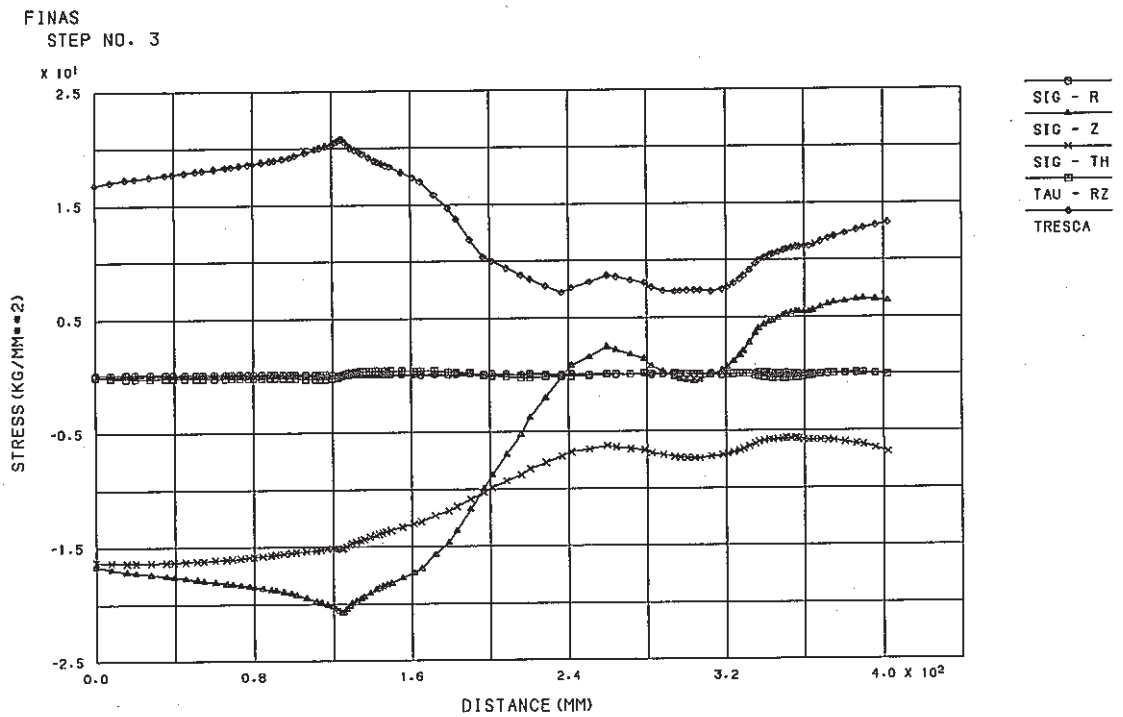


Fig. C.4.4-2 Stress Distribution along Outer-2 Surface at Cold Shock of Conical-Bottom Head (crack depth a=15 mm)

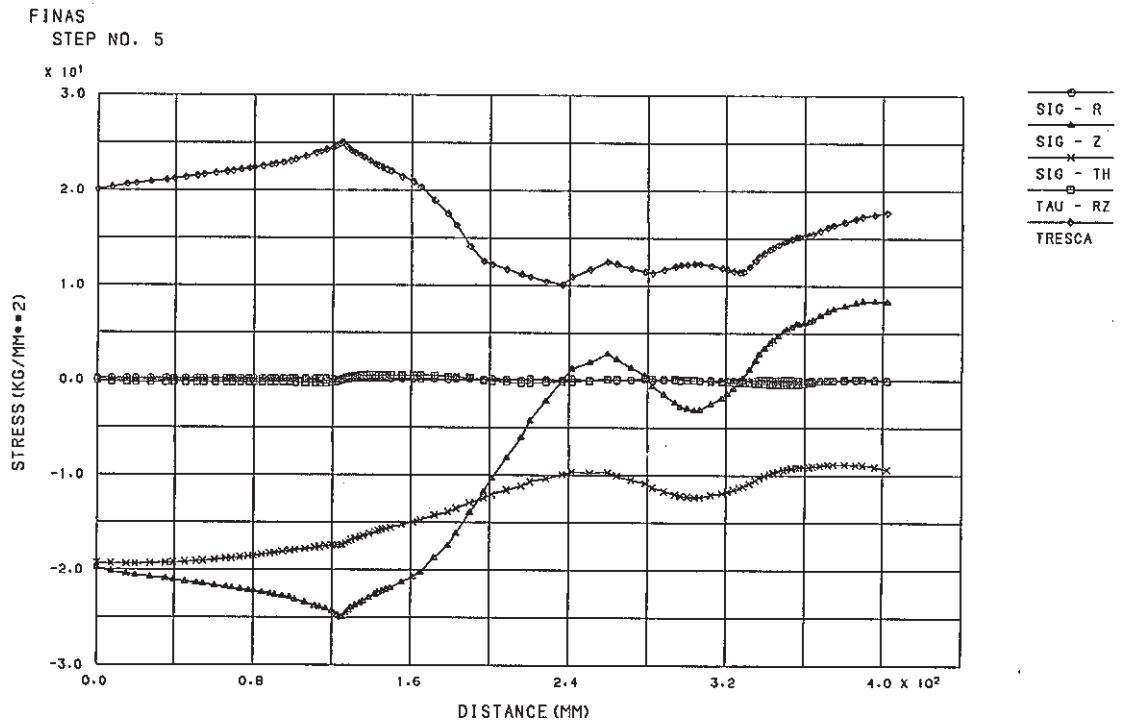


Fig. C.4.4-3 Stress Distribution along Outer-2 Surface at Cold Shock of Conical-Bottom Head (crack depth $a=32$ mm)

FINAS
STEP NO. 3

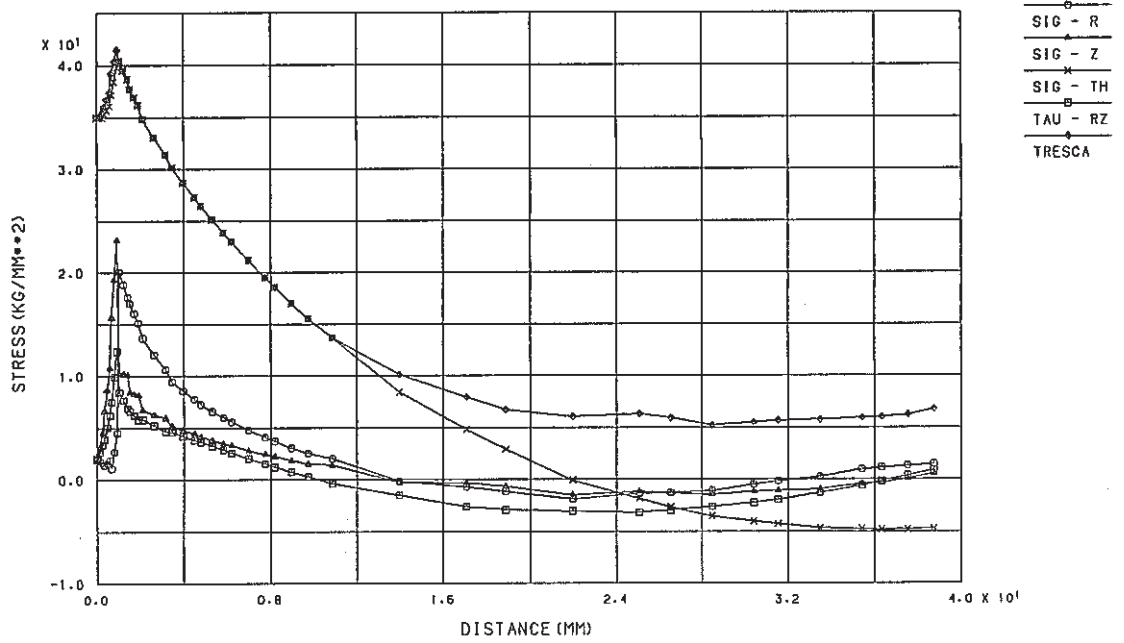


Fig. C.4.5-1 Stress Distribution along Crack Line at Cold Shock of Conical-Bottom Head (crack depth a=1 mm)

FINAS
STEP NO. 3

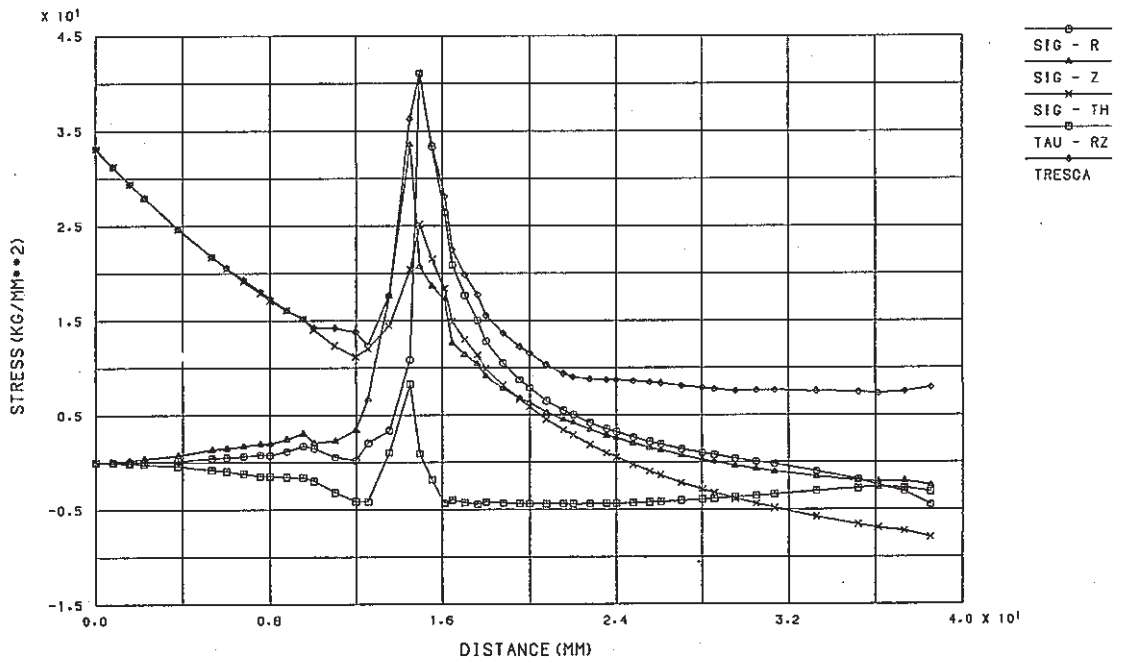


Fig. C.4.5-2 Stress Distribution along Crack Line at Cold Shock of Conical-Bottom Head (crack depth a=15 mm)

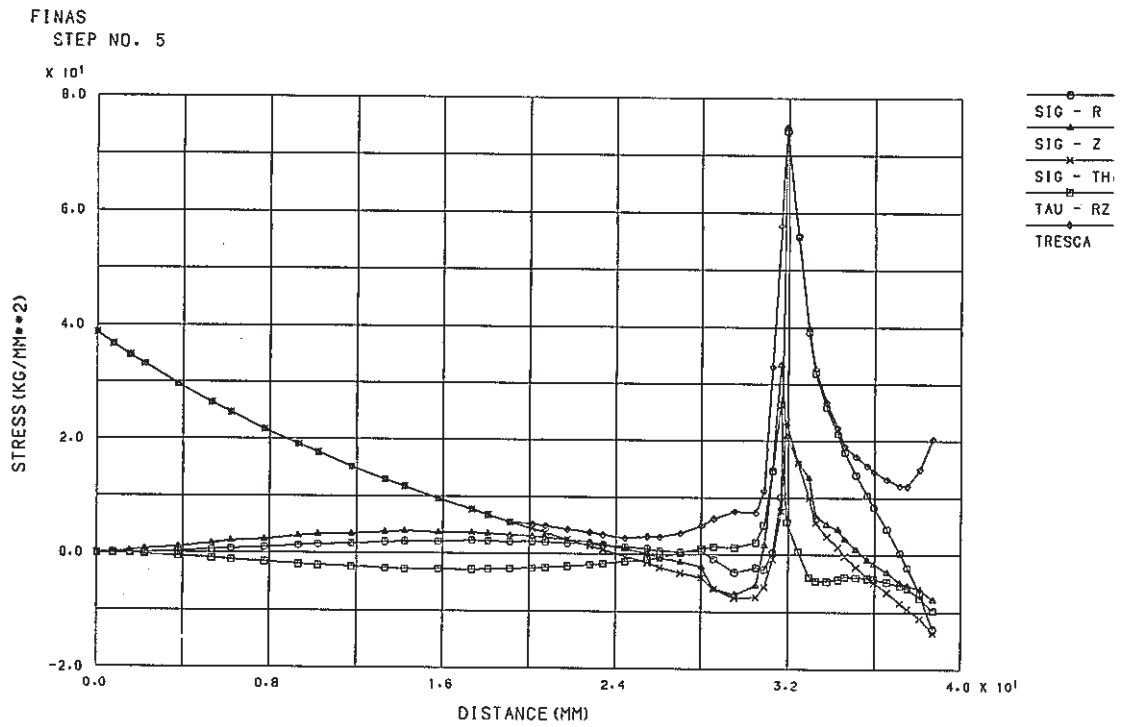


Fig. C.4.5-3 Stress Distribution along Crack Line at Cold Shock of Conical-Bottom Head (crack depth a=32 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-23.3000
2	-16.2000
3	-9.10000
4	-2.00000
5	5.100000
6	12.20000
7	19.30000
8	26.40000
9	33.50000
10	40.60000

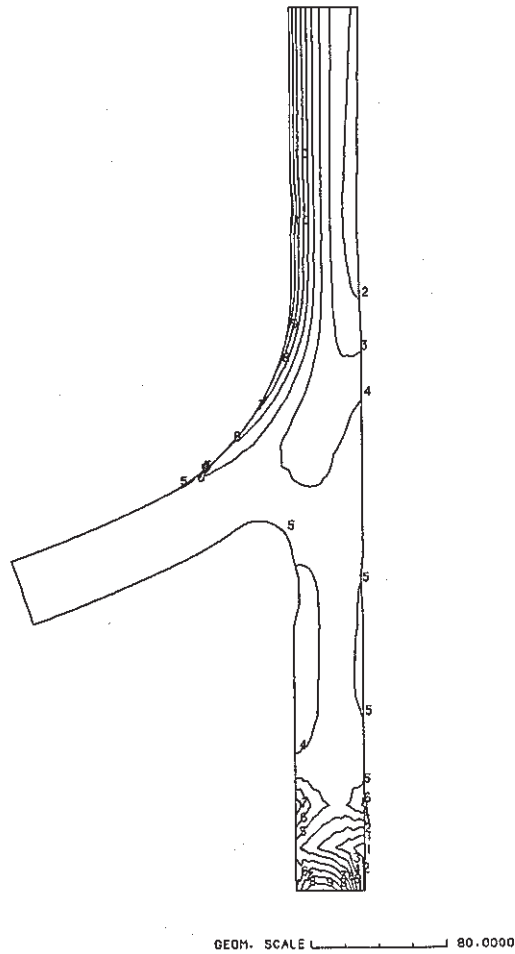


Fig. C.4.6-1
Contour of Axial Stress at Cold Shock of
Conical-Bottom Head
(crack depth $a=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-23.0000
2	-15.9000
3	-8.80000
4	-1.70000
5	5.400000
6	12.50000
7	19.60000
8	26.70000
9	33.80000
10	40.90000

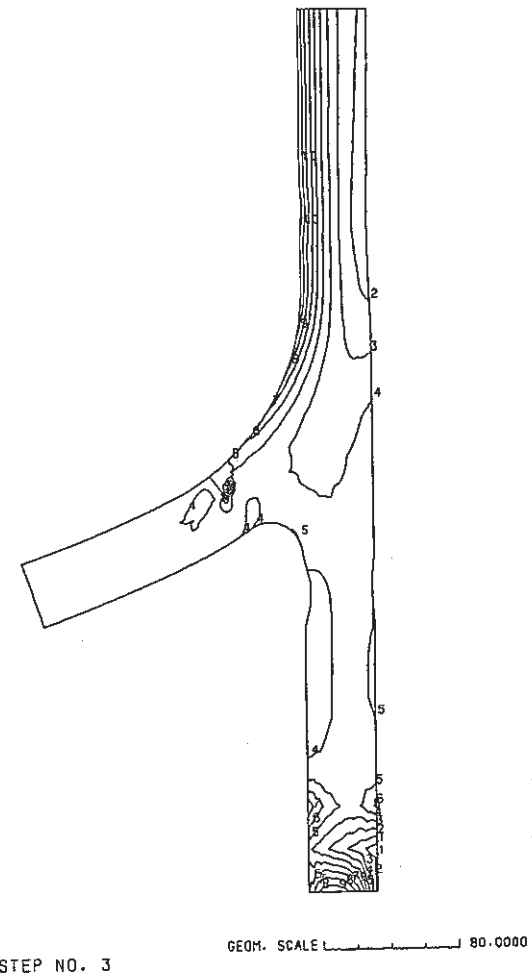


Fig. C.4.6-2
Contour of Axial Stress at Cold Shock of
Conical-Bottom Head
(crack depth $a=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-25.4000
2	-17.5000
3	-9.60000
4	-1.70000
5	6.200000
6	14.10000
7	22.00000
8	29.90000
9	37.80000
10	45.70000

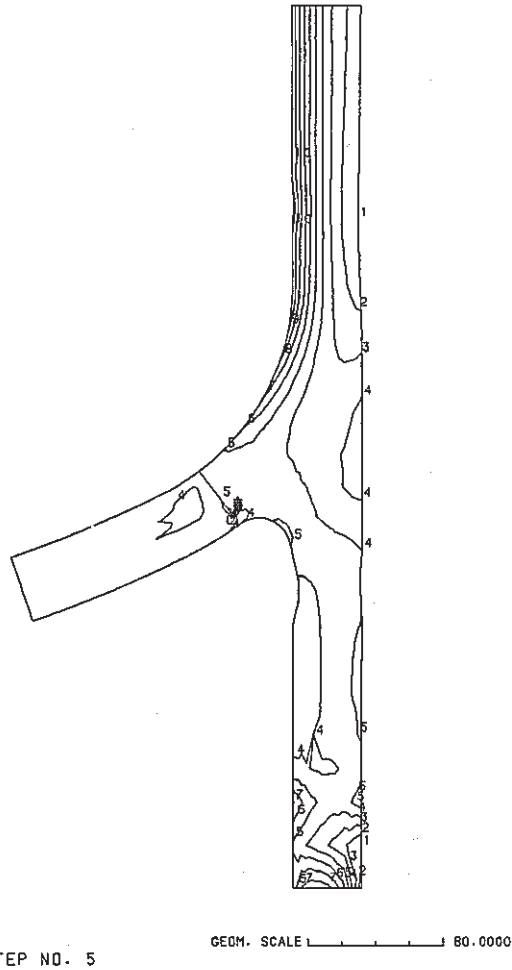


Fig. C.4.6-3
Contour of Axial Stress at Cold Shock of
Conical-Bottom Head
(crack depth $a=32$ mm)

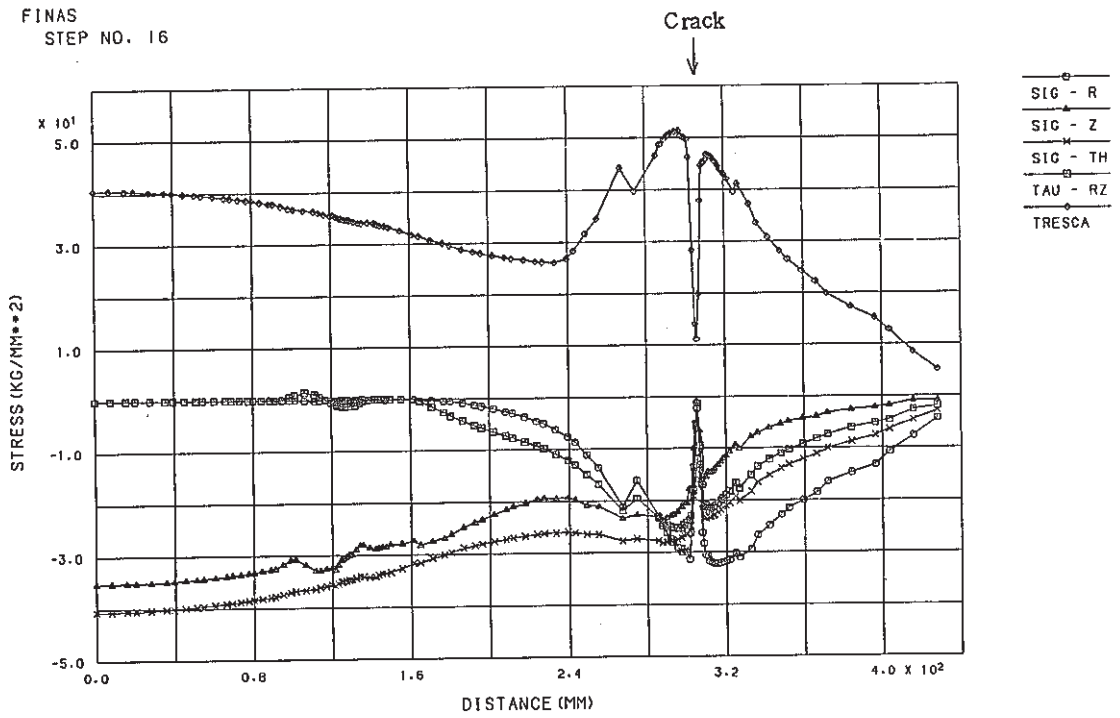


Fig. C.4.7-1 Stress Distribution along Inner Surface at Hot Shock of Conical-Bottom Head (crack depth a=1 mm)

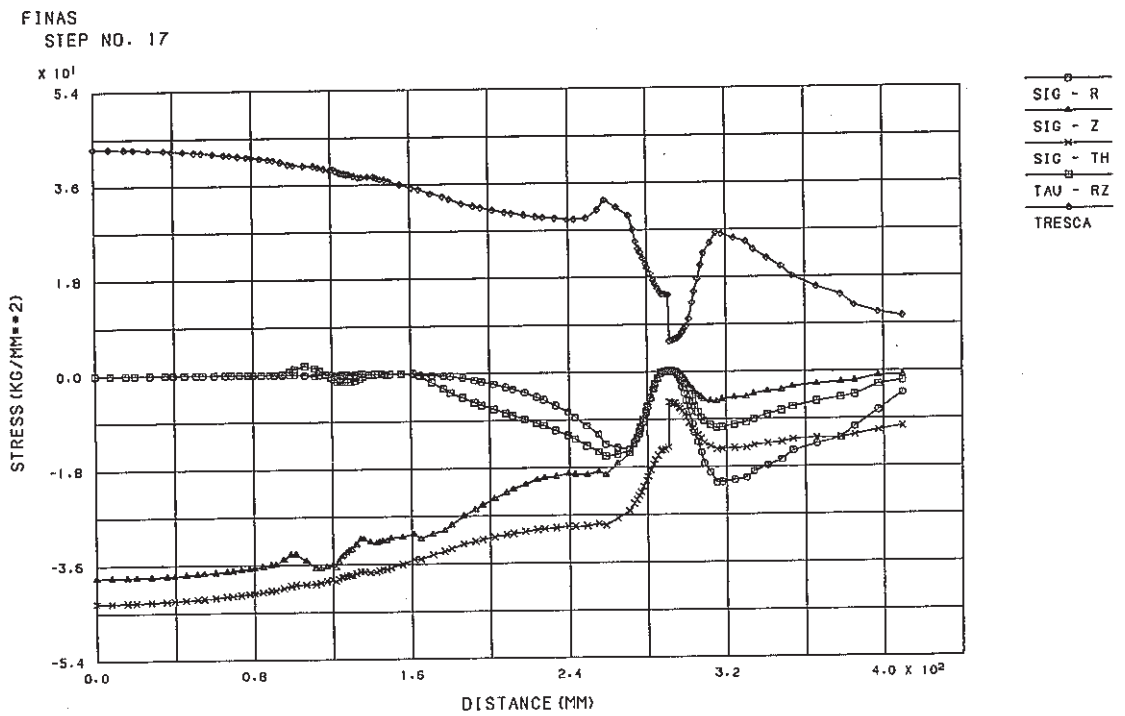


Fig. C.4.7-2 Stress Distribution along Inner Surface at Hot Shock of Conical-Bottom Head (crack depth a=15 mm)

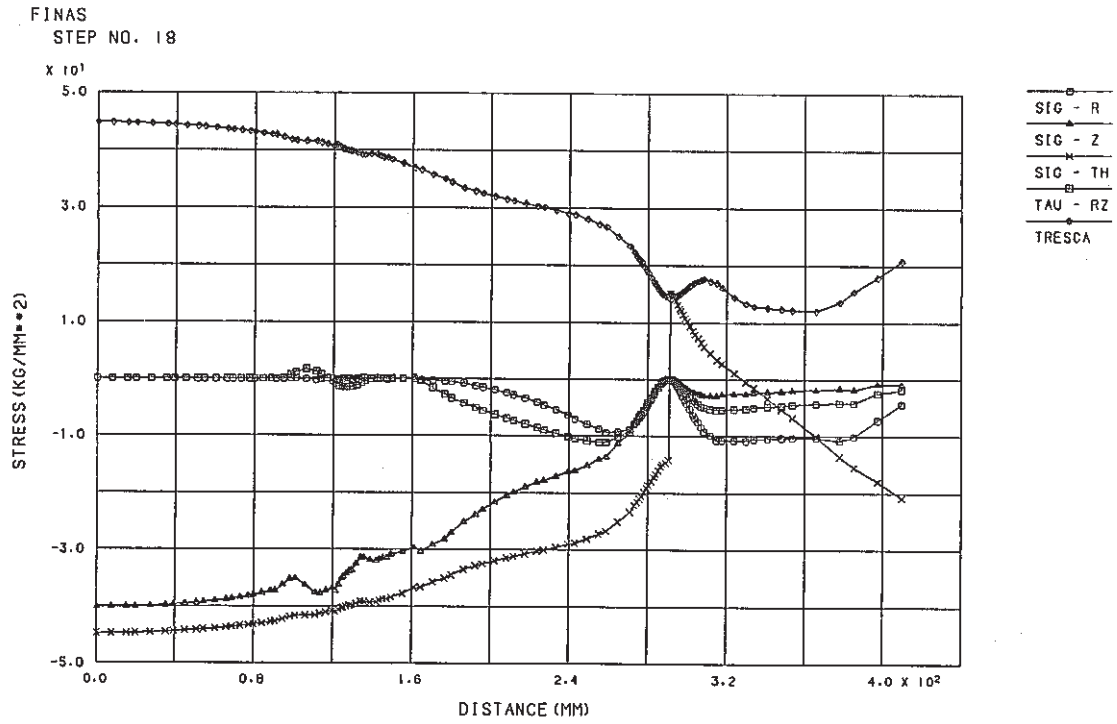


Fig. C.4.7-3 Stress Distribution along Inner Surface at Hot Shock of Conical-Bottom Head (crack depth a=32 mm)

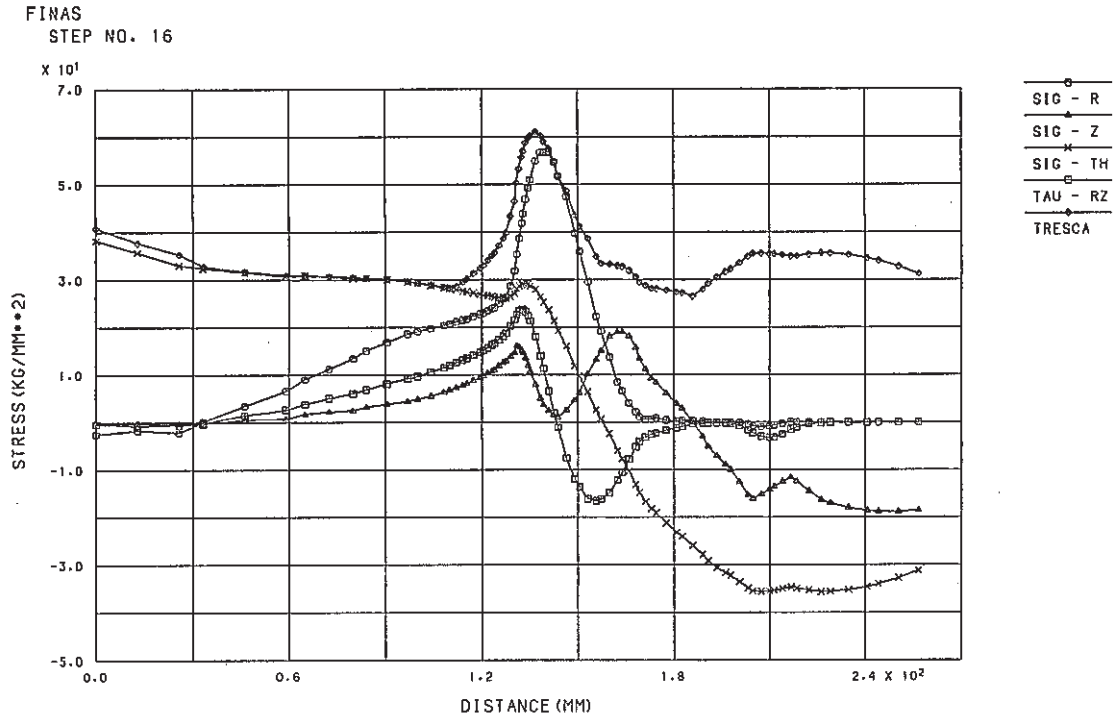


Fig. C.4.8-1 Stress Distribution along Outer-1 Surface at Hot Shock of Conical-Bottom Head (crack depth a=1 mm)

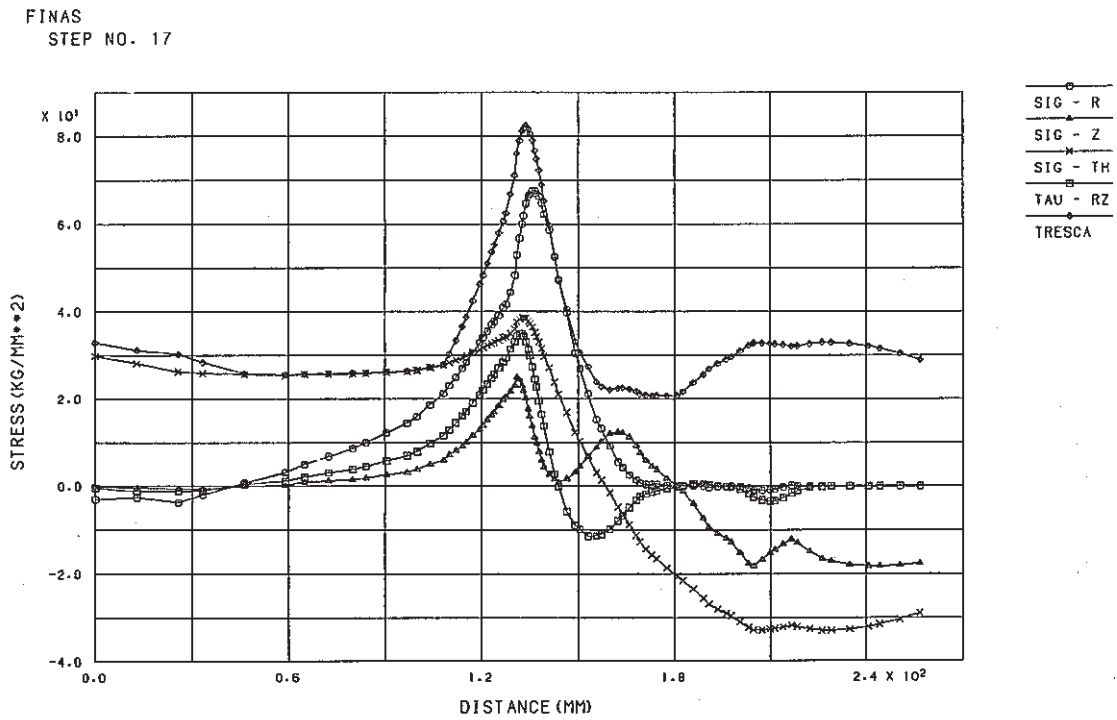


Fig. C.4.8-2 Stress Distribution along Outer-1 Surface at Hot Shock of Conical-Bottom Head (crack depth a=15 mm)

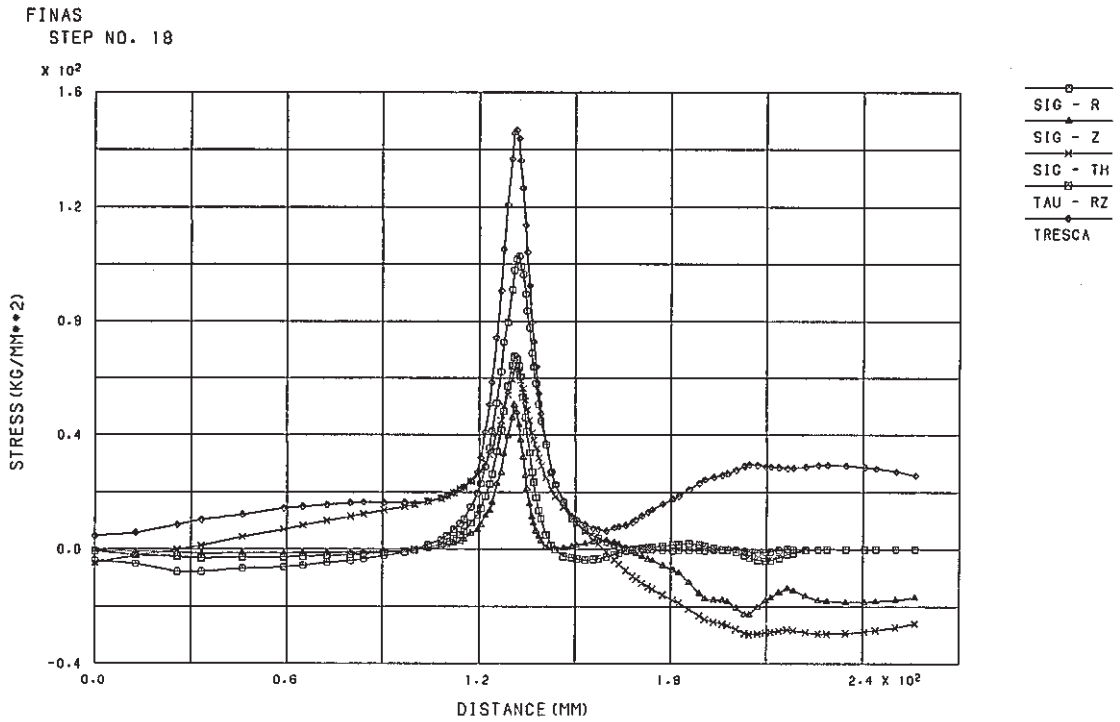


Fig. C.4.8-3 Stress Distribution along Outer-l Surface at Hot Shock of Conical-Bottom Head (crack depth a=32 mm)

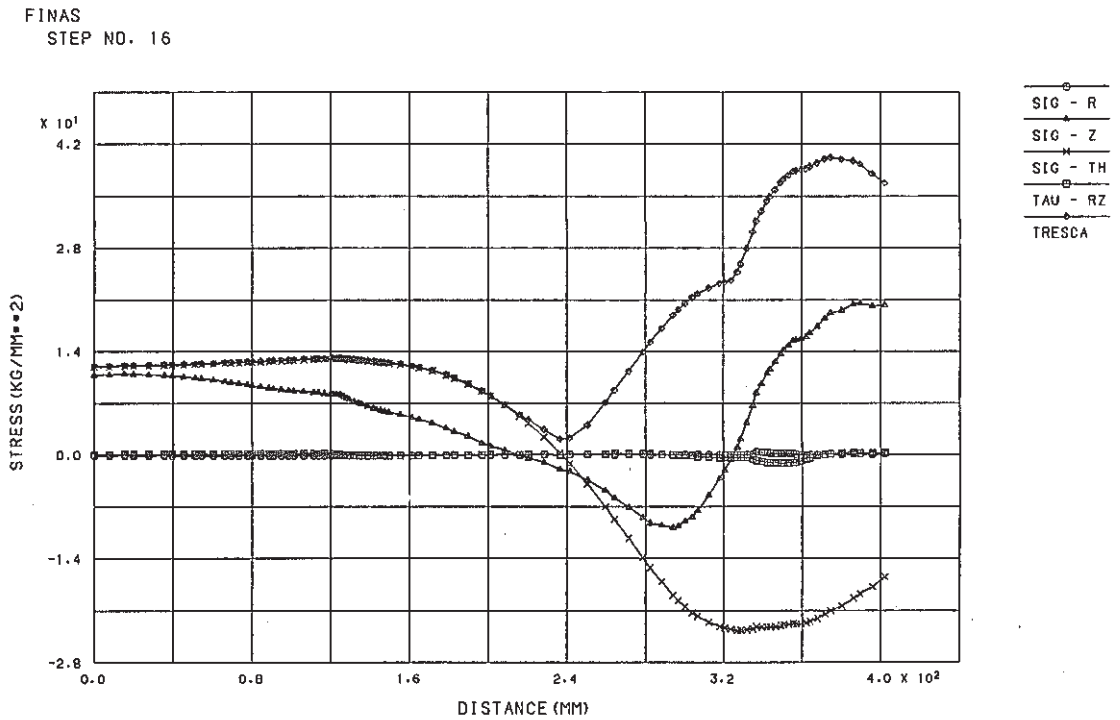


Fig. C.4.9-1 Stress Distribution along Outer-2 Surface at Hot Shock of Conical-Bottom Head (crack depth a=1 mm)

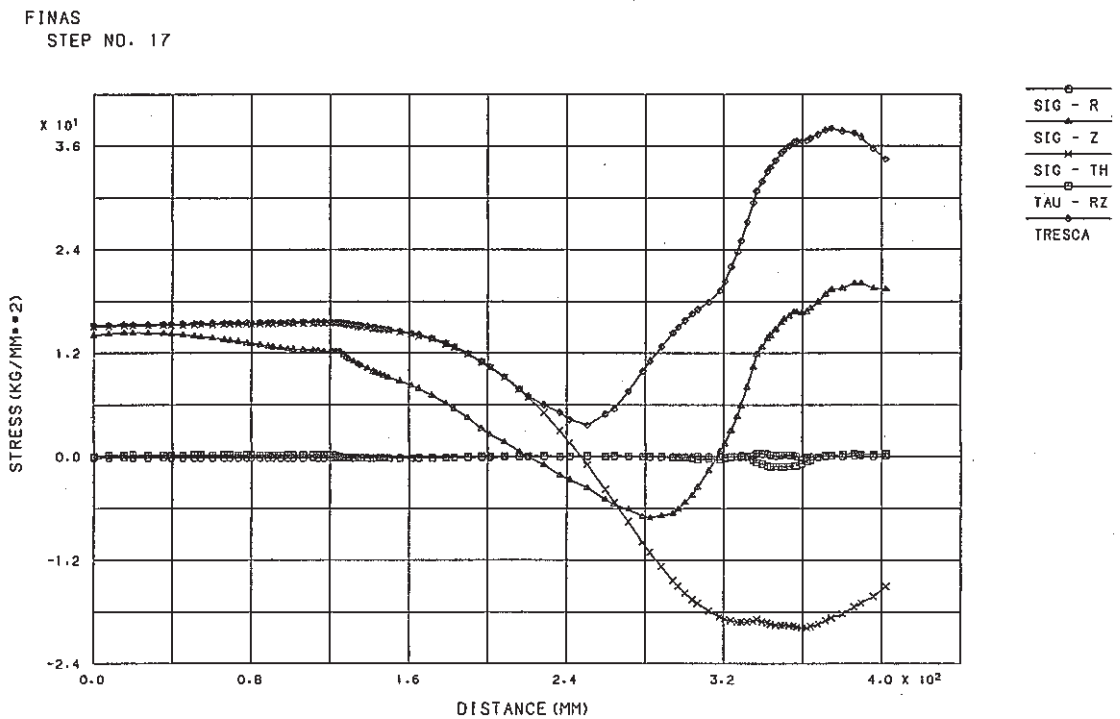


Fig. C.4.9-2 Stress Distribution along Outer-2 Surface at Hot Shock of Conical-Bottom Head (crack depth a=15 mm)

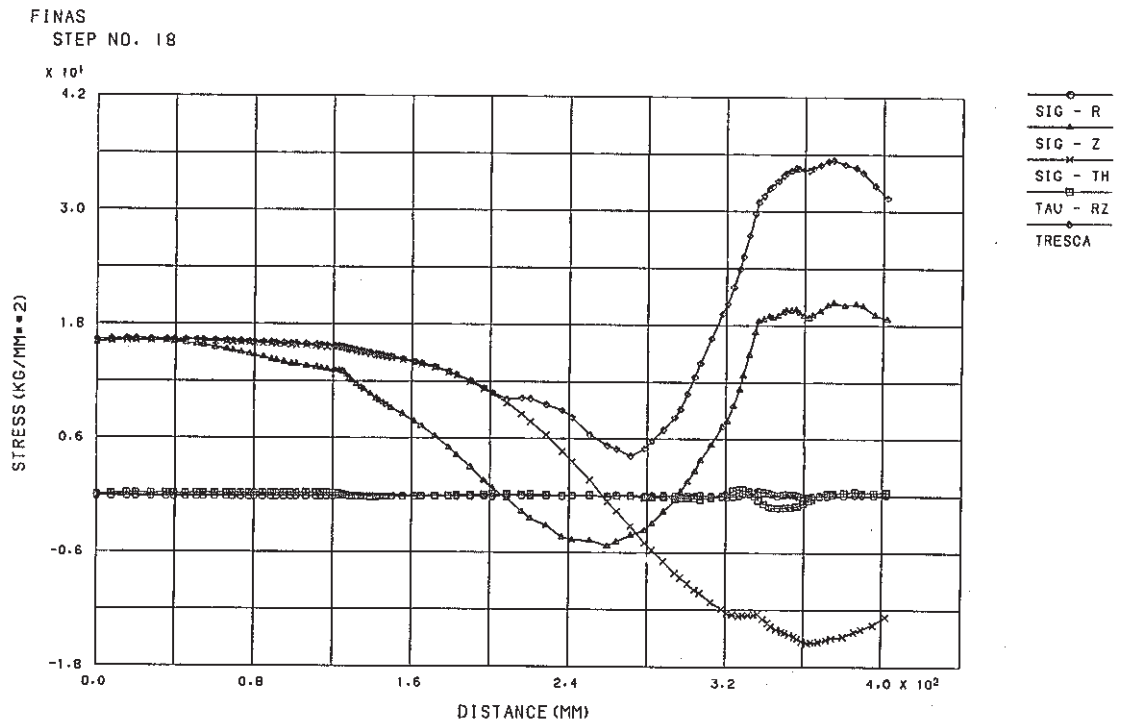


Fig. C.4.9-3 Stress Distribution along Outer-2 Surface at Hot Shock of Conical-Bottom Head (crack depth $a=32$ mm)

FINAS
STEP NO. 16

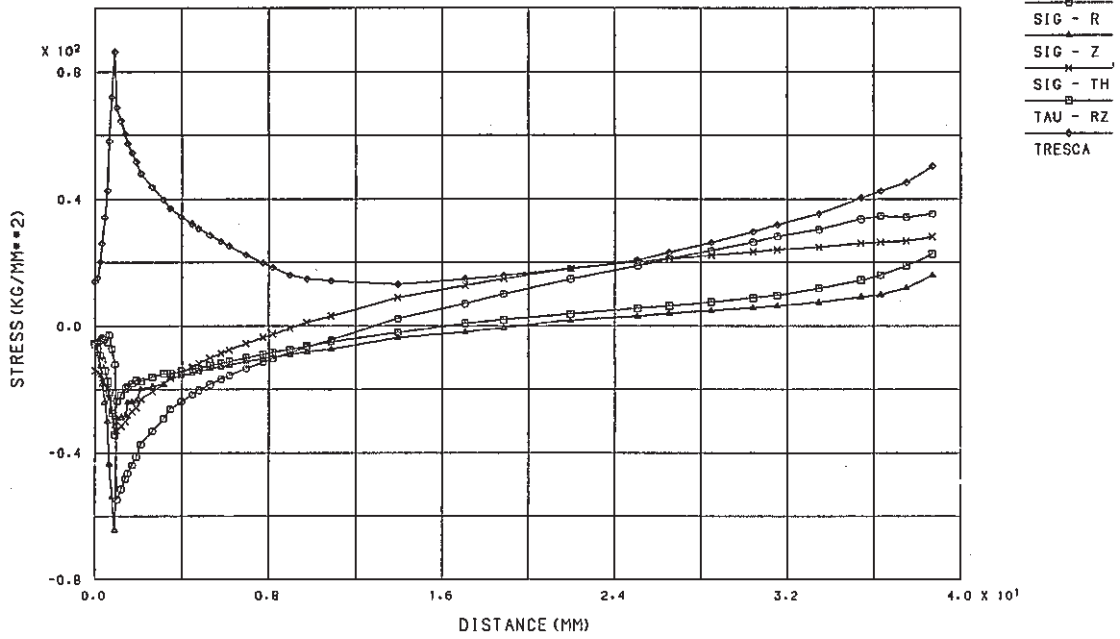


Fig. C.4.10-1 Stress Distribution along Crack Line at Hot Shock of Conical-Bottom Head (crack depth a=1 mm)

FINAS
STEP NO. 17

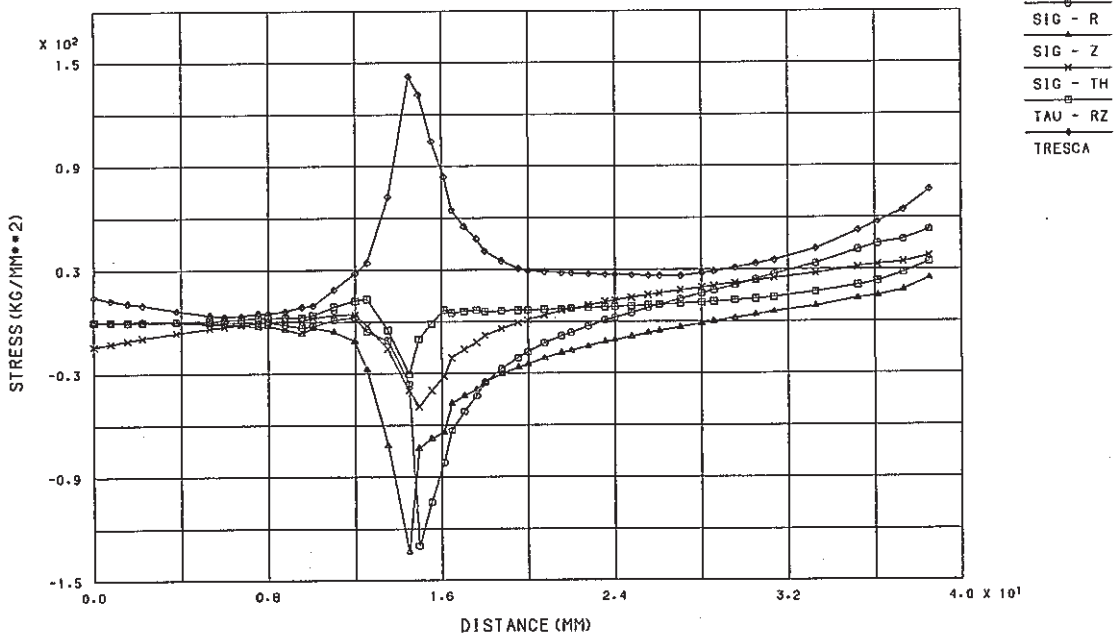


Fig. C.4.10-2 Stress Distribution along Crack Line at Hot Shock of Conical-Bottom Head (crack depth a=15 mm)

FINAS
STEP NO. 18

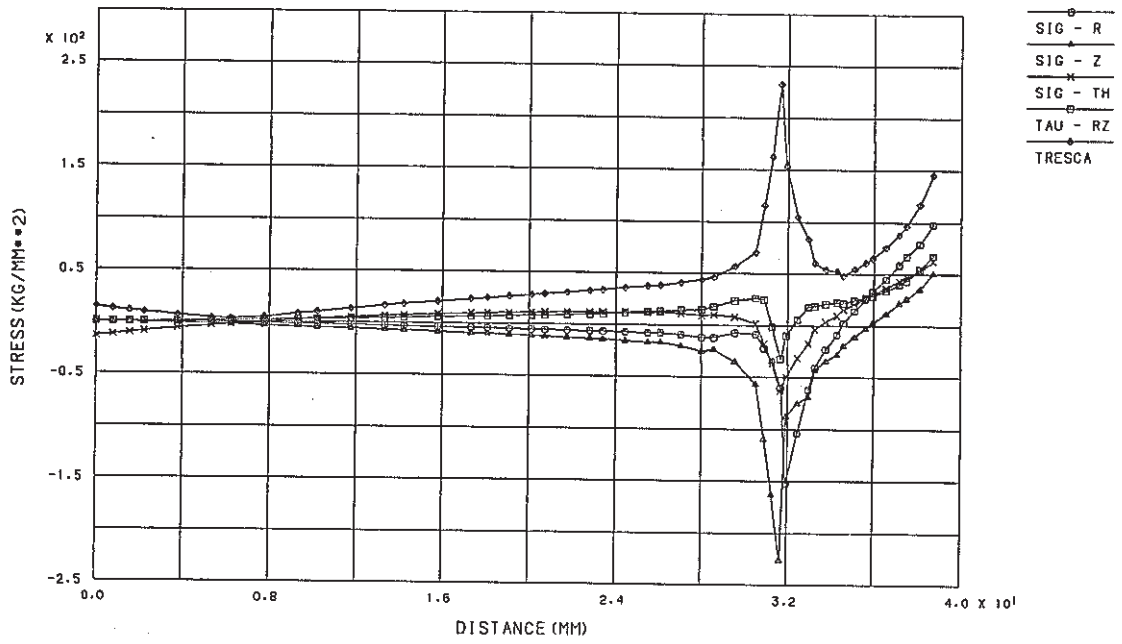
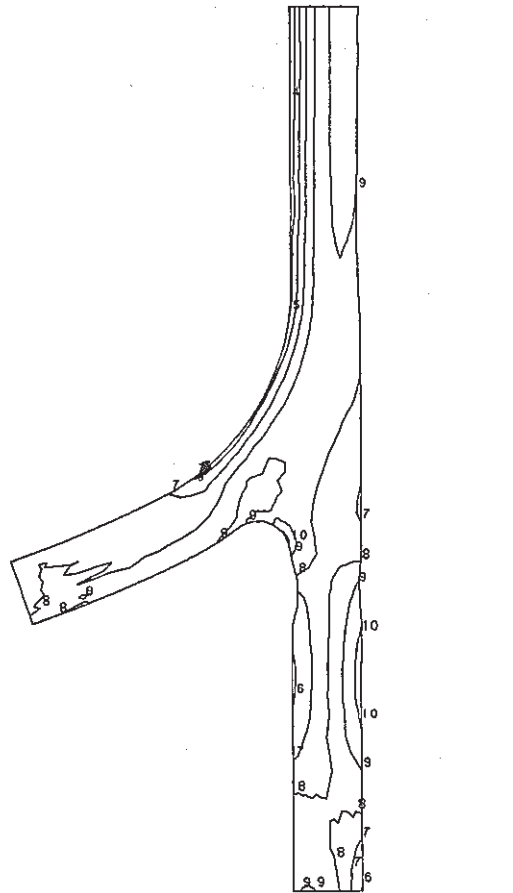


Fig. C.4.10-3 Stress Distribution along Crack Line at Hot Shock of Conical-Bottom Head (crack depth a=32 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-61.2000
2	-52.5000
3	-43.8000
4	-35.1000
5	-26.4000
6	-17.7000
7	-9.00000
8	-0.30000
9	8.400000
10	17.10000



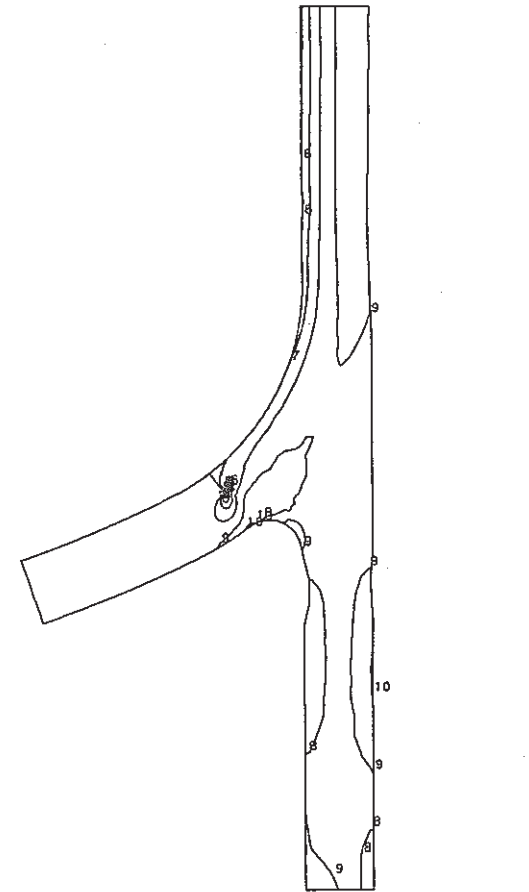
STEP NO. 16

Fig. C.4.11-1
Contour of Axial Stress at Hot Shock of
Conical-Bottom Head
(crack depth $a=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-106.000
2	-92.0000
3	-78.0000
4	-64.0000
5	-50.0000
6	-36.0000
7	-22.0000
8	-8.00000
9	6.000000
10	20.00000



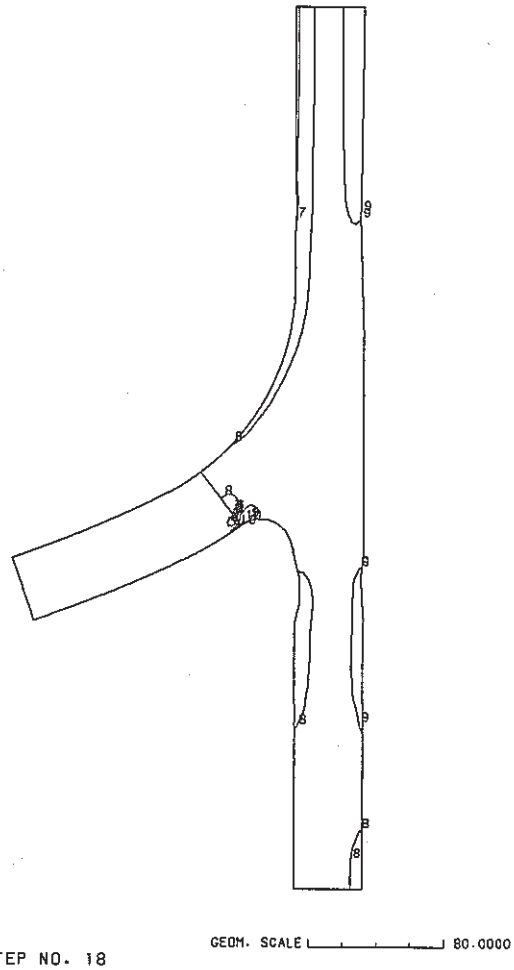
STEP NO. 17

Fig. C.4.11-2
Contour of Axial Stress at Hot Shock of
Conical-Bottom Head
(crack depth $a=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-179.000
2	-155.000
3	-131.000
4	-107.000
5	-83.0000
6	-59.0000
7	-35.0000
8	-11.0000
9	13.00000
10	37.00000



-281-

Fig. C.4.11-3
Contour of Axial Stress at Hot Shock of
Conical-Bottom Head
(crack depth a=32 mm)

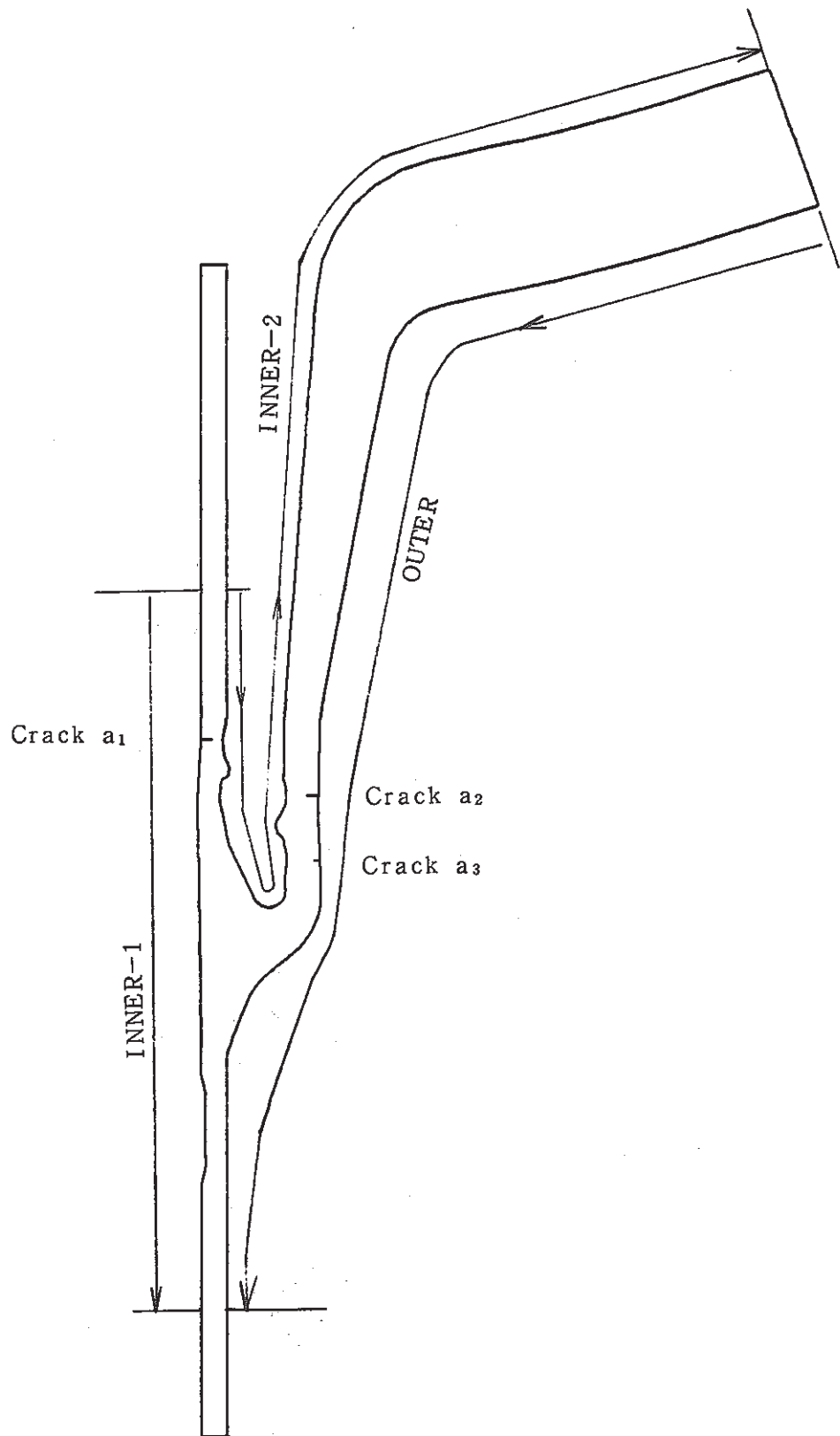


Fig. C.5-1 Evaluation Lines for Surface Stress Distribution of Outlet Nozzle

FINAS

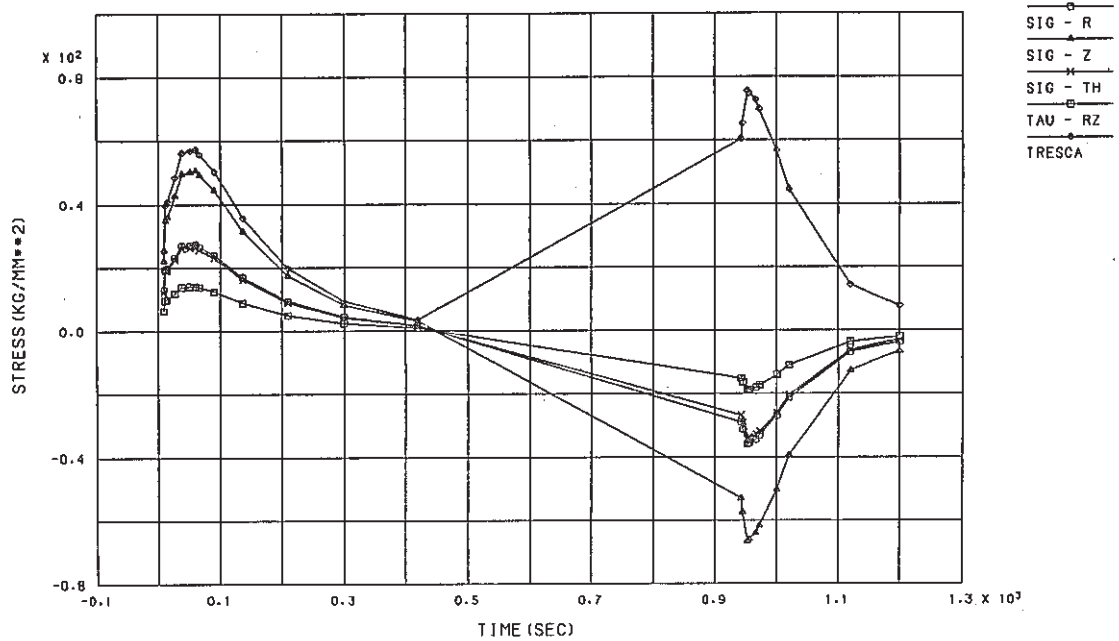


Fig. C.5.1-1 Stress History ahead of Crack Tip of Outlet Nozzle, crack a_1 (crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

FINAS

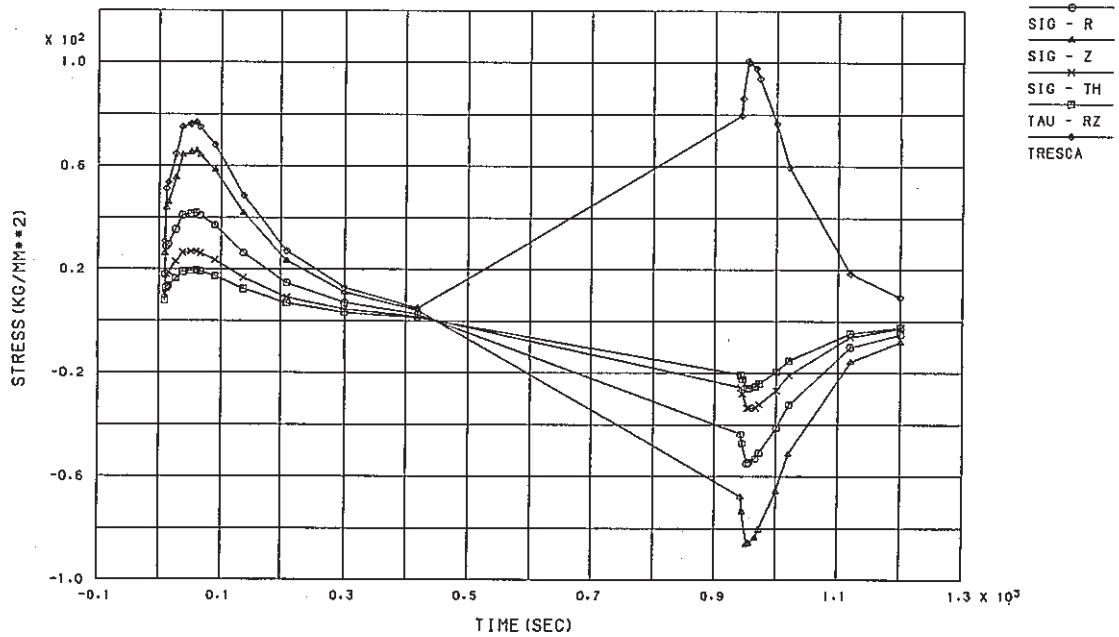


Fig. C.5.1-2 Stress History ahead of Crack Tip of Outlet Nozzle, crack a_1 (crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

FINAS

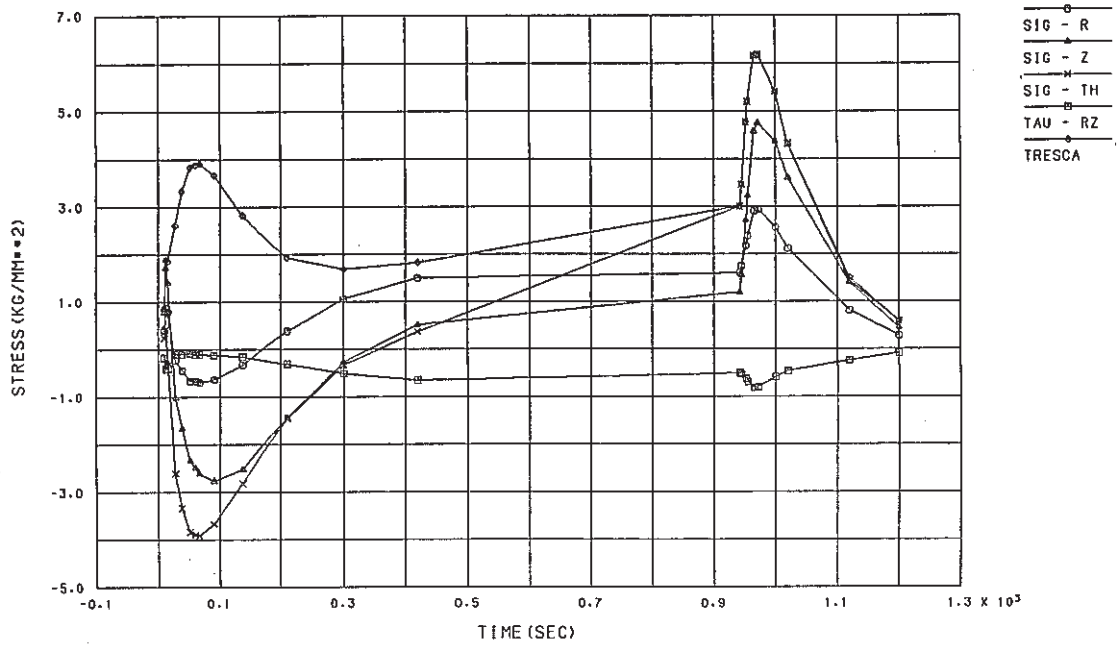


Fig. C.5.2-1 Stress History ahead of Crack Tip of Outlet Nozzle, crack a₂
(crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

FINAS

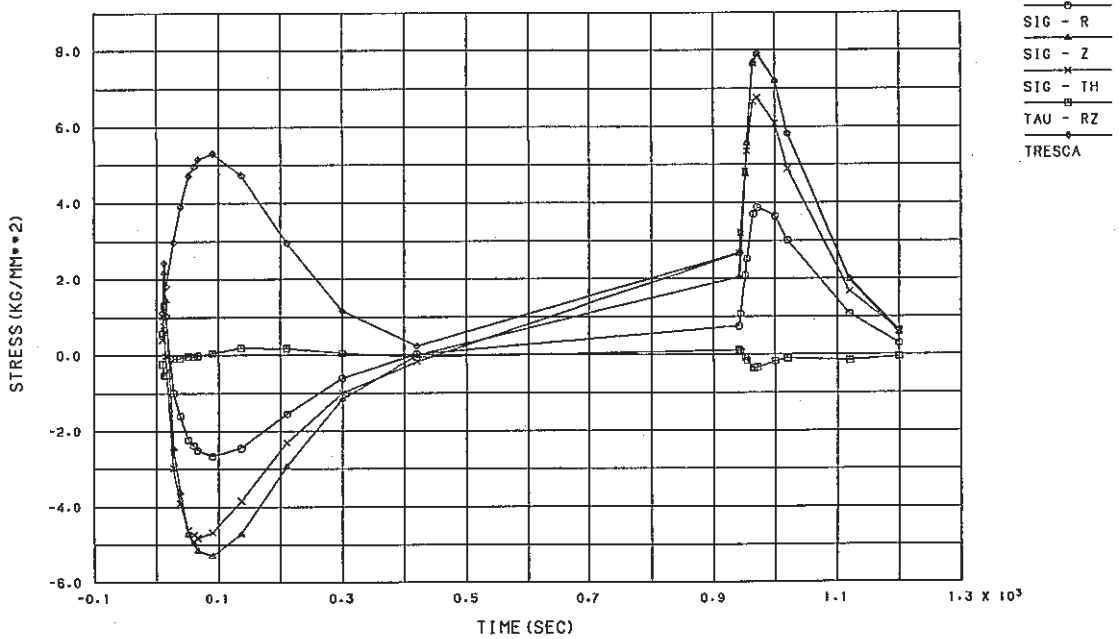


Fig. C.5.2-2 Stress History ahead of Crack Tip of Outlet Nozzle, crack a₂
(crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

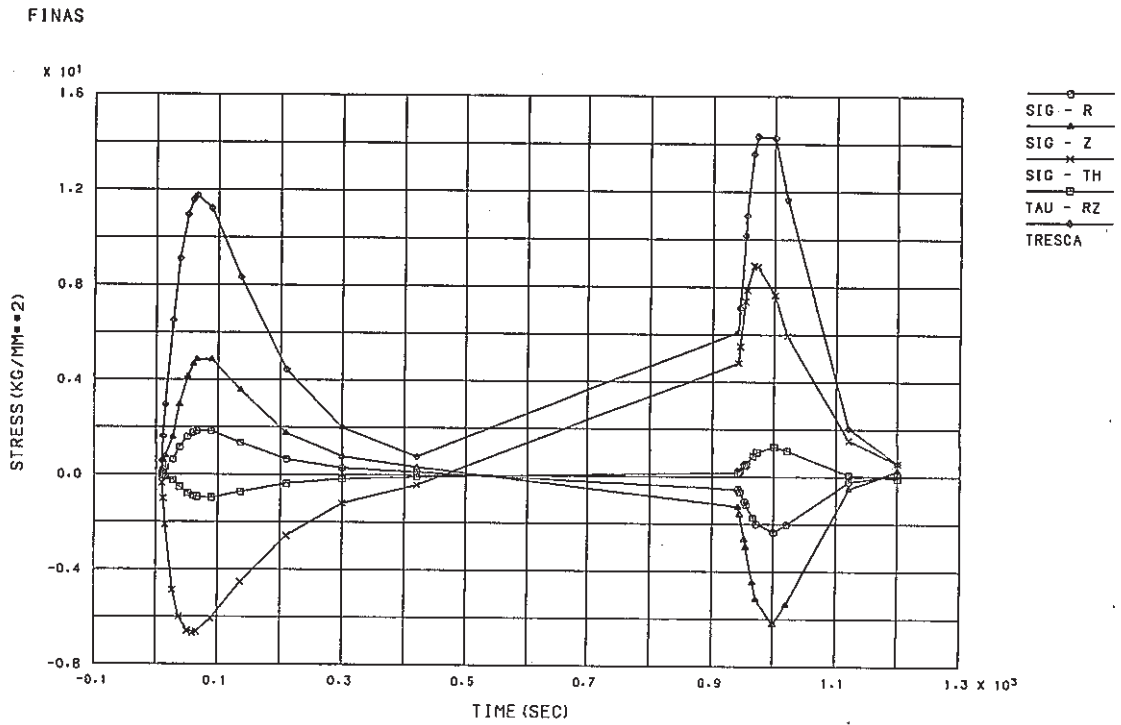


Fig. C.5.3-1 Stress History ahead of Crack Tip of Outlet Nozzle, crack a₃ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

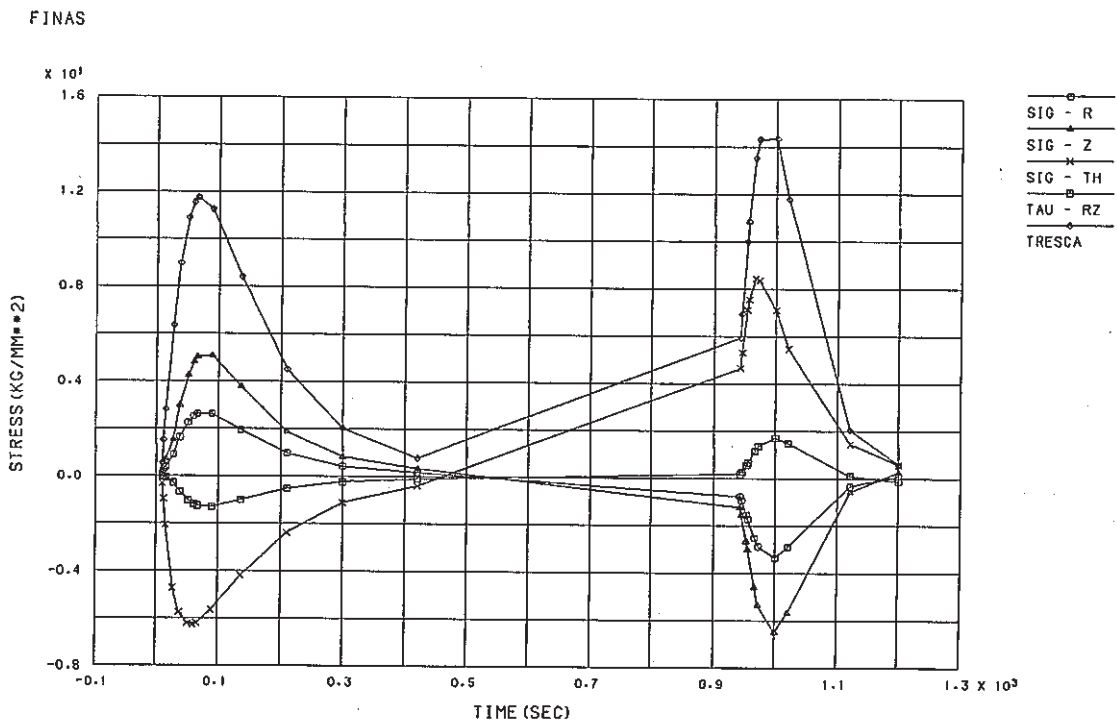


Fig. C.5.3-2 Stress History ahead of Crack Tip of Outlet Nozzle, crack a₃ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

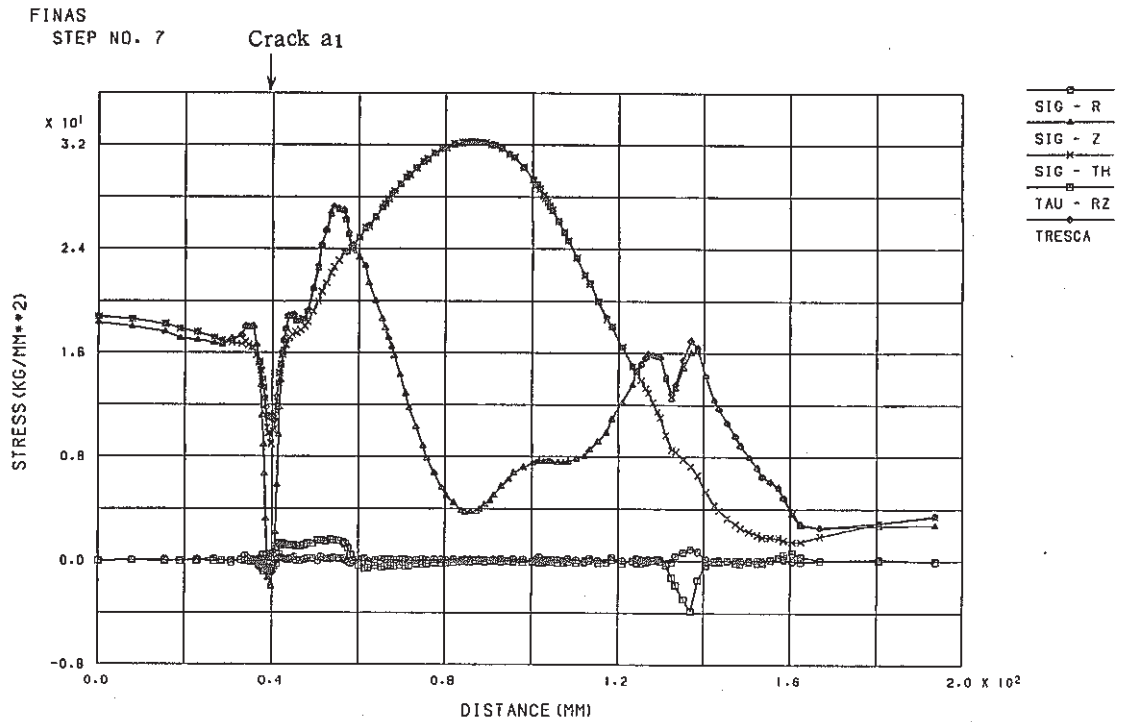


Fig. C.5.4-1 Stress Distribution along Inner-1 Surface at Cold Shock of Outlet Nozzle
(crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

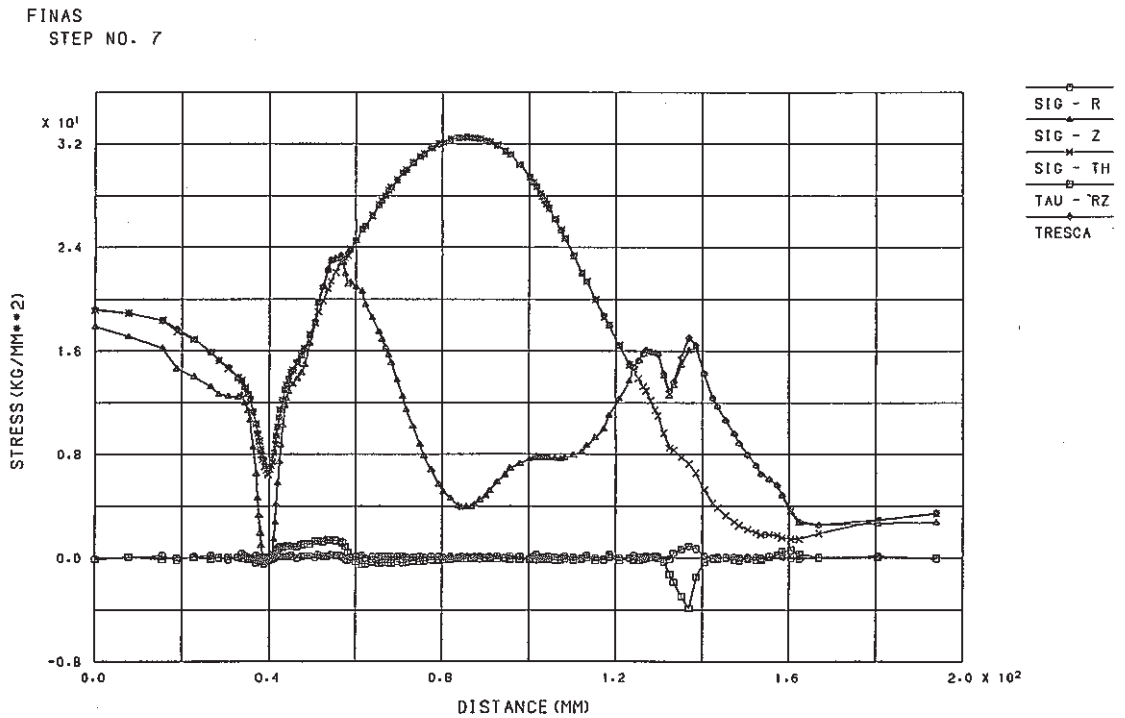


Fig. C.5.4-2 Stress Distribution along Inner-1 Surface at Cold Shock of Outlet Nozzle
(crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

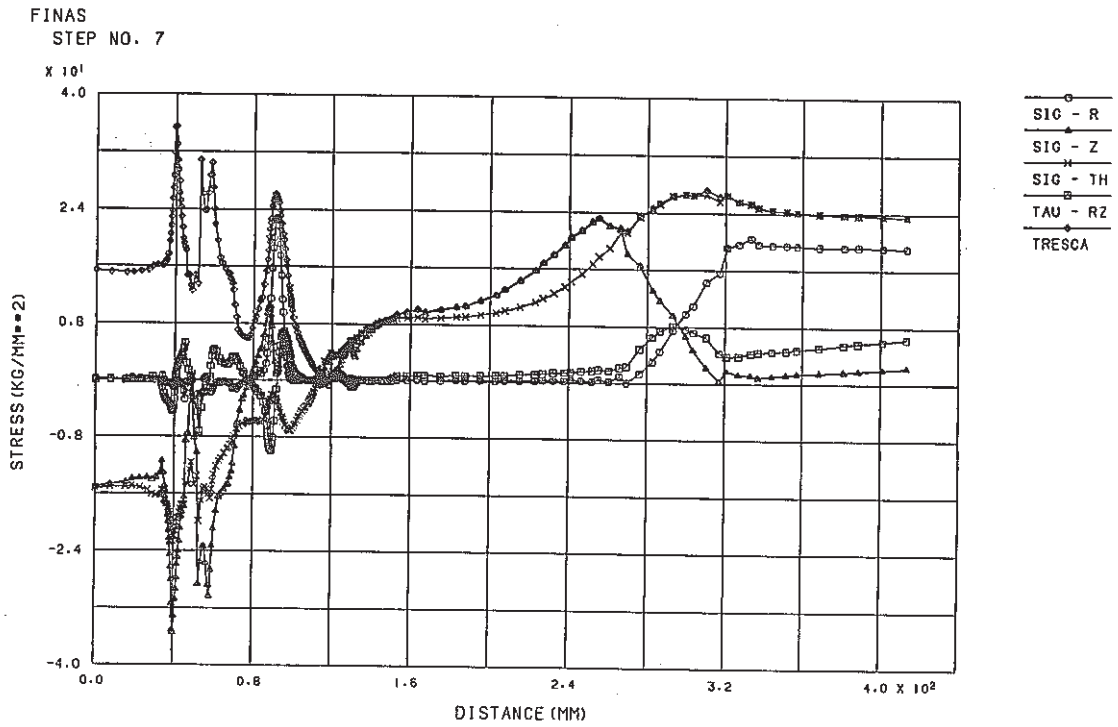


Fig. C.5.5-1 Stress Distribution along Inner-2 Surface at Cold Shock of Outlet Nozzle
(crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

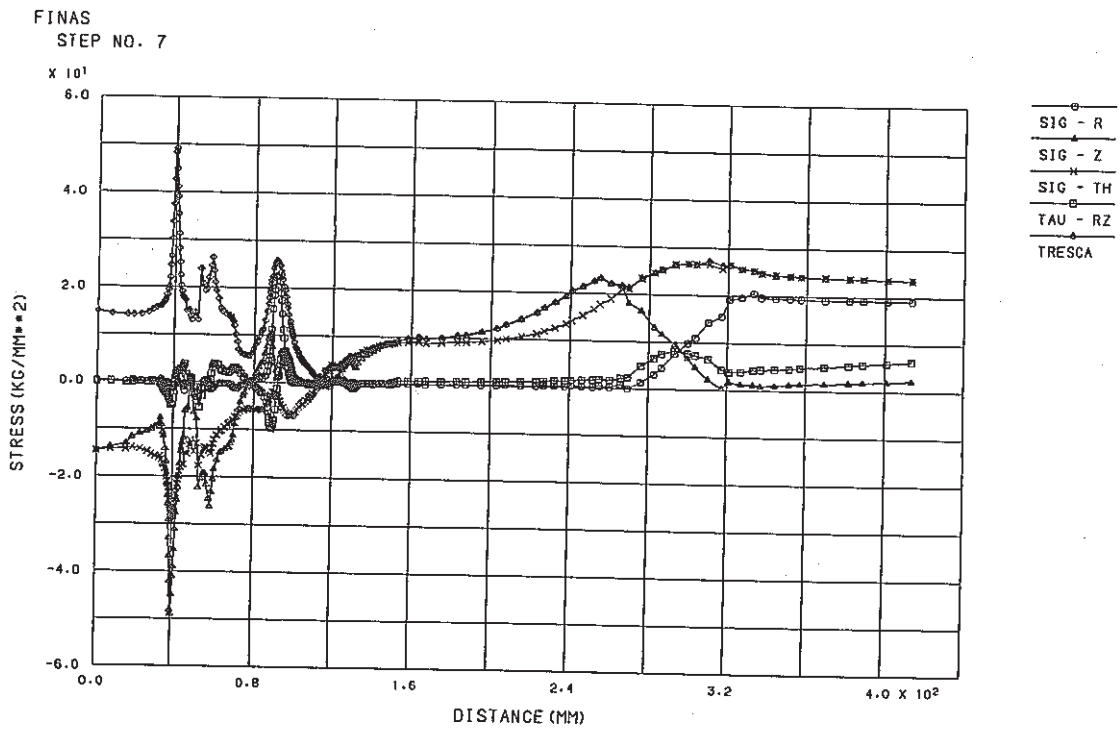


Fig. C.5.5-2 Stress Distribution along Inner-2 Surface at Cold Shock of Outlet Nozzle
(crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

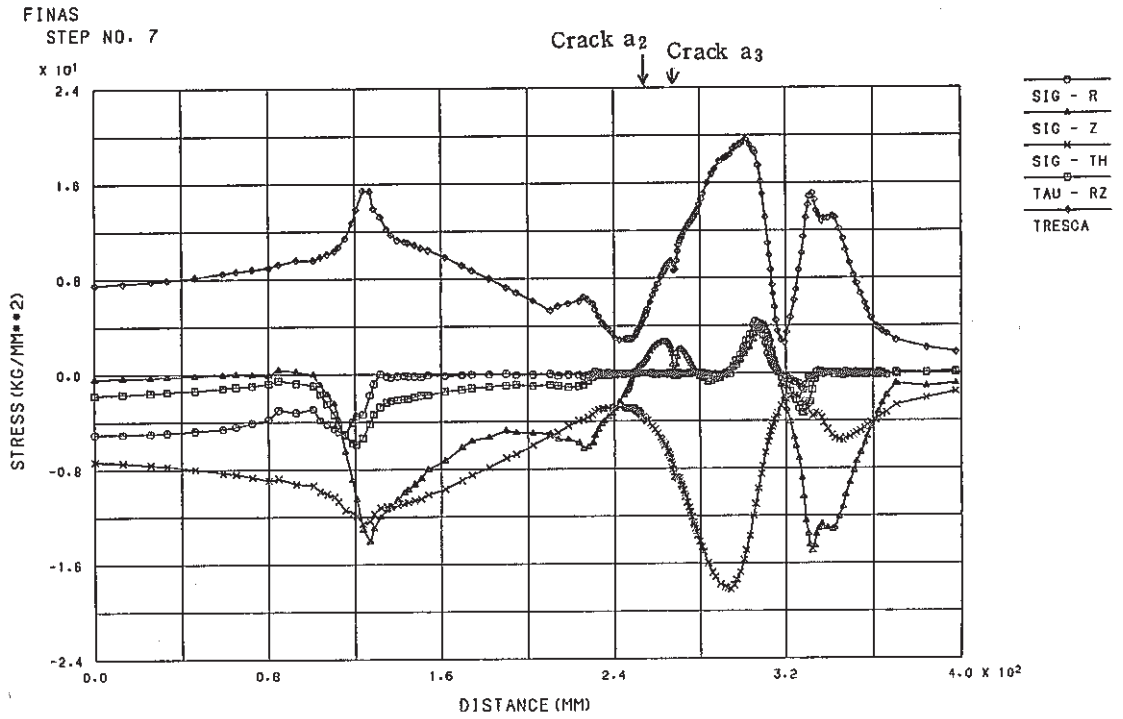


Fig. C.5.6-1 Stress Distribution along Outer Surface at Cold Shock of Outlet Nozzle
(crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

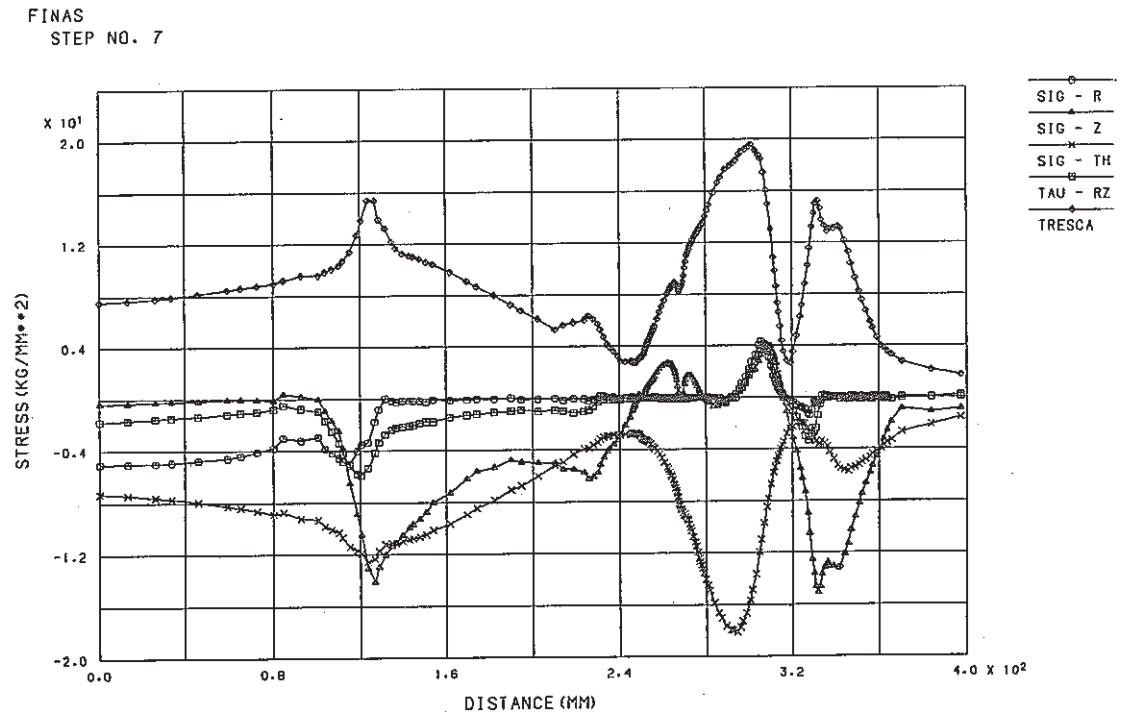


Fig. C.5.6-2 Stress Distribution along Outer Surface at Cold Shock of Outlet Nozzle
(crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

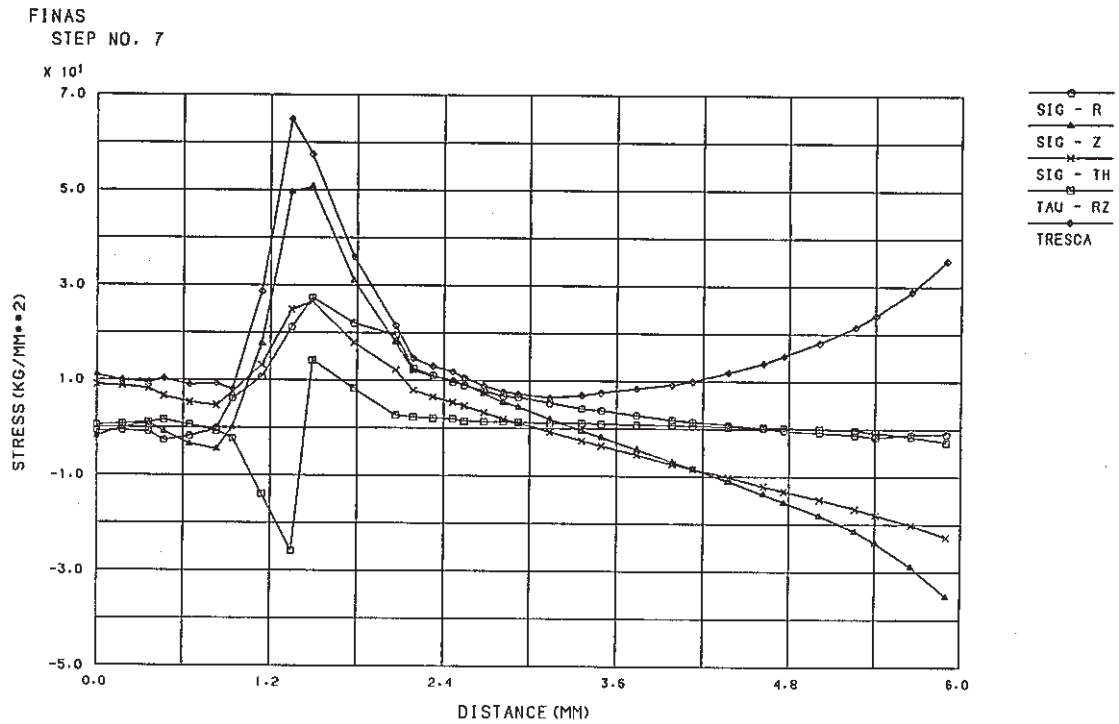


Fig. C.5.7-1 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a_1 (crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

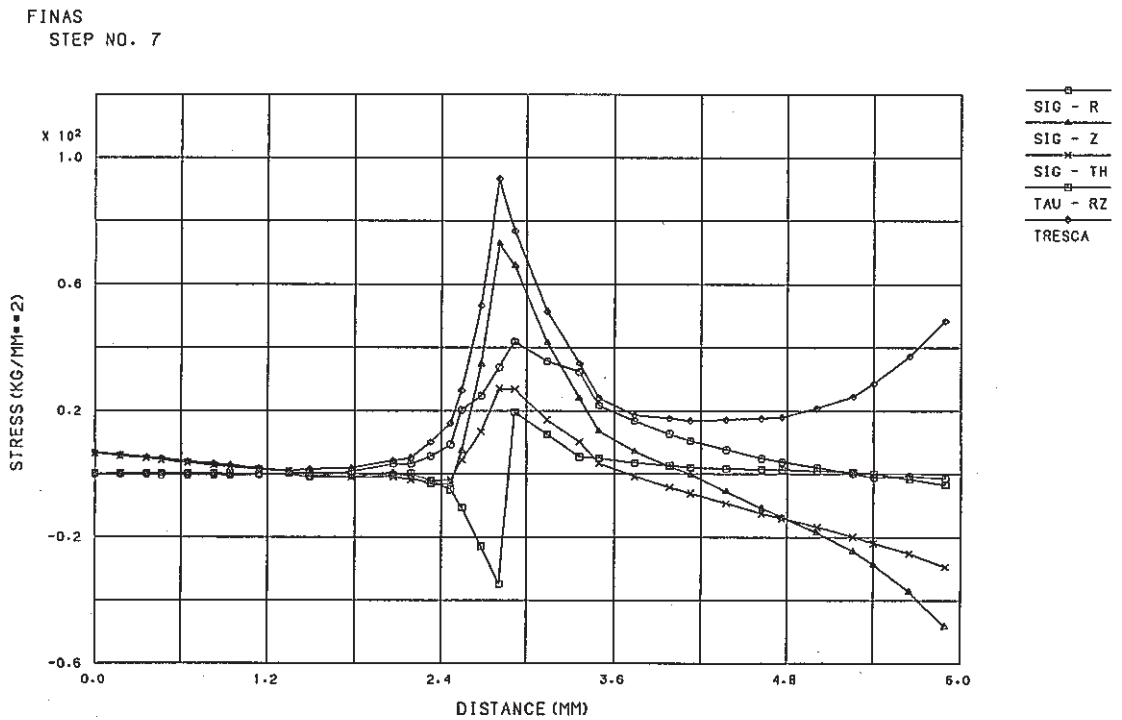


Fig. C.5.7-2 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a_1 (crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

FINAS
STEP NO. 2

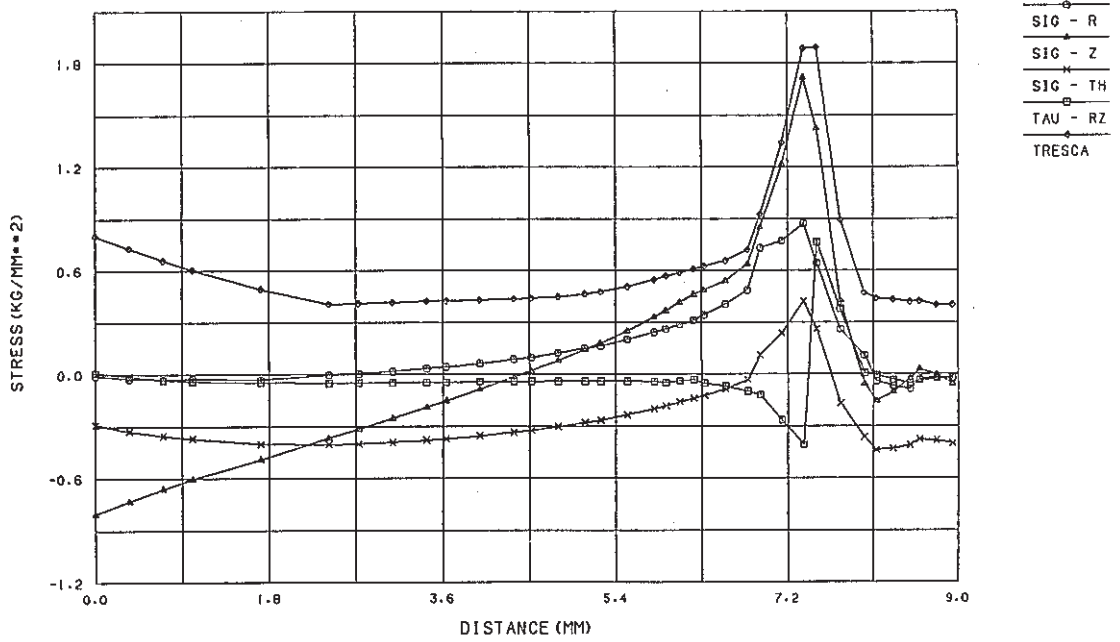


Fig. C.5.8-1 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a₂ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

FINAS
STEP NO. 2

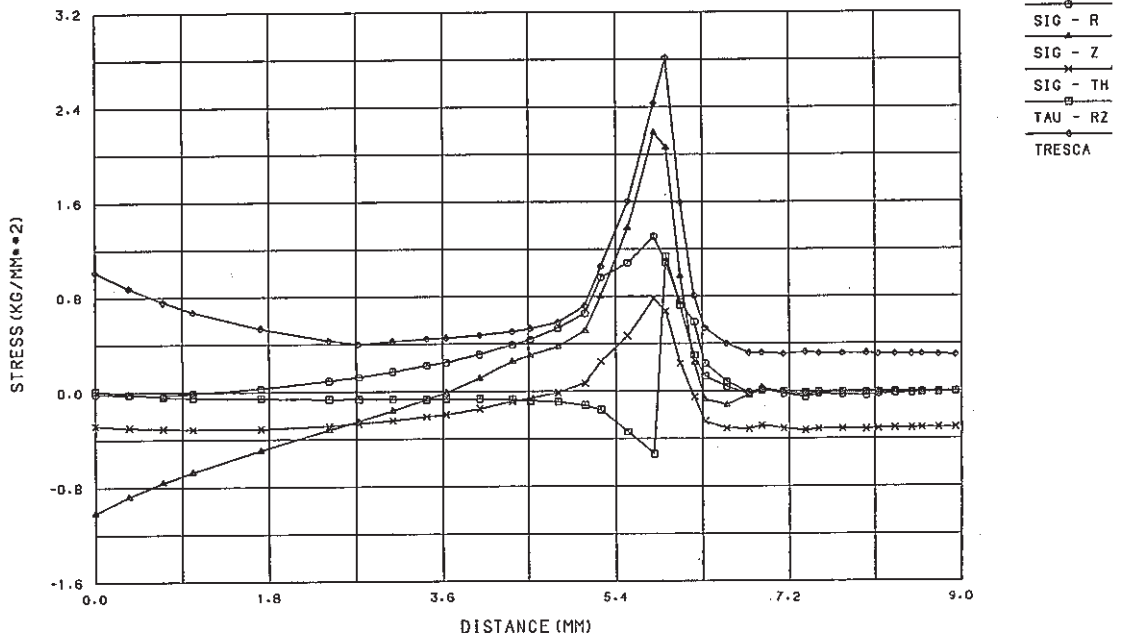


Fig. C.5.8-2 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a₂ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

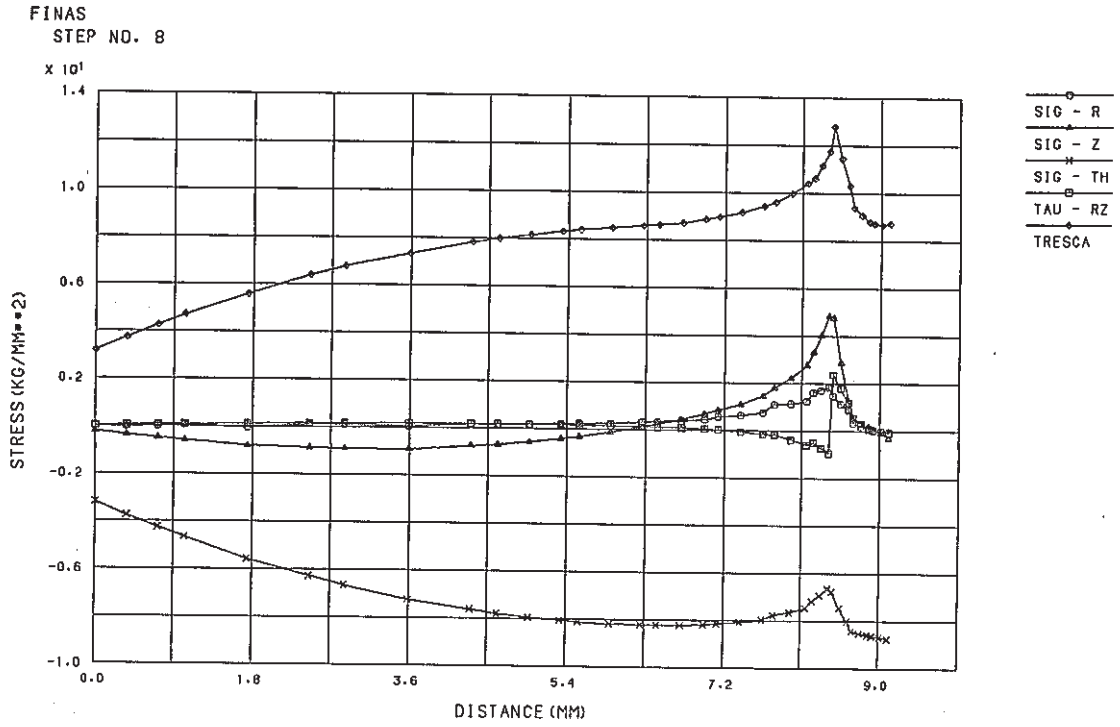


Fig. C.5.9-1 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a₃ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

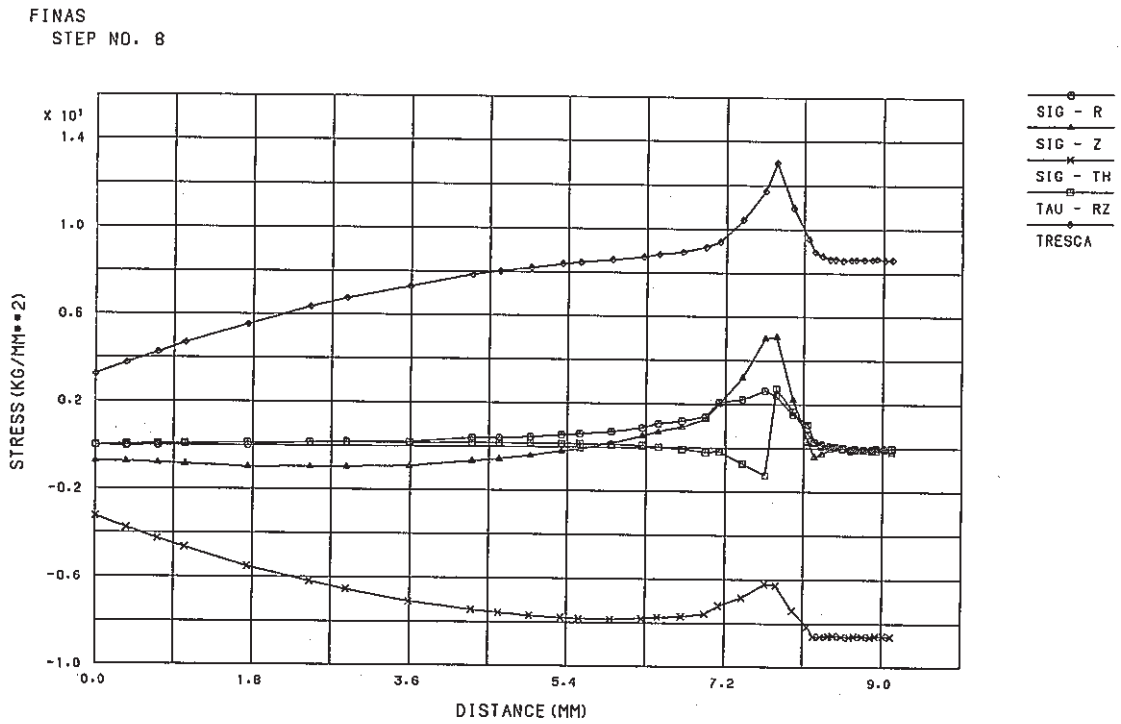


Fig. C.5.9-2 Stress Distribution along Crack Line at Cold Shock of Outlet Nozzle, crack a₃ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

- 1 -32.7000
- 2 -23.0000
- 3 -13.3000
- 4 -3.60000
- 5 6.100000
- 6 15.80000
- 7 25.50000
- 8 35.20000
- 9 44.90000
- 10 54.60000

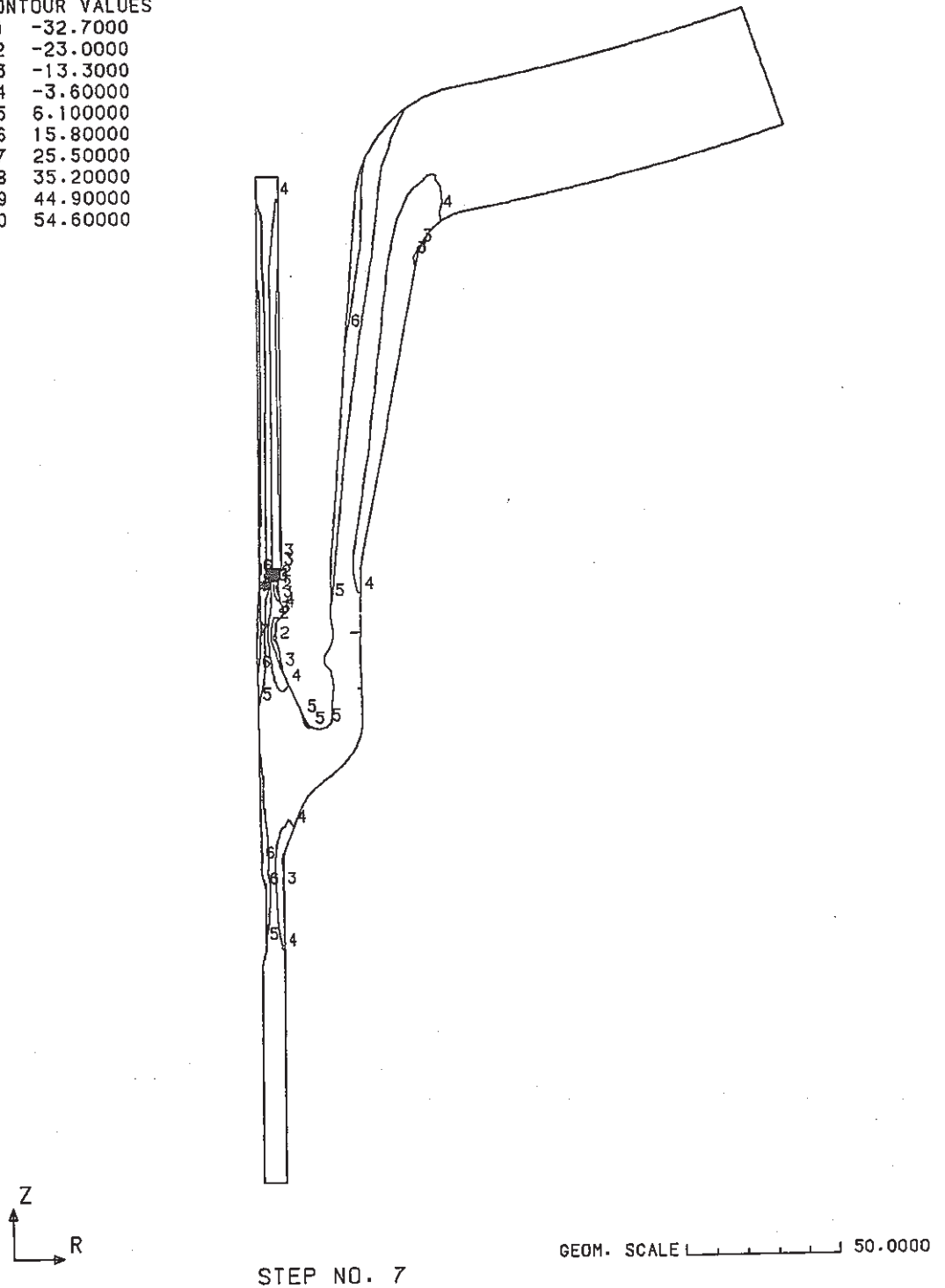


Fig. C.5.10-1 Contour of Axial Stress at Cold Shock of
Outlet Nozzle
(crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

- 1 -46.0000
- 2 -33.0000
- 3 -20.0000
- 4 -7.00000
- 5 6.000000
- 6 19.00000
- 7 32.00000
- 8 45.00000
- 9 58.00000
- 10 71.00000

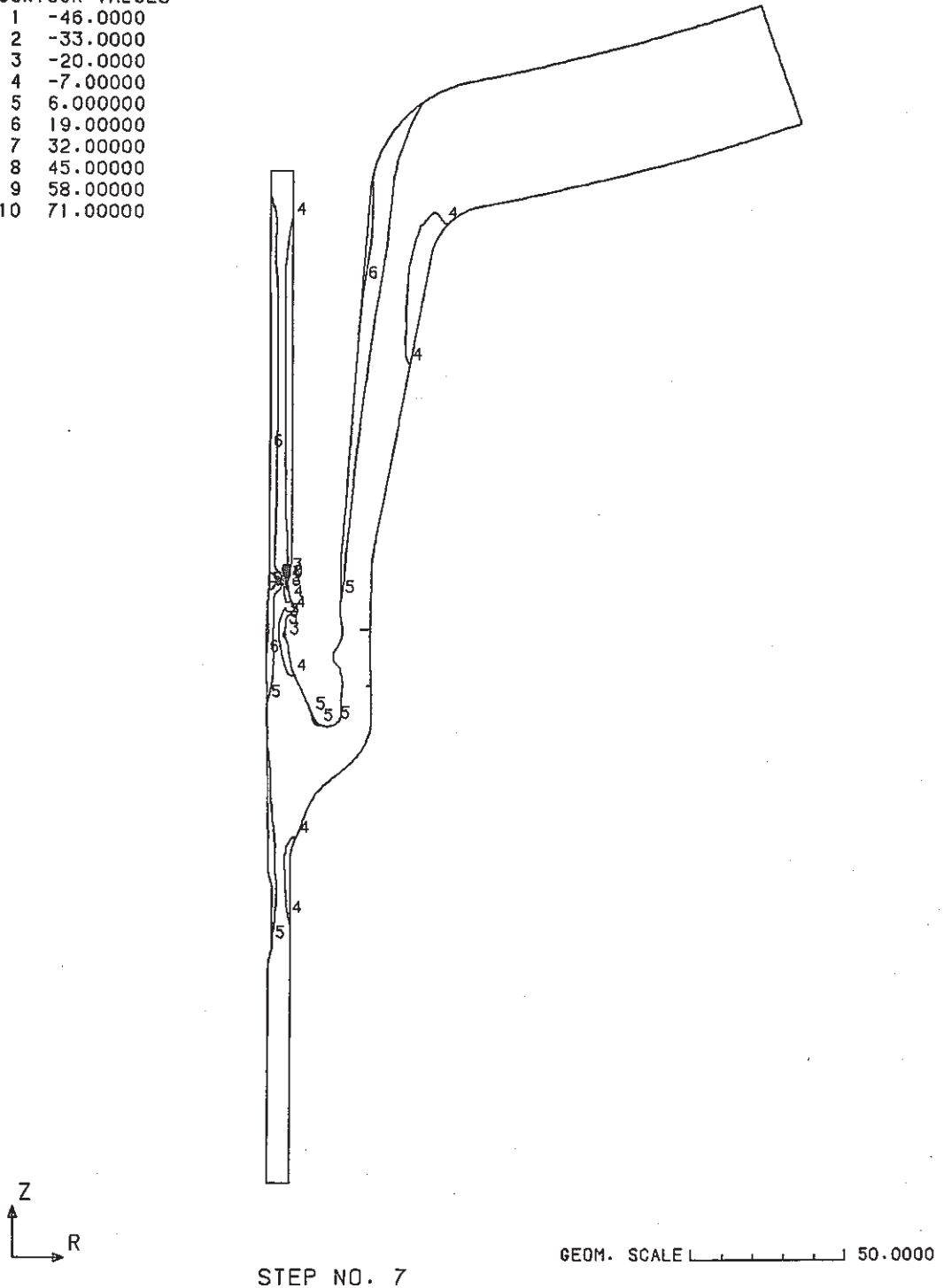


Fig. C.5.10-2 Contour of Axial Stress at Cold Shock of
Outlet Nozzle
(crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

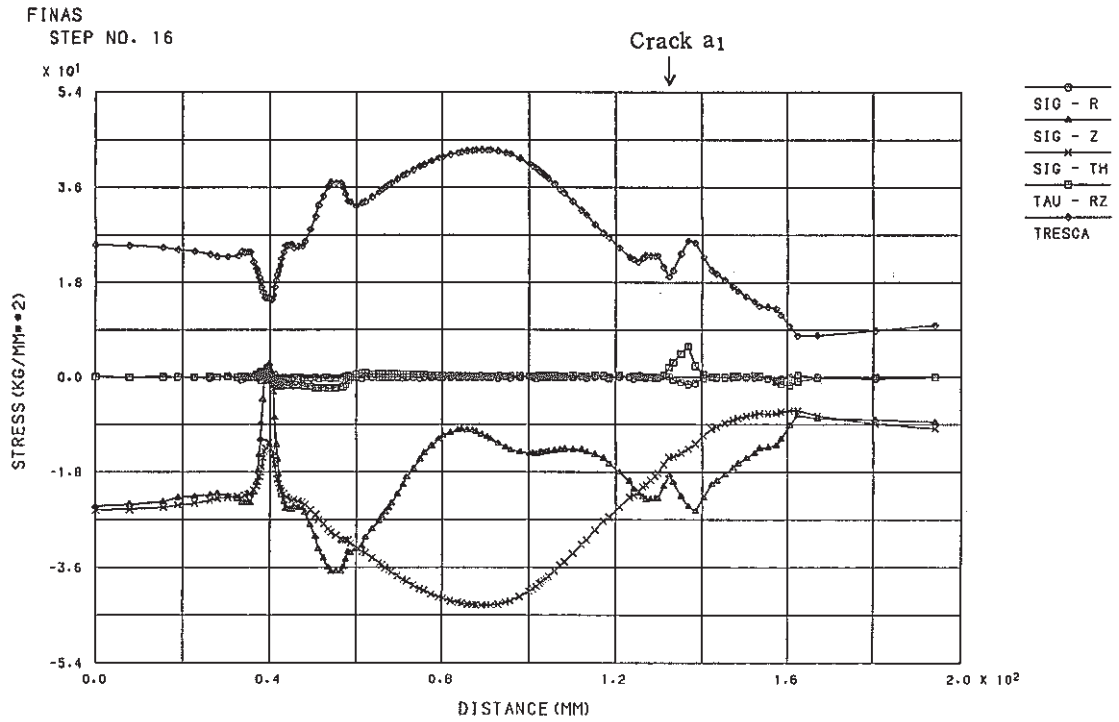


Fig. C.5.11-1 Stress Distribution along Inner-1 Surface at Hot Shock of Outlet Nozzle
(crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

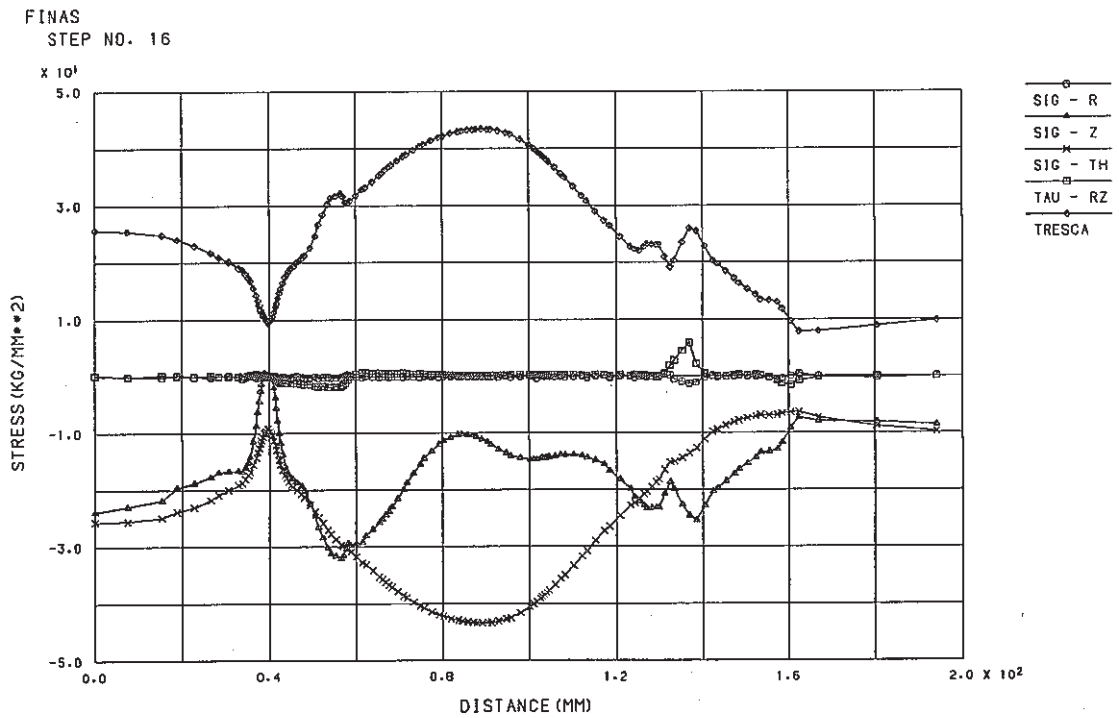


Fig. C.5.11-2 Stress Distribution along Inner-2 Surface at Hot Shock of Outlet Nozzle
(crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

FINAS
STEP NO. 16

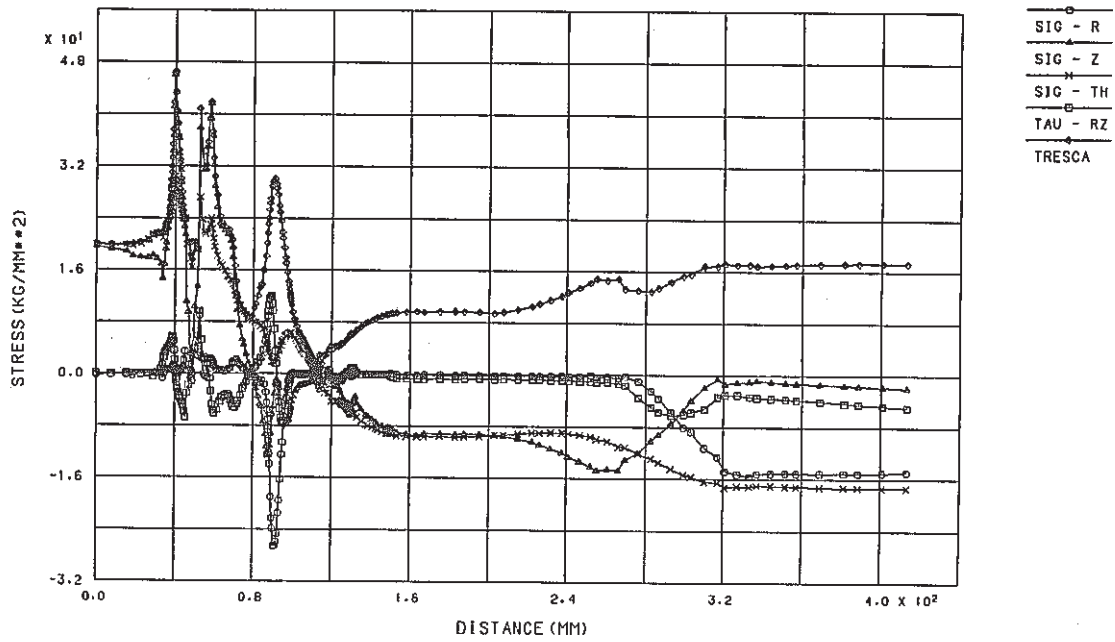


Fig. C.5.12-1 Stress Distribution along Inner-2 Surface at Hot Shock of Outlet Nozzle (crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

FINAS
STEP NO. 16

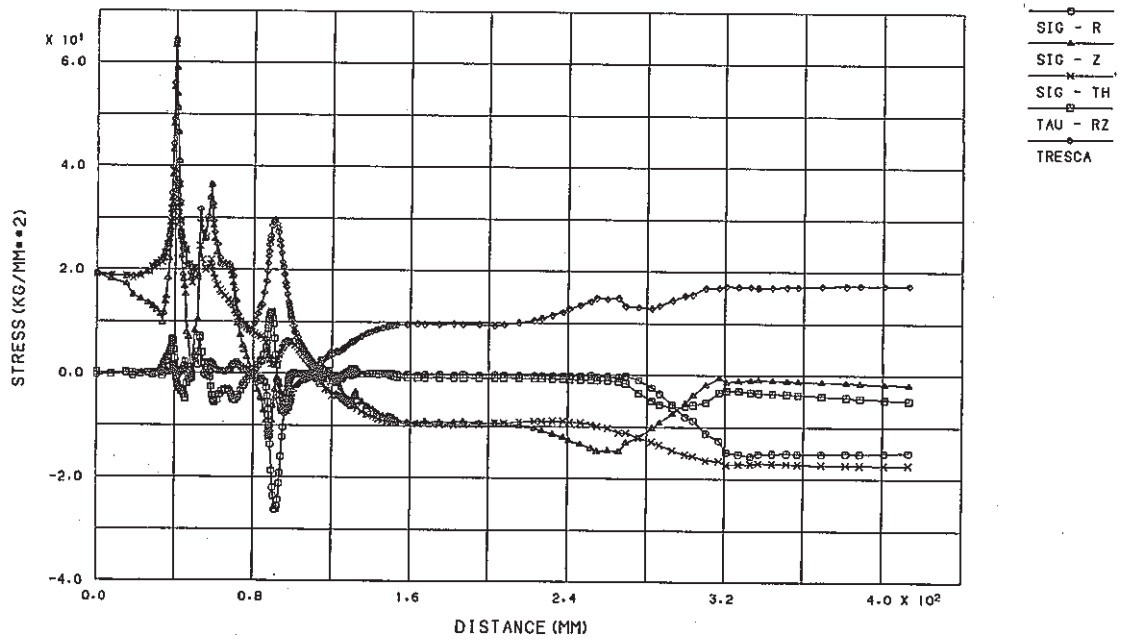


Fig. C.5.12-2 Stress Distribution along Inner-2 Surface at Hot Shock of Outlet Nozzle (crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)

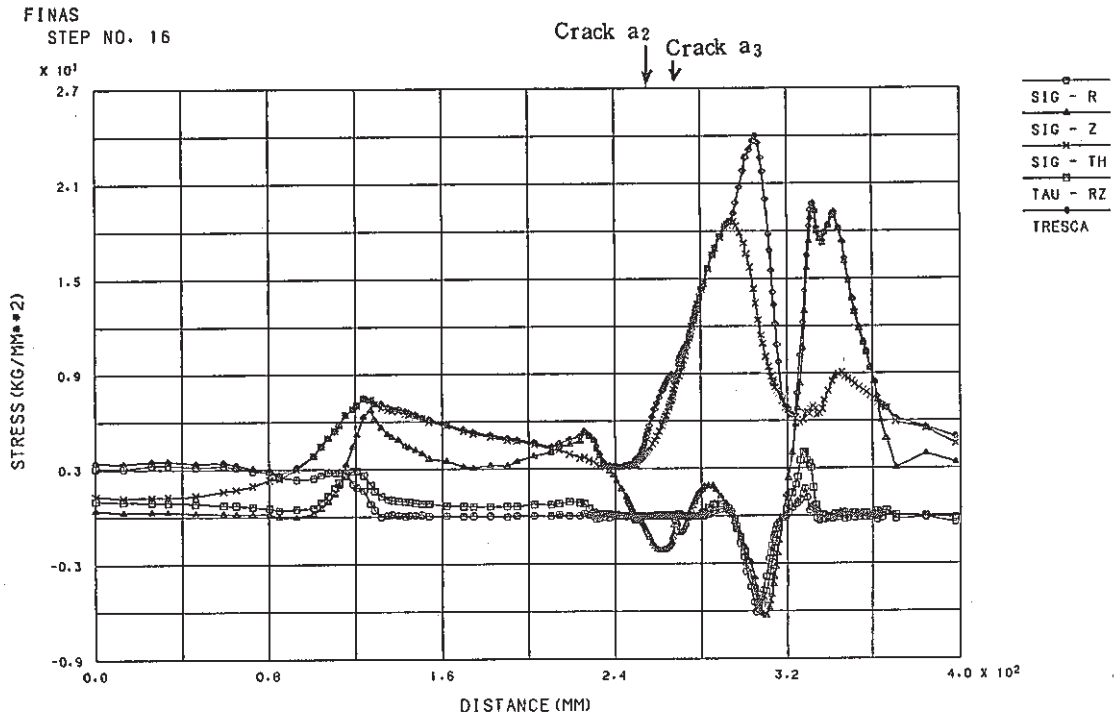


Fig. C.5.13-1 Stress Distribution along Outer Surface at Hot Shock of Outlet Nozzle (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

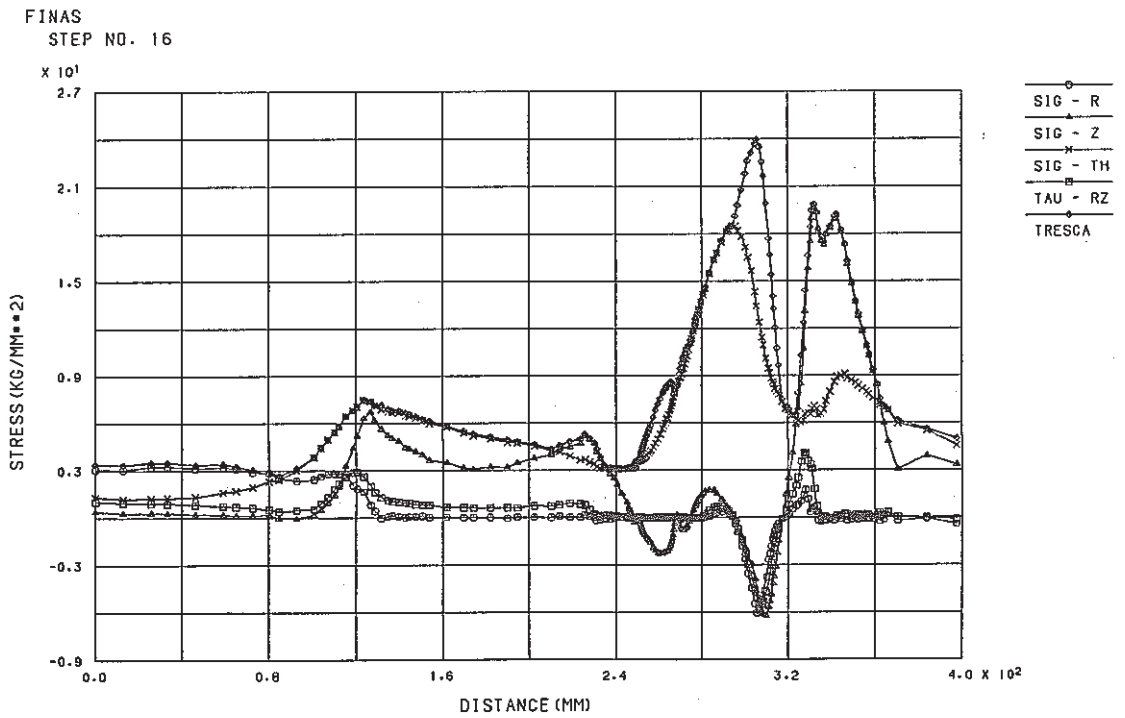


Fig. C.5.13-2 Stress Distribution along Outer Surface at Hot Shock of Outlet Nozzle (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

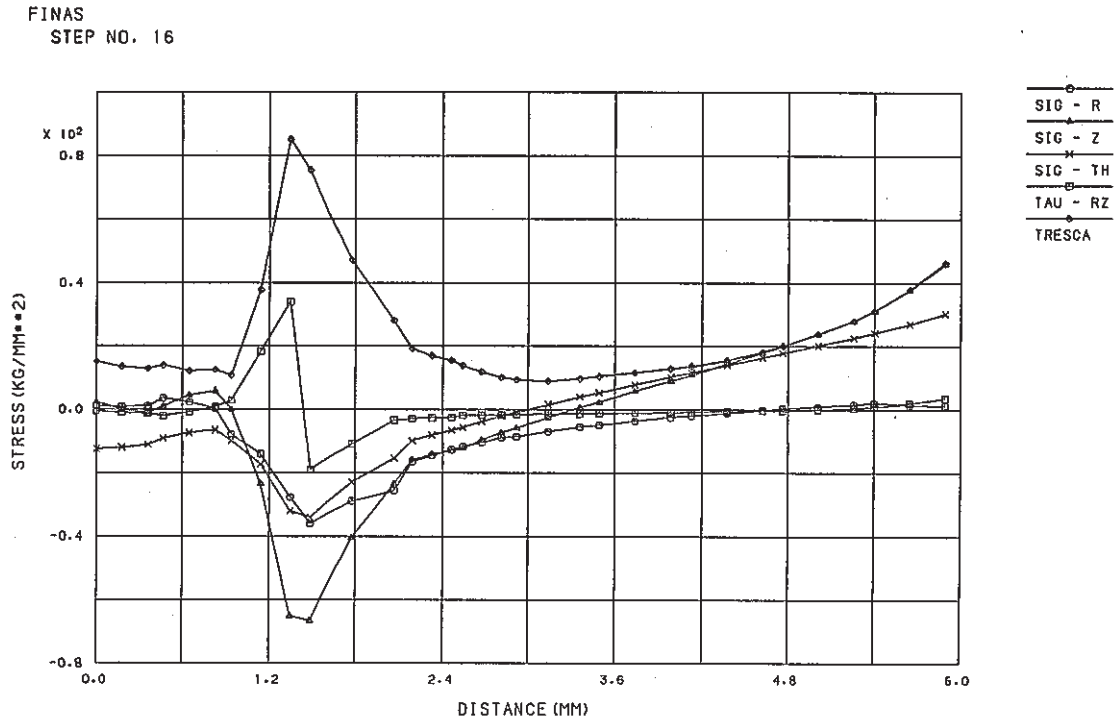


Fig. C.5.14-1 Stress Distribution along Crack Line at Hot Shock of Outlet Nozzle, crack a₁ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

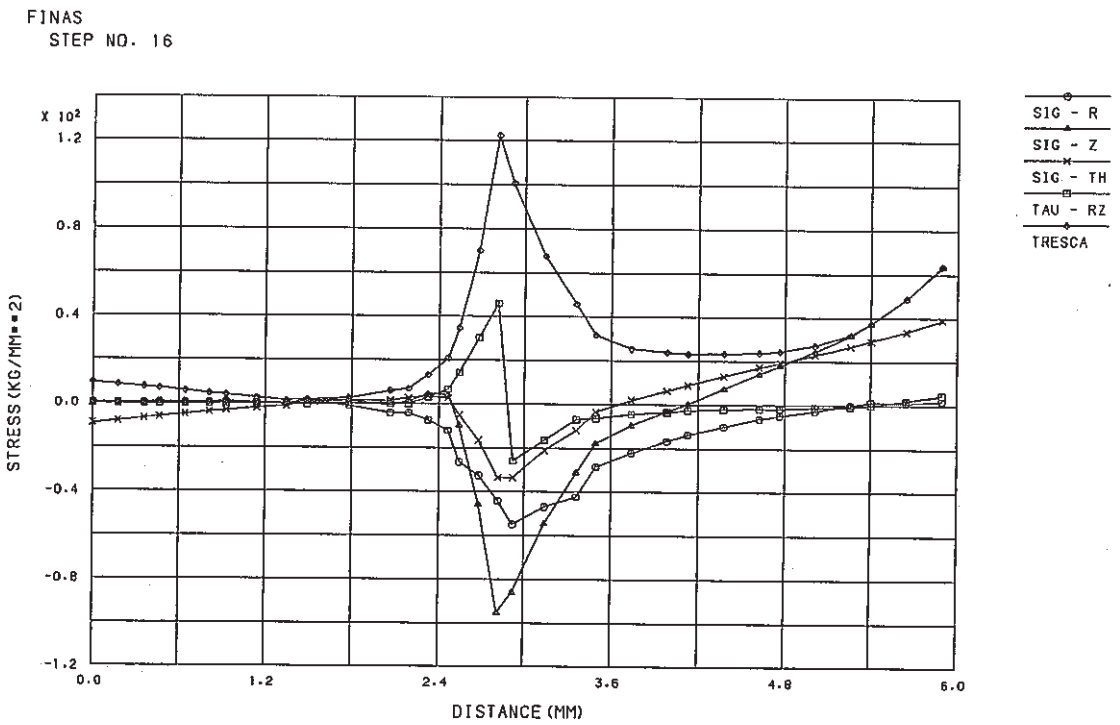


Fig. C.5.14-2 Stress Distribution along Crack Line a Hot Shock of Outlet Nozzle, crack a₁ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

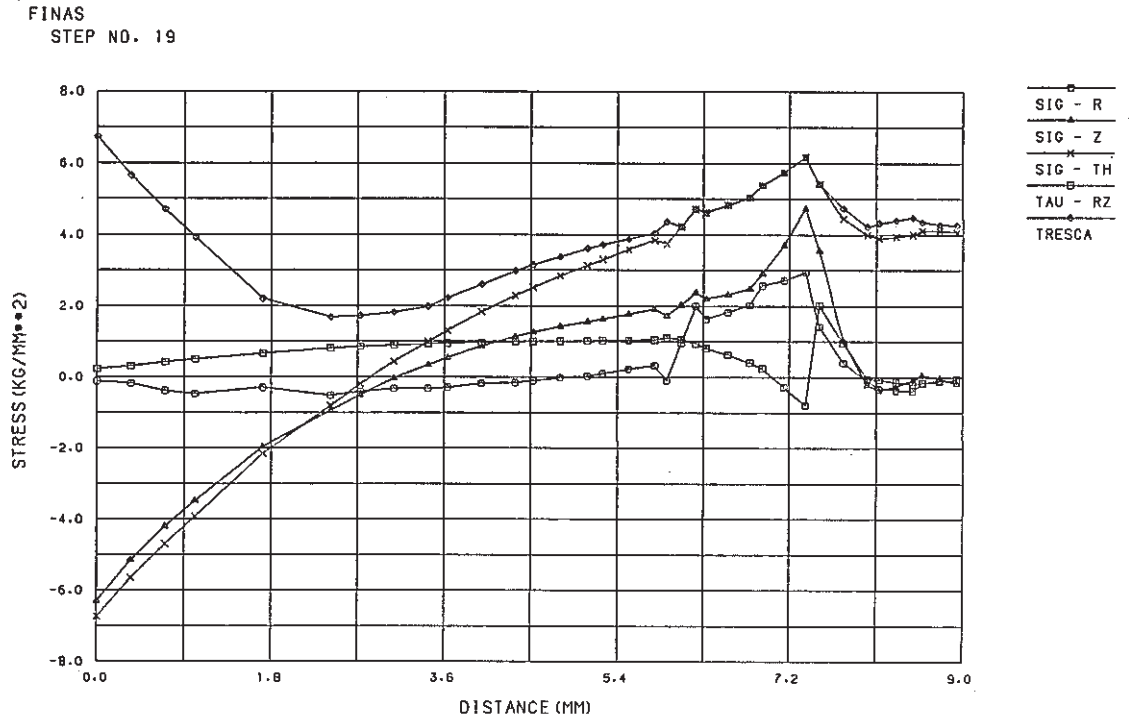


Fig. C.5.15-1 Stress Distribution along Crack Line at Hot Shock of Outlet Nozzle, crack a₂ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

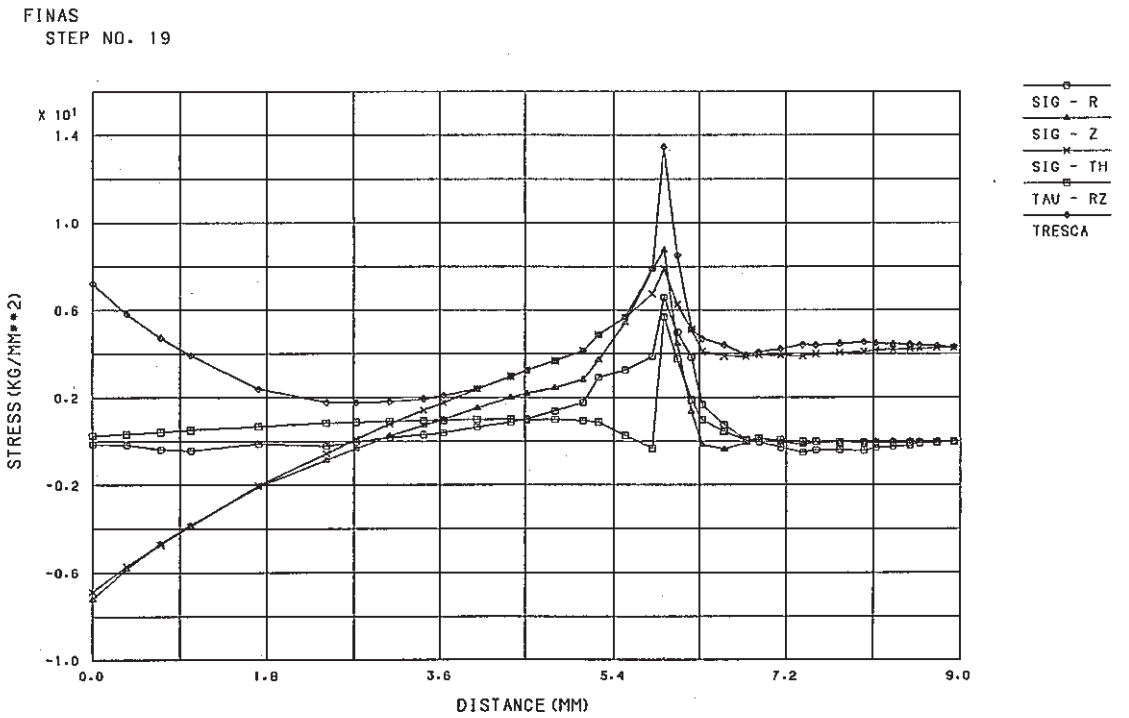


Fig. C.5.15-2 Stress Distribution along Crack Line at Hot Shock of Outlet Nozzle, crack a₂ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

FINAS
STEP NO. 20

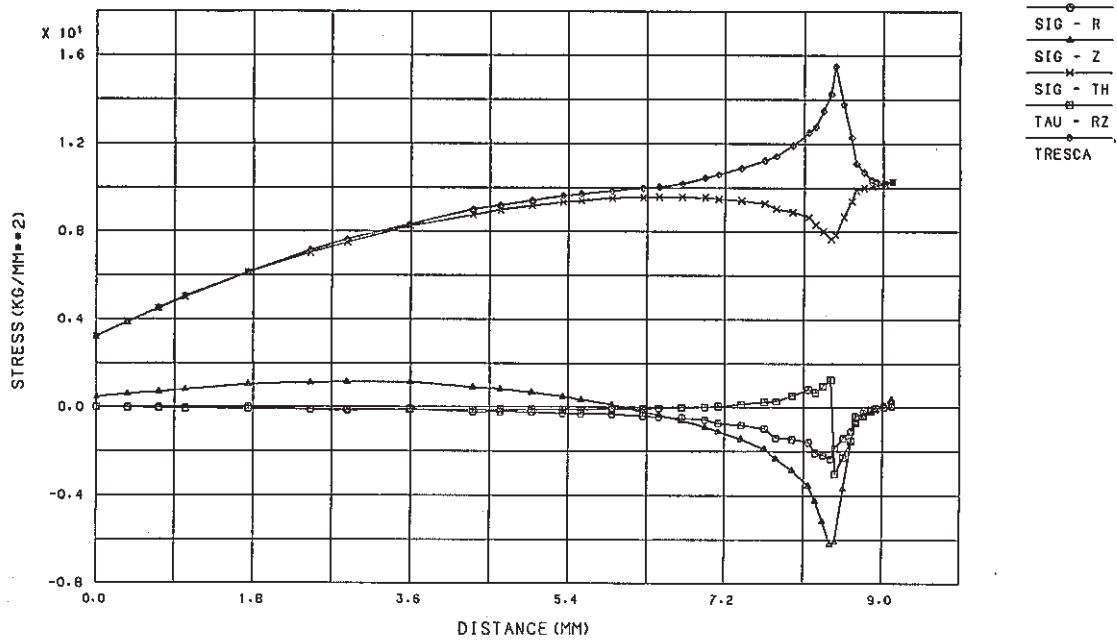


Fig. C.5.16-1 Stress Distribution along Crack Line at Hot Shock of Outlet Nozzle, crack a₃ (crack depth a₁=1.45mm, a₂=1.55mm, a₃=0.7mm)

FINAS
STEP NO. 20

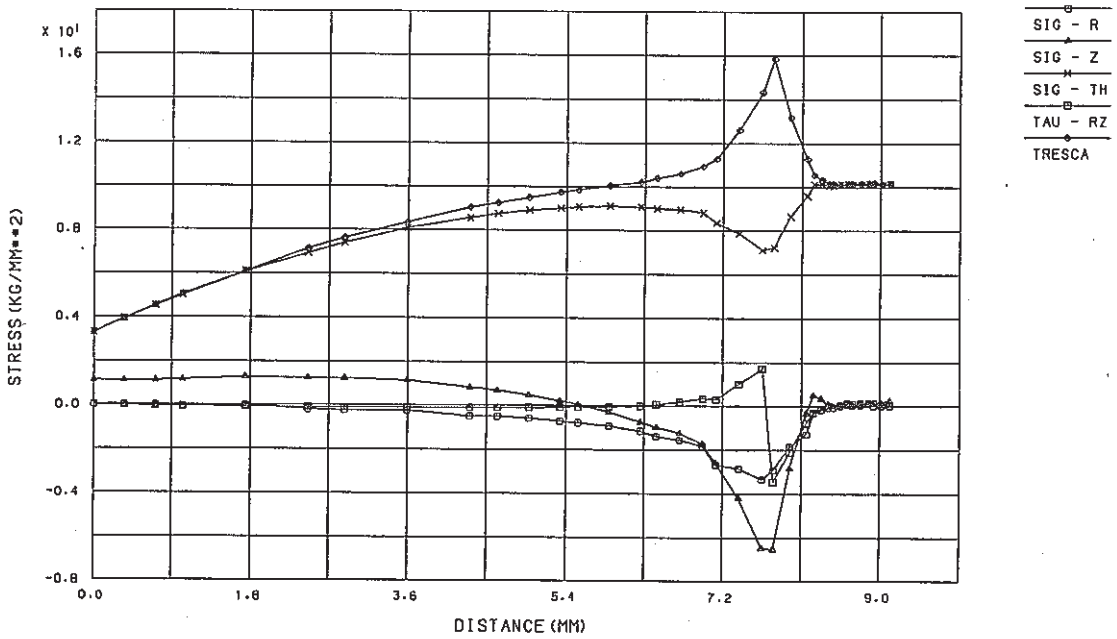


Fig. C.5.16-2 Stress Distribution along Crack Line at Hot Shock of Outlet Nozzle, crack a₃ (crack depth a₁=2.9mm, a₂=3.1mm, a₃=1.4mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-71.0000
2	-58.0000
3	-45.0000
4	-32.0000
5	-19.0000
6	-6.00000
7	7.000000
8	20.00000
9	33.00000
10	46.00000

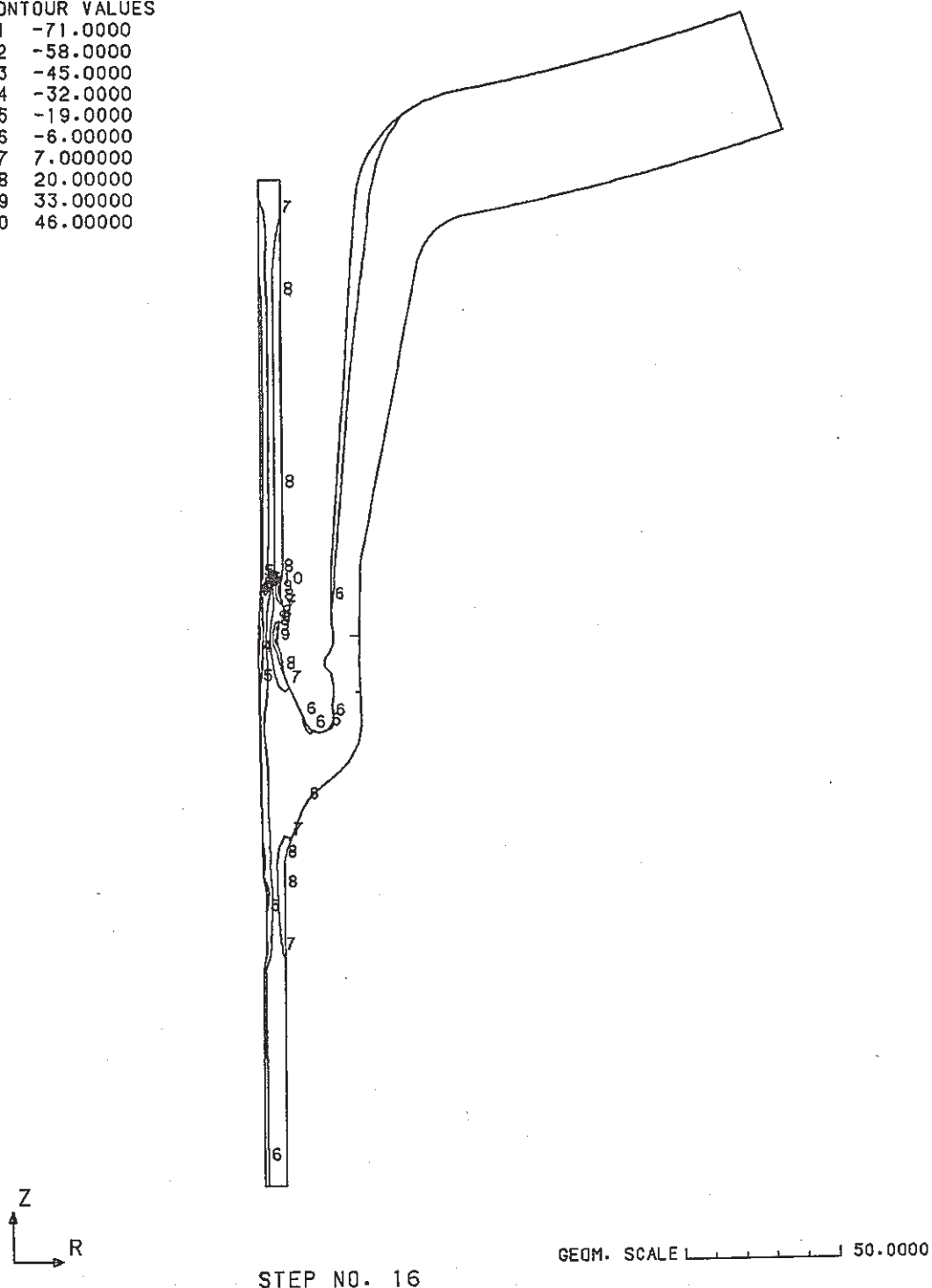


Fig. C.5.17-1 Contour of Axial Stress at Hot Shock of
Outlet Nozzle
(crack depth $a_1=1.45\text{mm}$, $a_2=1.55\text{mm}$, $a_3=0.7\text{mm}$)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

- 1 -96.0000
- 2 -79.0000
- 3 -62.0000
- 4 -45.0000
- 5 -28.0000
- 6 -11.0000
- 7 6.000000
- 8 23.00000
- 9 40.00000
- 10 57.00000

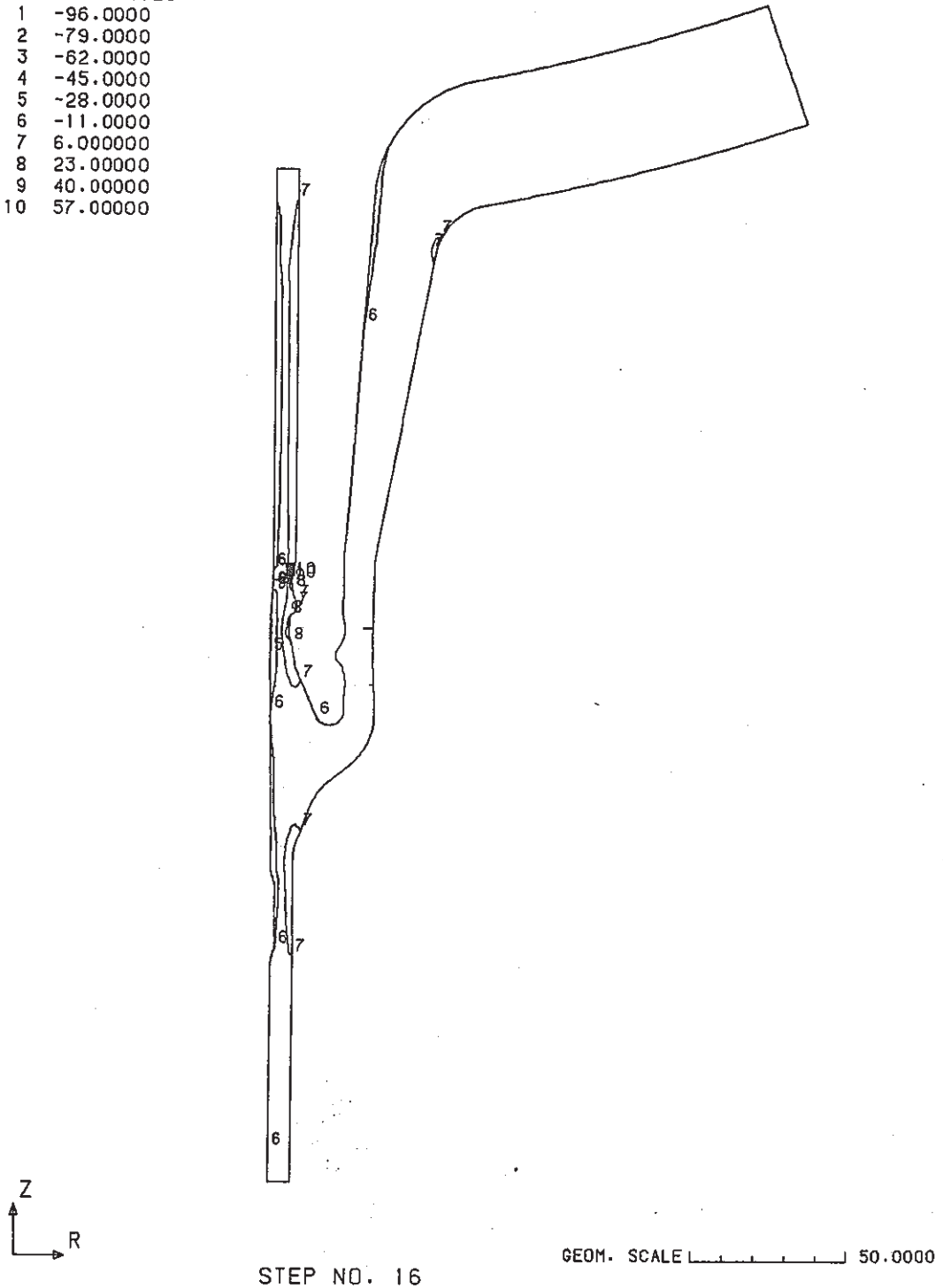
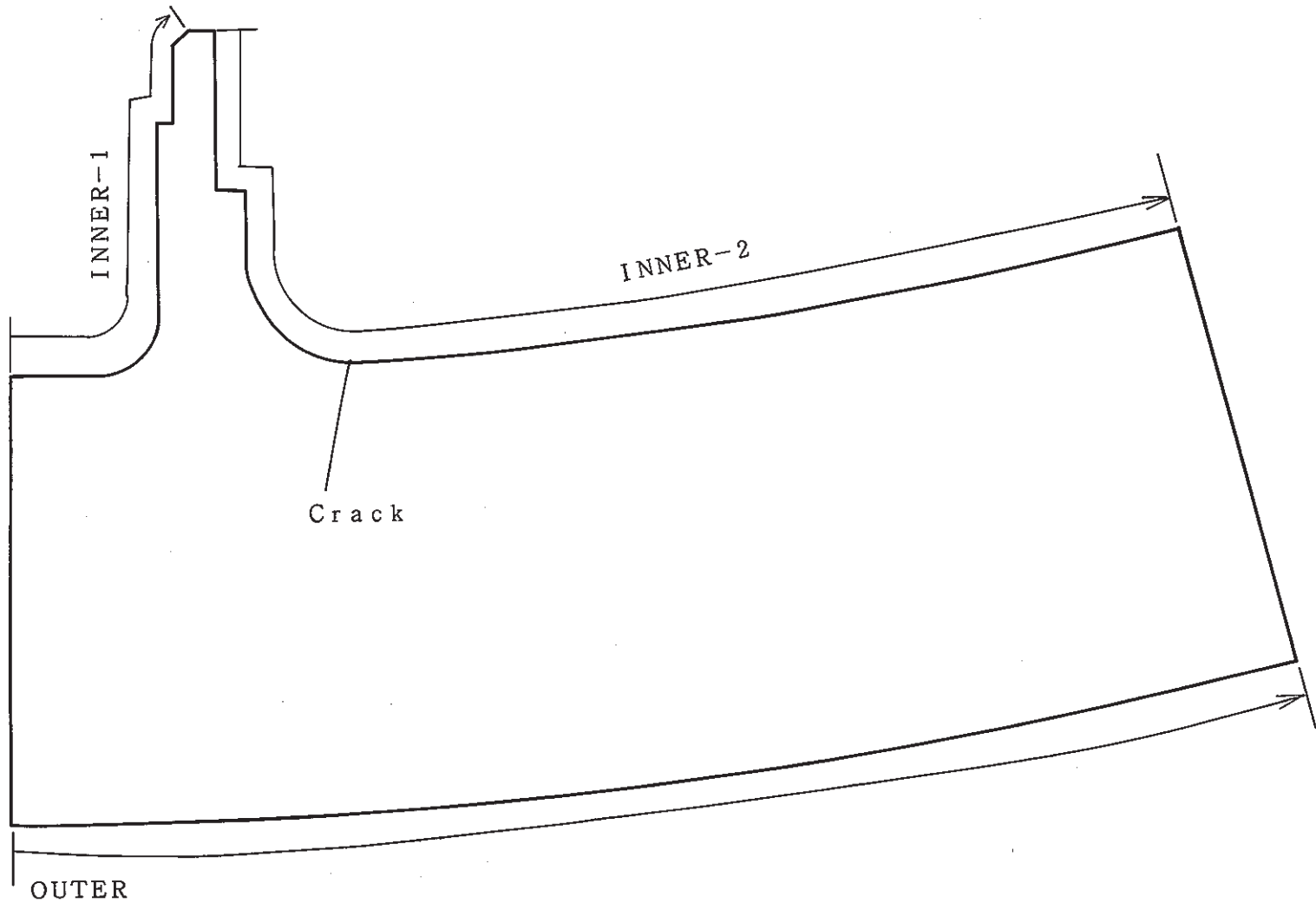


Fig. C.5.17-2 Contour of Axial Stress at Hot Shock of
Outlet Nozzle
(crack depth $a_1=2.9\text{mm}$, $a_2=3.1\text{mm}$, $a_3=1.4\text{mm}$)



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Fig. C.6-1 Evaluation Lines for Surface Stress Distribution of Stud Bolt

FINAS

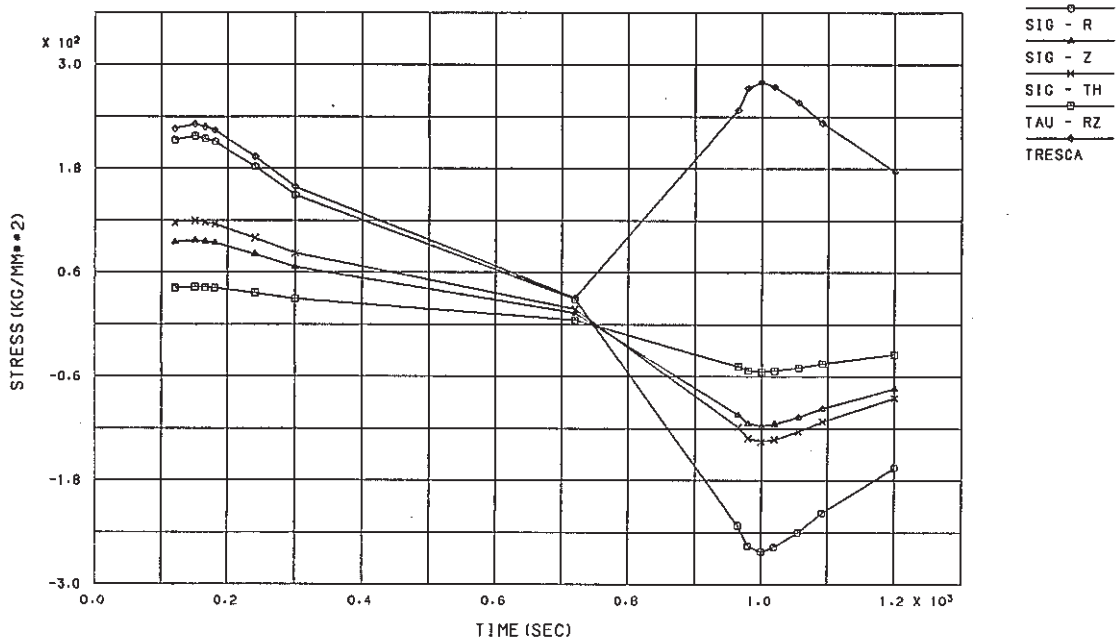


Fig. C.6.1-1 Stress History ahead of Crack Tip of Stud Bolt
 (crack depth a=1 mm)

FINAS

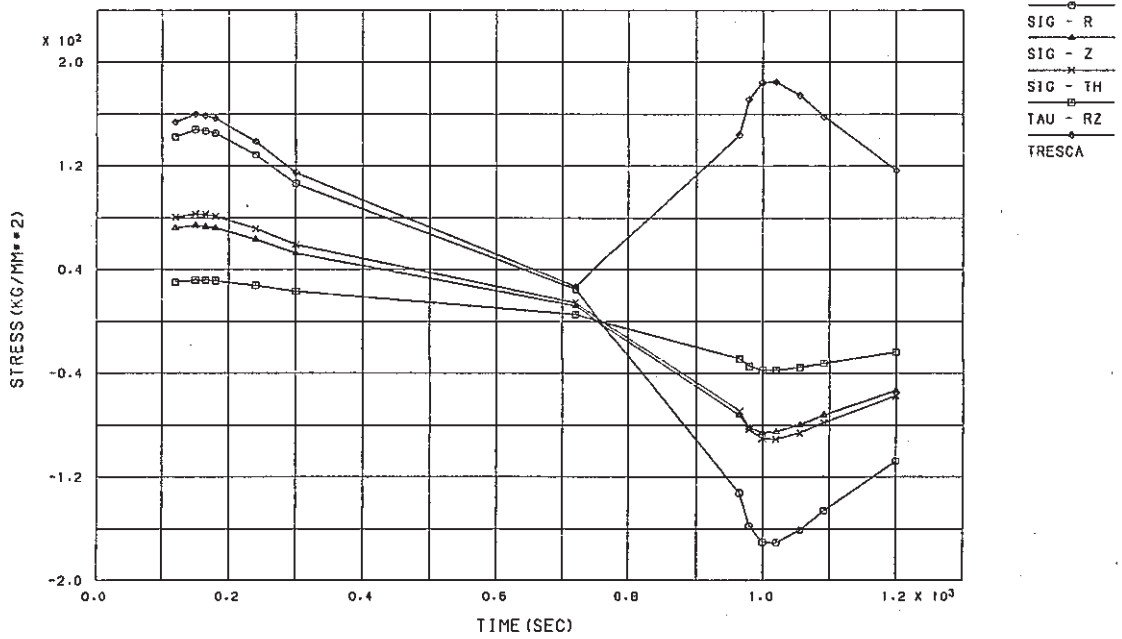


Fig. C.6.1-2 Stress History ahead of Crack Tip of Stud Bolt
 (crack depth a=7 mm)

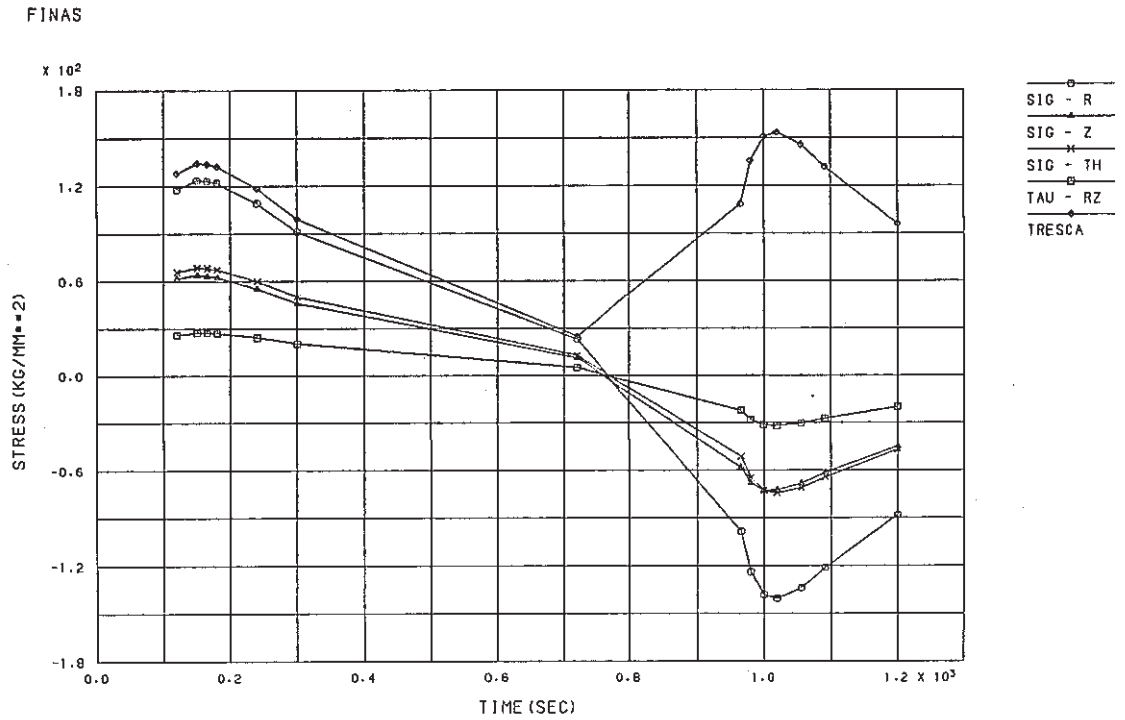


Fig. C.6.1-3 Stress History ahead of Crack Tip of Stud Bolt
(crack depth a=10 mm)

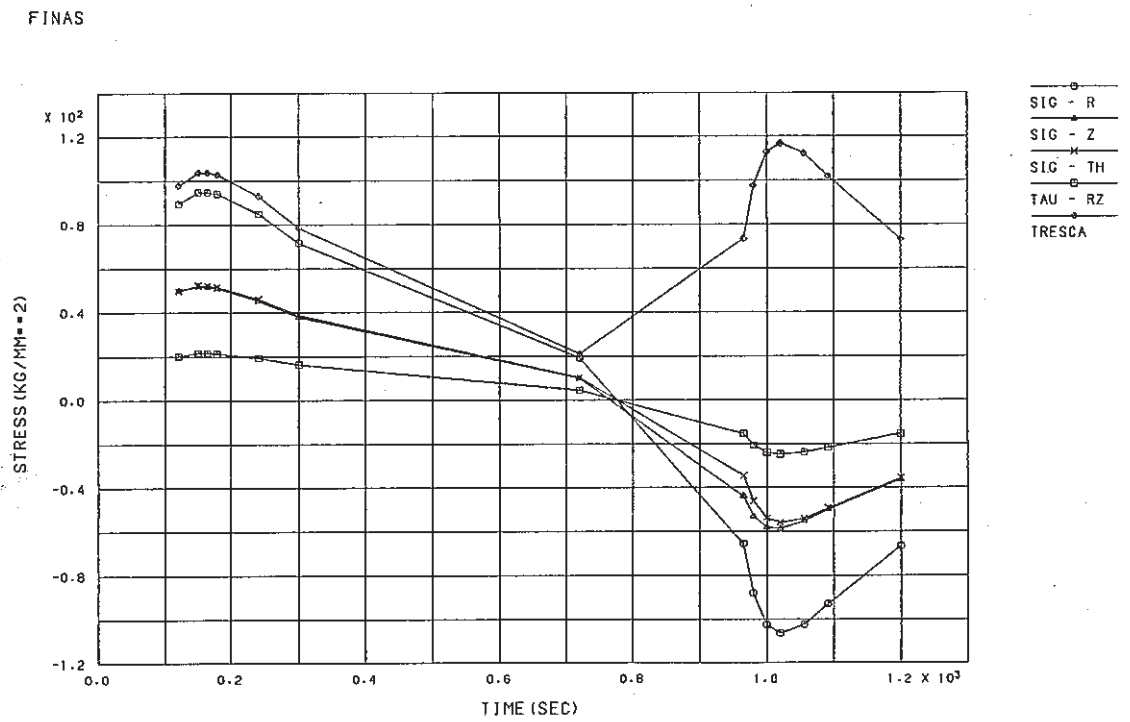


Fig. C.6.1-4 Stress History ahead of Crack Tip Stud Bolt
(crack depth a=13 mm)

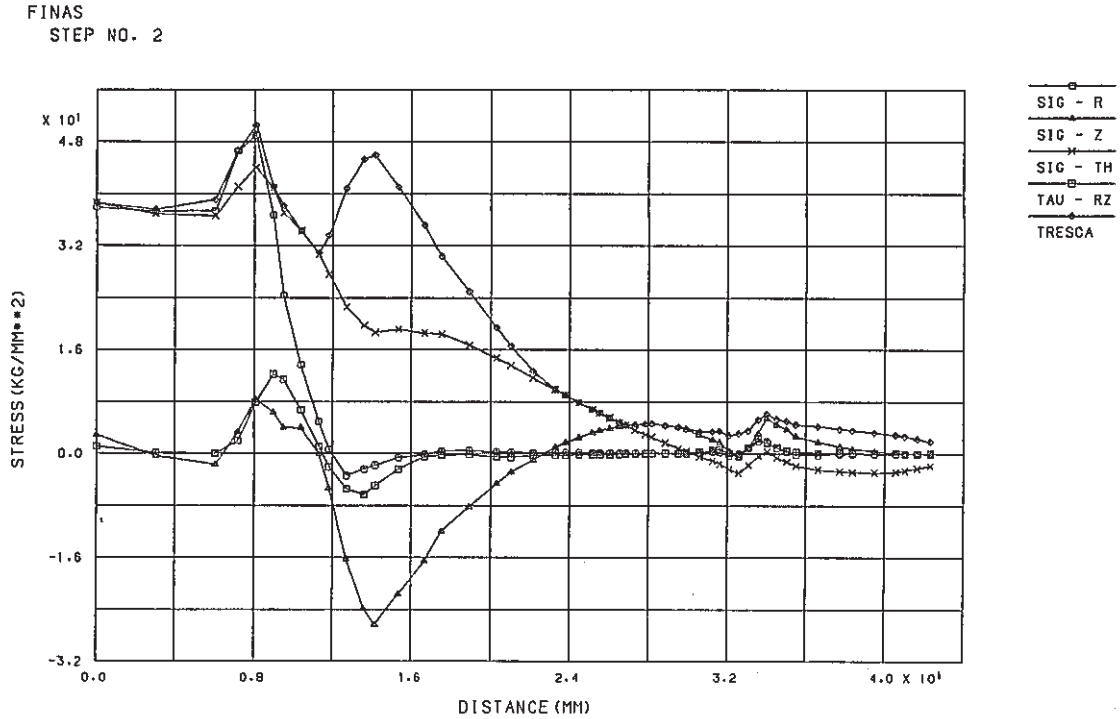


Fig. C.6.2-1 Stress Distribution along Inner-1 Surface at Cold Shock of Stud Bolt (crack depth a=1 mm)

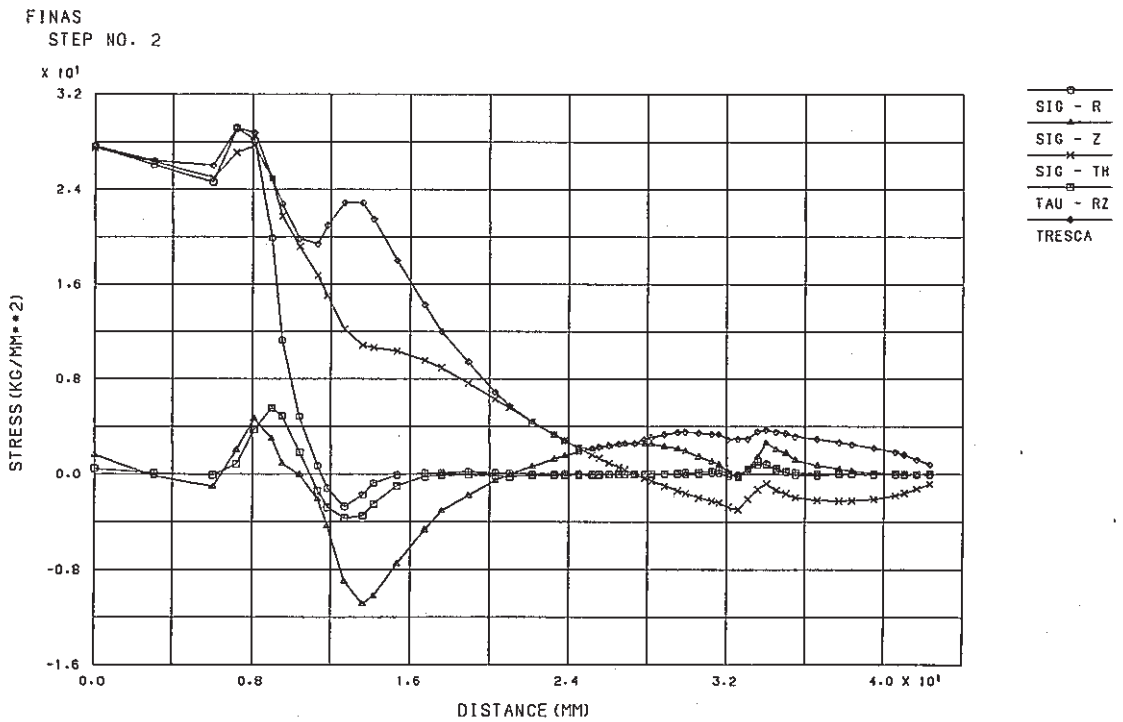


Fig. C.6.2-2 Stress Distribution along Inner-1 Surface at Cold Shock of Stud Bolt (crack depth a=7 mm)

FINAS
STEP NO. 2

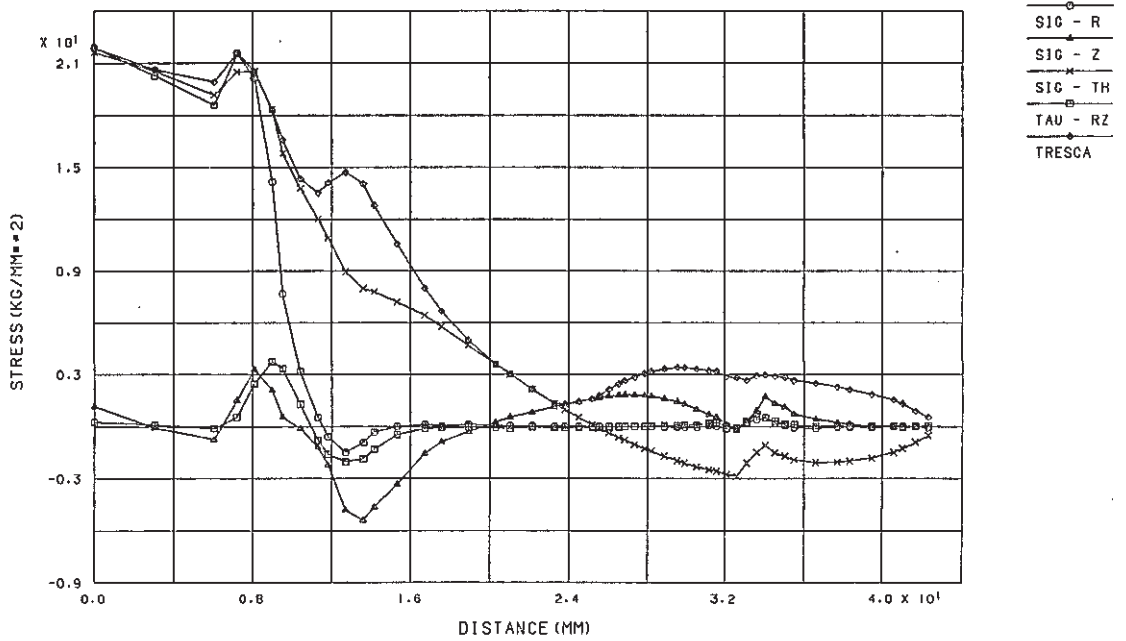


Fig. C.6.2-3 Stress Distribution along Inner-1 Surface at Cold Shock of Stud Bolt (crack depth a=10 mm)

FINAS
STEP NO. 2

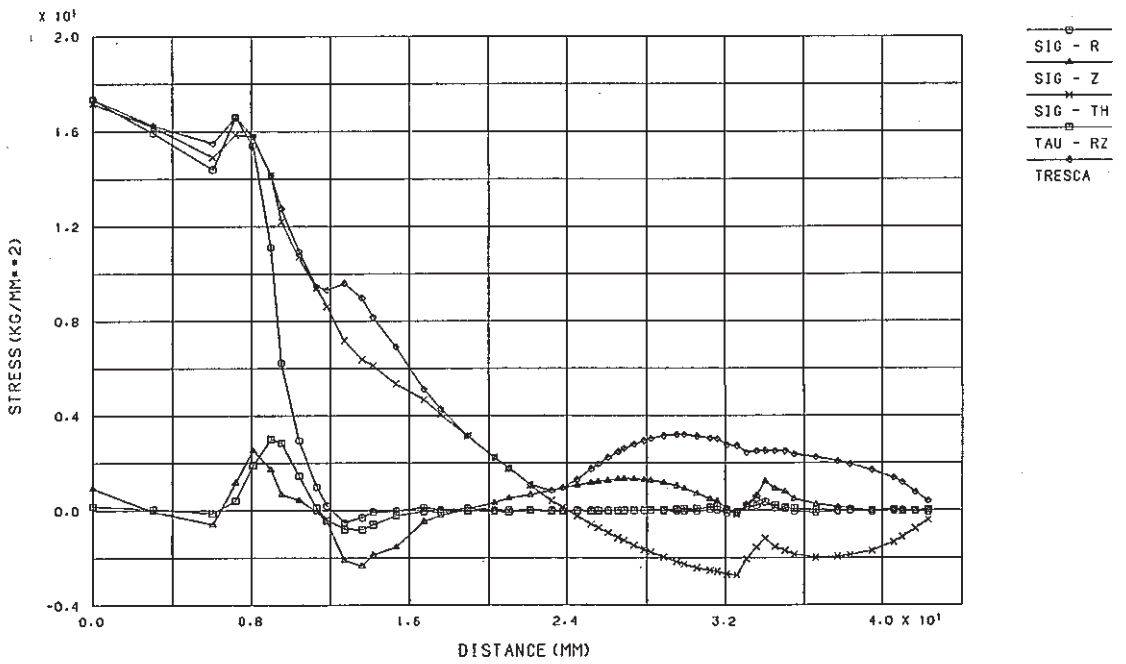


Fig. C.6.2-4 Stress Distribution along Inner-1 Surface at Cold Shock of Stud Bolt (crack depth a=13 mm)

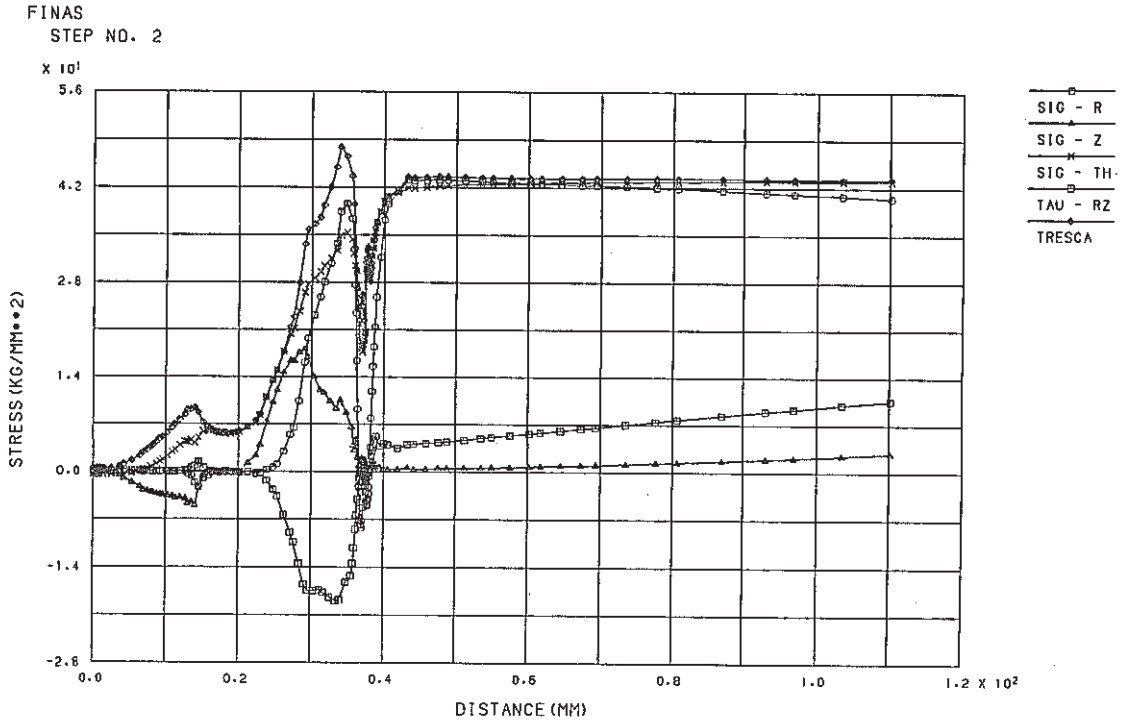


Fig. C.6.3-1 Stress Distribution along Inner-2 Surface at Cold Shock of Stud Bolt (crack depth a=1 mm)

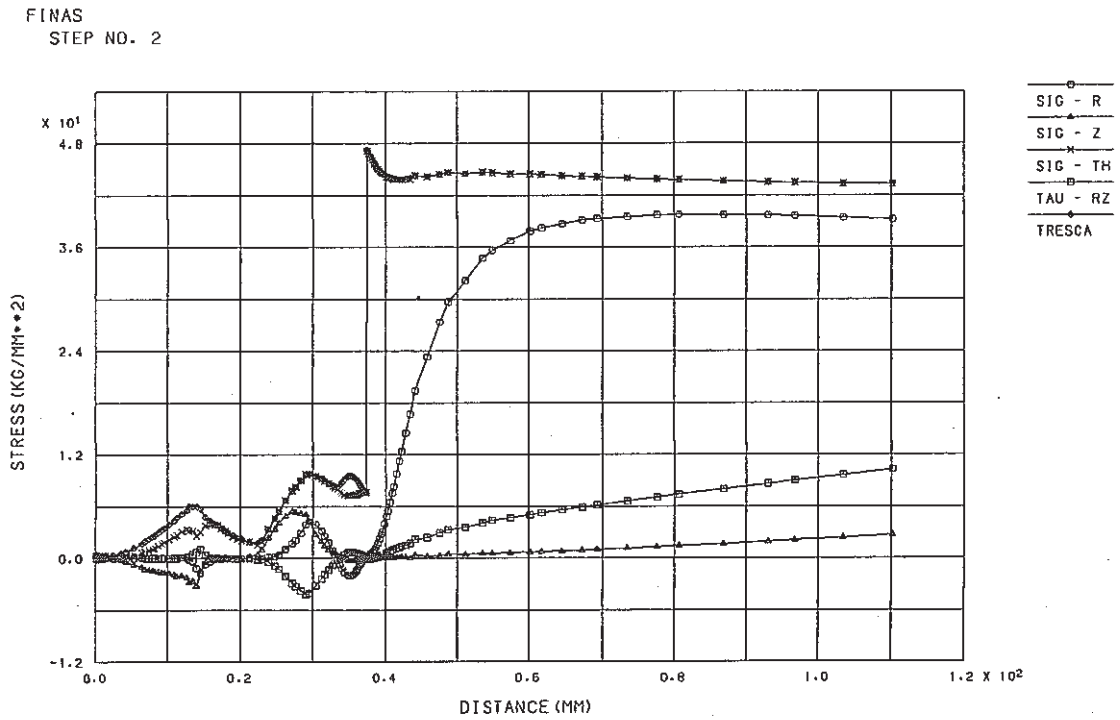


Fig. C.6.3-2 Stress Distribution along Inner-2 Surface at Cold Shock of Stud Bolt (crack depth a=7 mm)

FINAS
STEP NO. 2

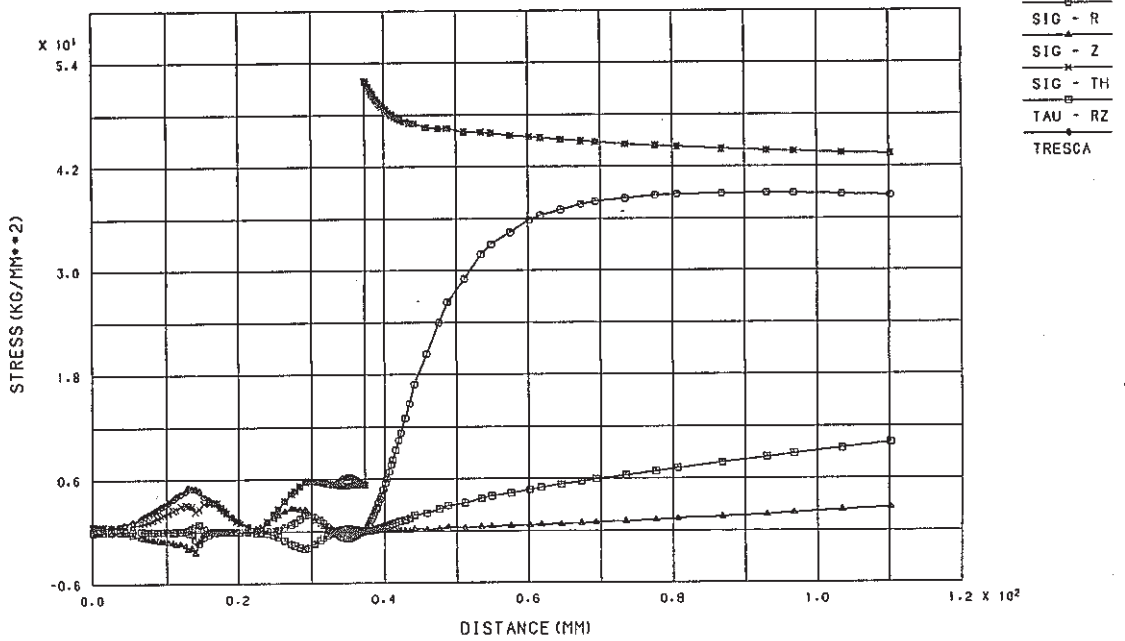


Fig. C.6.3-3 Stress Distribution along Inner-2 Surface at Cold Shock of Stud Bolt (crack depth a=10 mm)

FINAS
STEP NO. 2

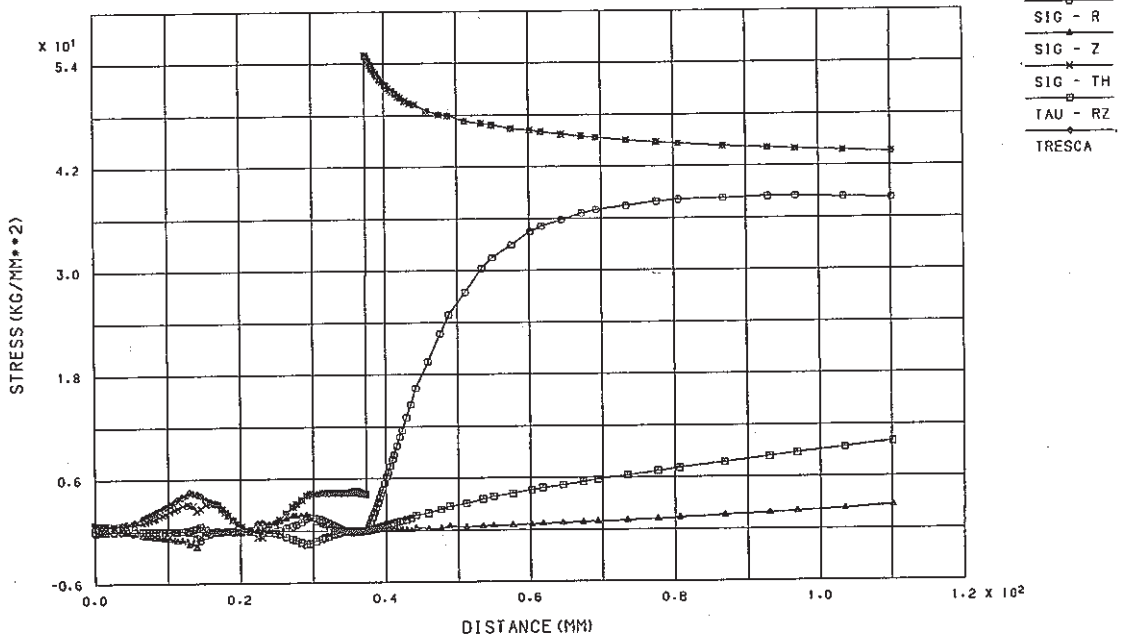


Fig. C.6.3-4 Stress Distribution along Inner-2 Surface at Cold Shock of Stud Bolt (crack depth a=13 mm)

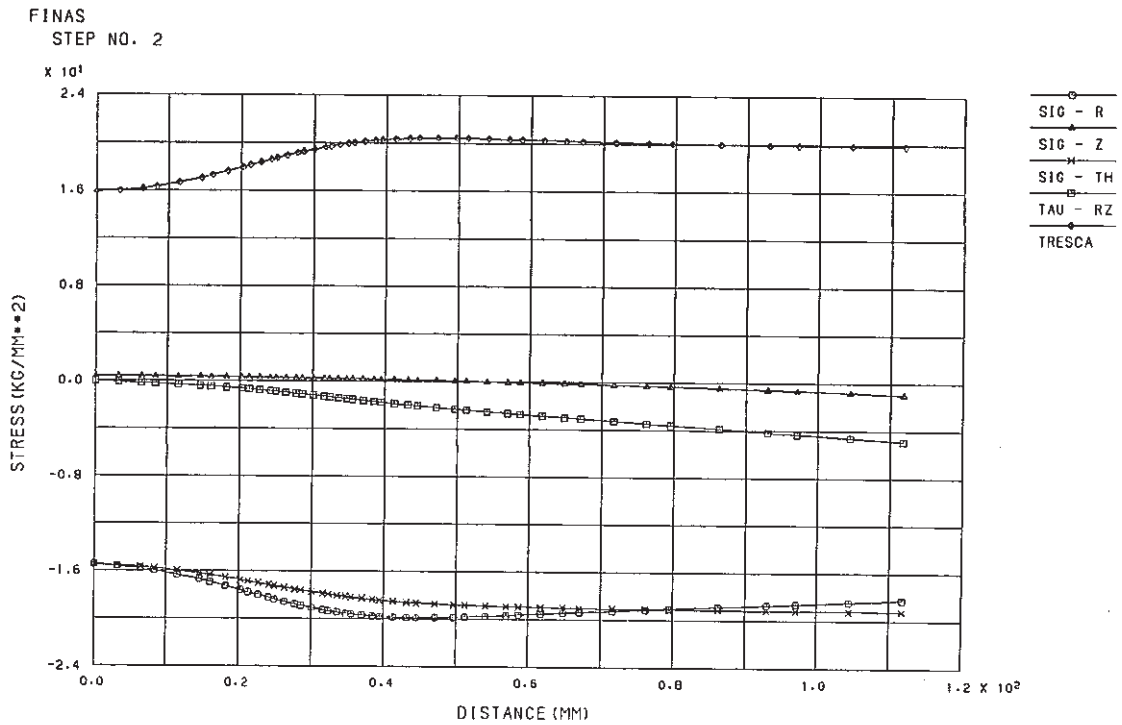


Fig. C.6.4-1 Stress Distribution along Outer Surface at Cold Shock of Stud Bolt (crack depth a=1 mm)

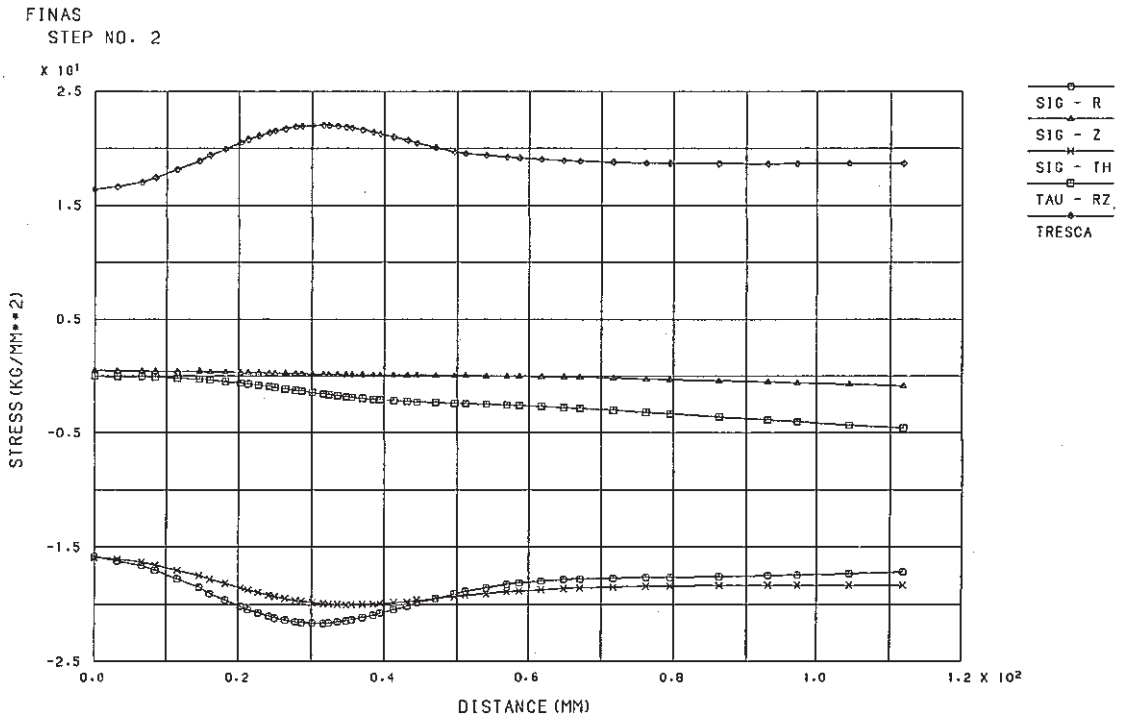


Fig. C.6.4-2 Stress Distribution along Outer Surface at Cold Shock of Stud Bolt (crack depth a=7 mm)

FINAS
STEP NO. 2

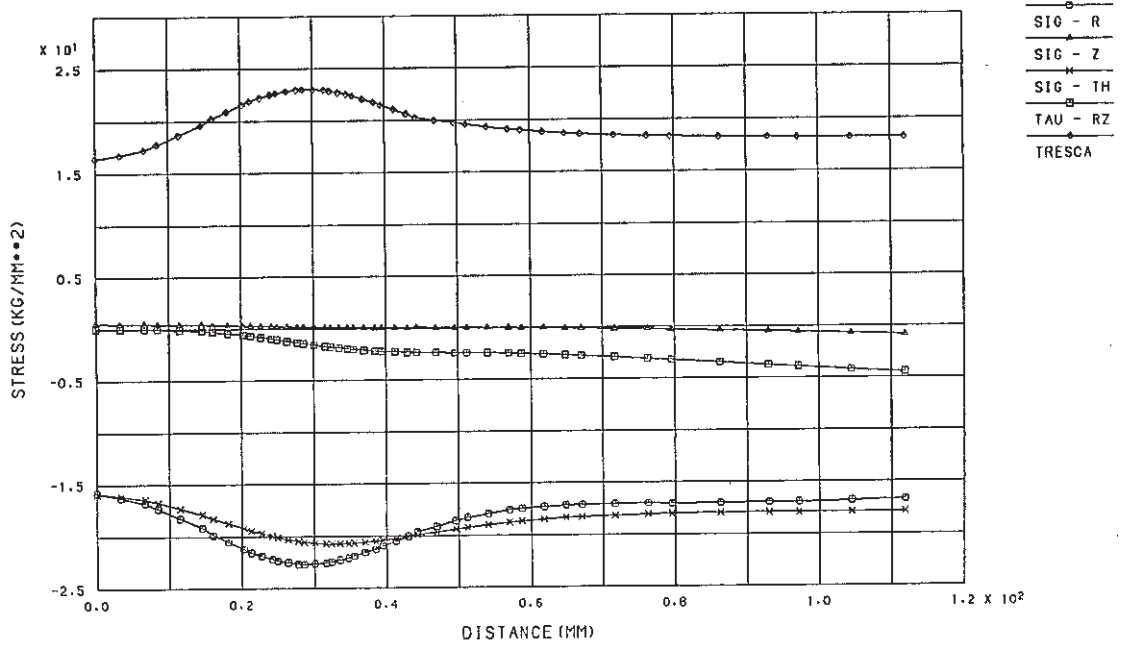


Fig. C.6.4-3 Stress Distribution along Outer Surface at Cold Shock of Stud Bolt (crack depth a=10 mm)

FINAS
STEP NO. 2

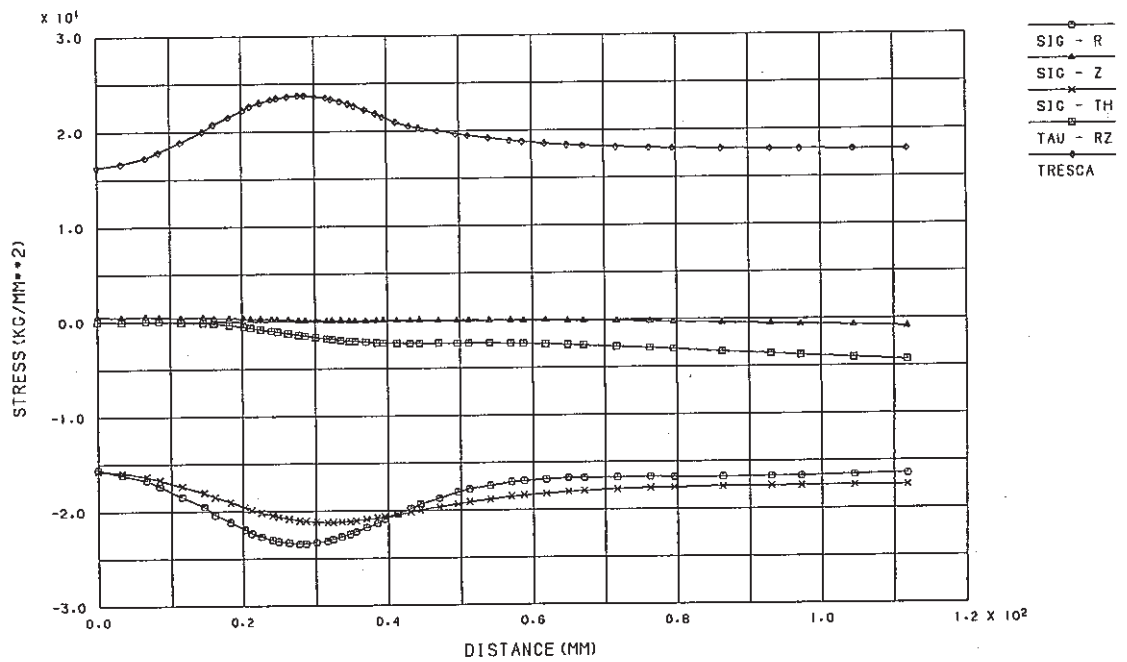


Fig. C.6.4-4 Stress Distribution along Outer Surface at Cold Shock of Stud Bolt (crack depth a=13 mm)

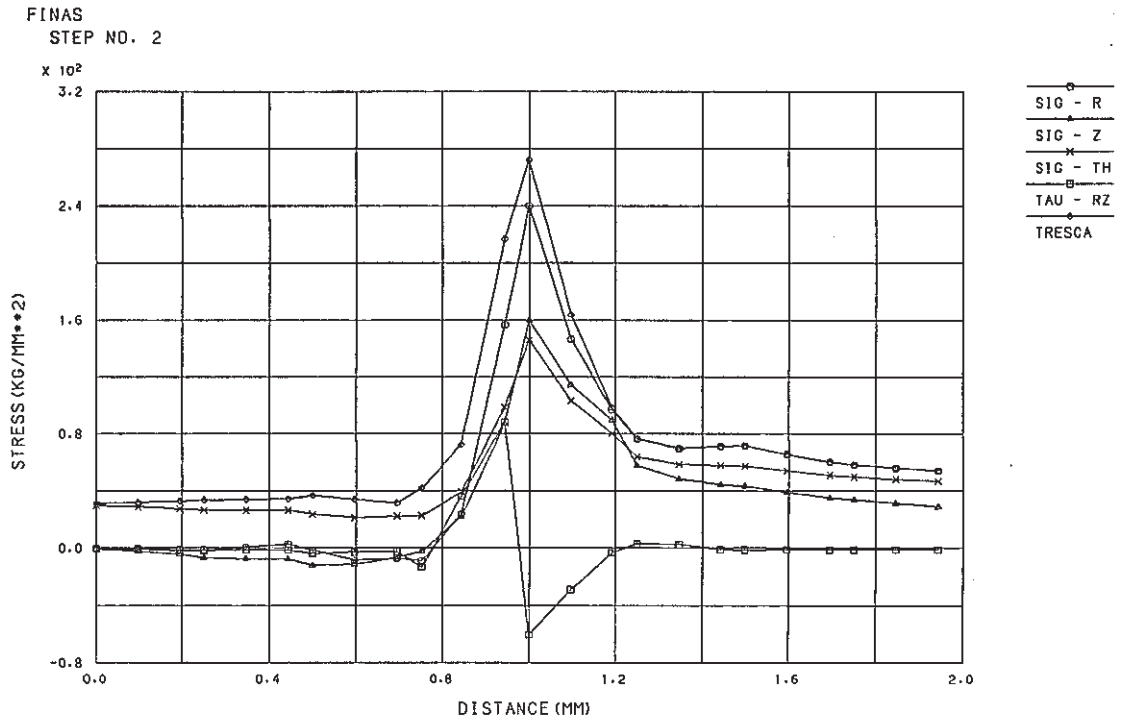


Fig. C.6.5-1 Stress Distribution along Crack Line at Cold Shock of Stud Bolt (crack depth a=1)

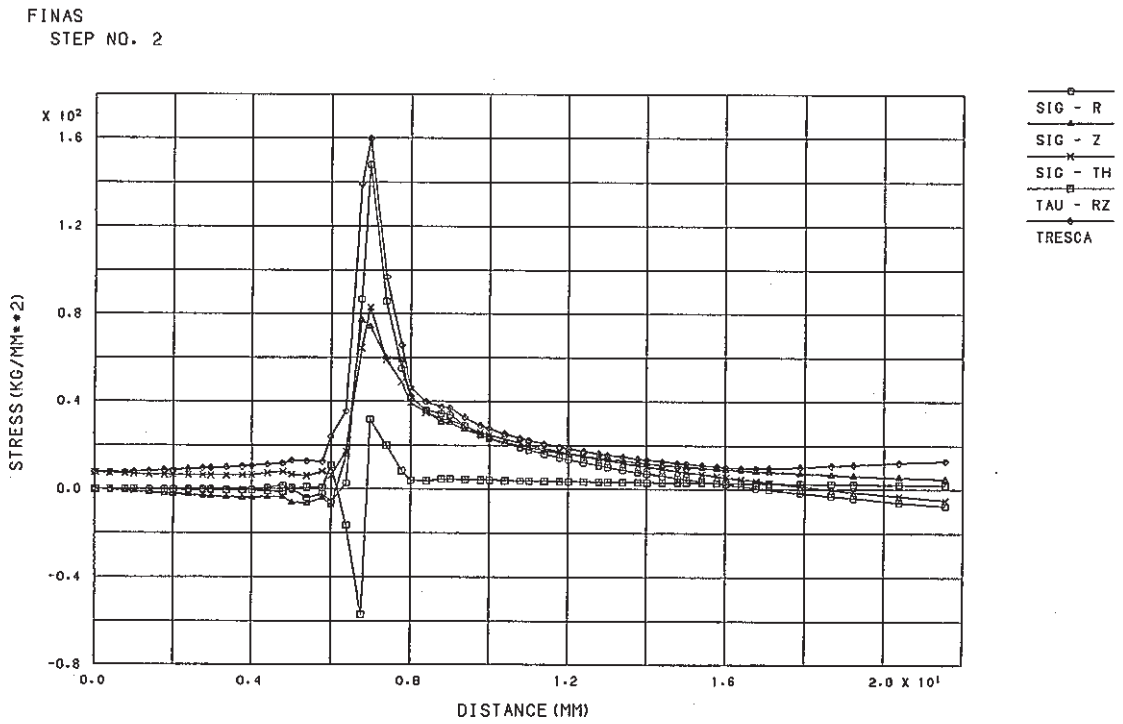


Fig. C.6.5-2 Stress Distribution along Crack Line at Cold Shock of Stud Bolt (crack depth a=7 mm)

FINAS
STEP NO. 2

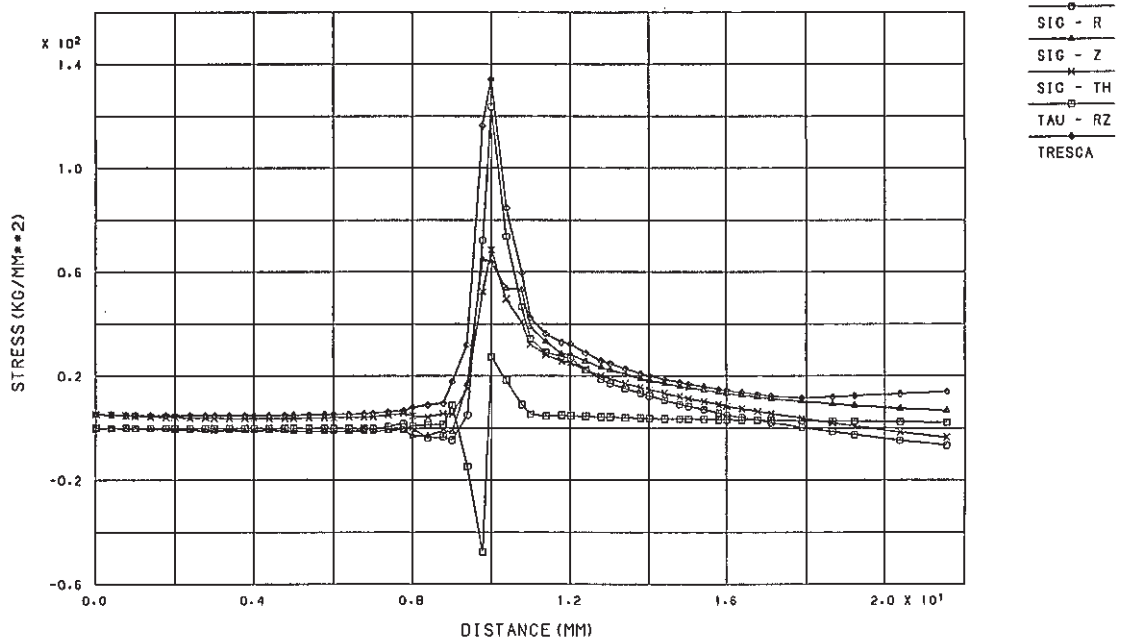


Fig. C.6.5-3 Stress Distribution along Crack Line at Cold Shock of Stud Bolt (crack depth a=10 mm)

FINAS
STEP NO. 2

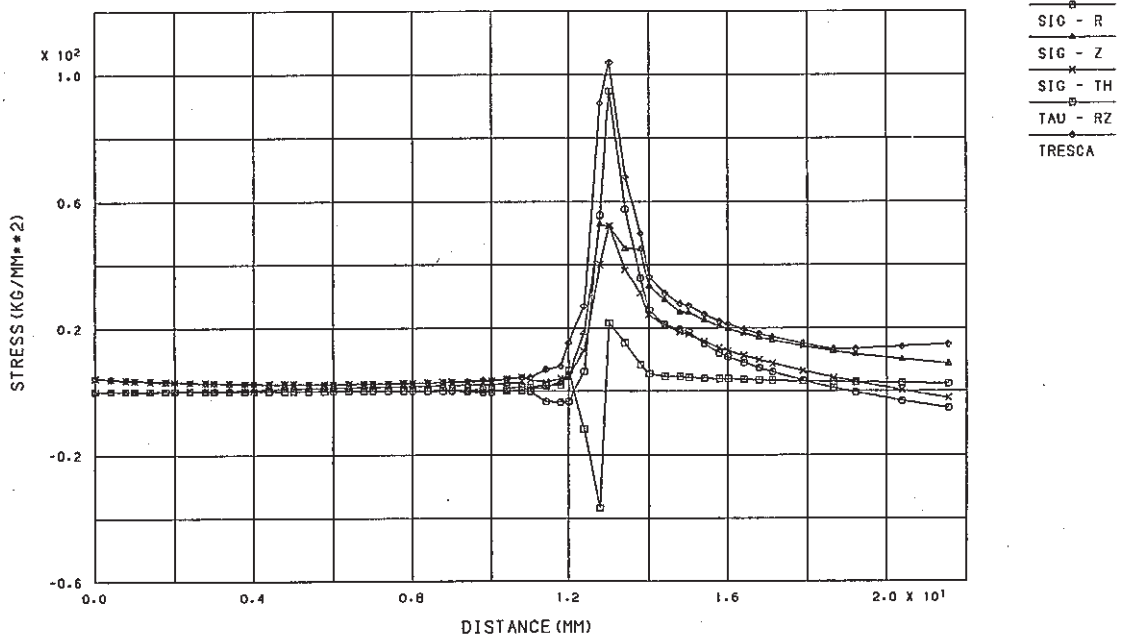


Fig. C.6.5-4 Stress Distribution along Crack Line at Cold Shock of Stud Bolt (crack depth a=13 mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -7.00000
2 18.00000
3 43.00000
4 68.00000
5 93.00000
6 118.0000
7 143.0000
8 168.0000
9 193.0000
10 218.0000

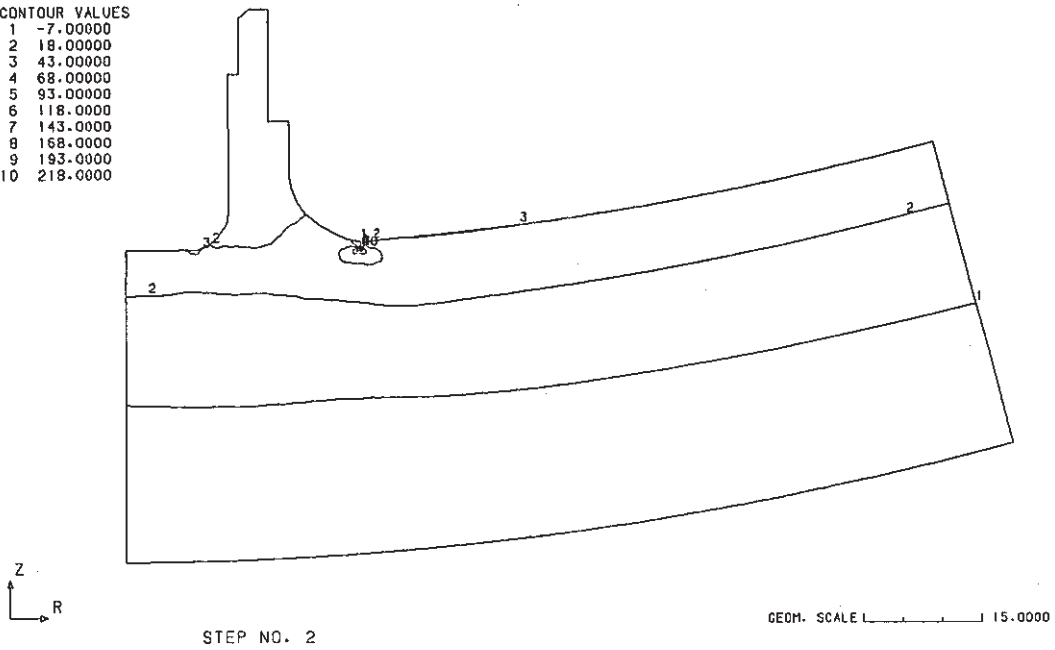


Fig. C.6.6-1 Contour of Radial Stress at Cold Shock of Stud Bolt
(crack depth $a=1$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -13.0000
2 4.000000
3 21.00000
4 38.00000
5 55.00000
6 72.00000
7 89.00000
8 106.0000
9 123.0000
10 140.0000

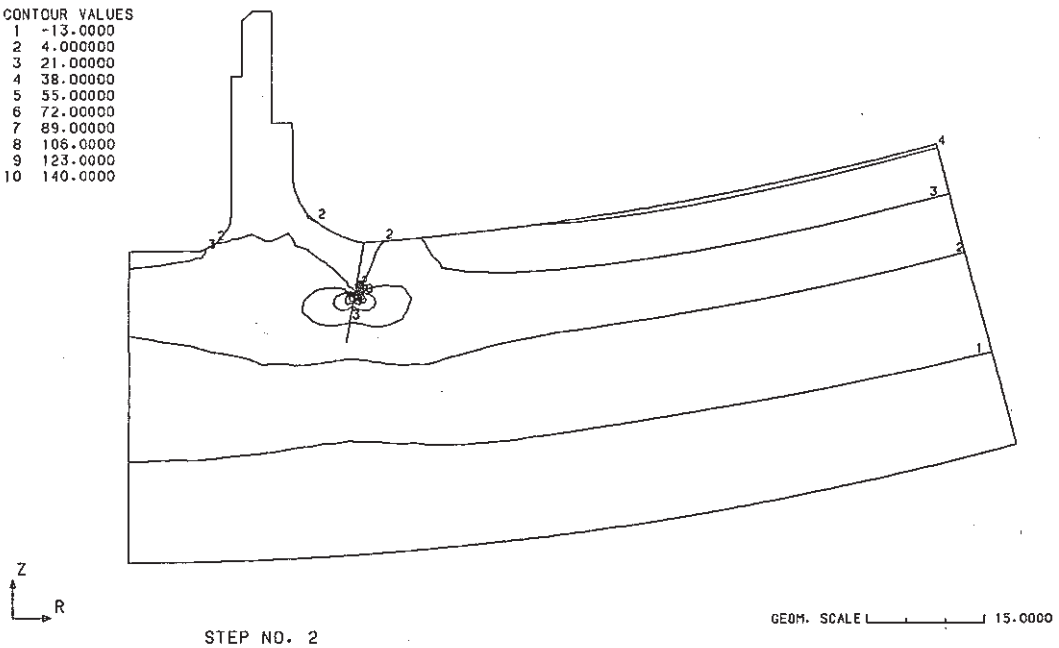


Fig. C.6.6-2 Contour of Radial Stress at Cold Shock of Stud Bolt
(crack depth $a=7$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -16.0000
2 -1.00000
3 14.00000
4 29.00000
5 44.00000
6 59.00000
7 74.00000
8 89.00000
9 104.0000
10 119.0000

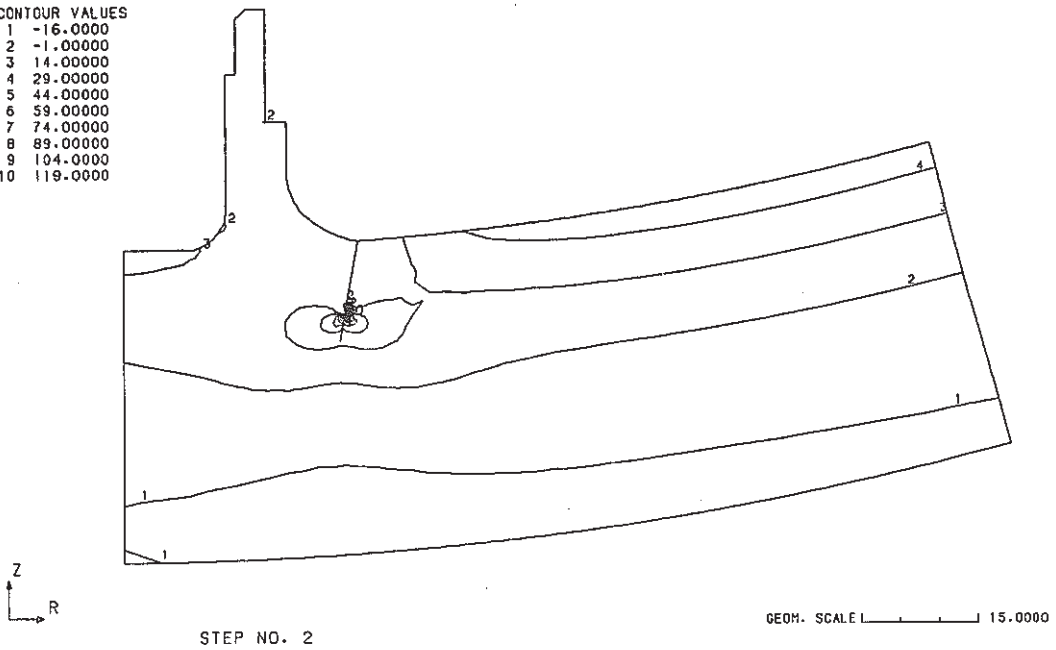


Fig. C.6.6-3 Contour of Radial Stress at Cold Shock of Stud Bolt
(crack depth $a=10$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -18.0000
2 -6.00000
3 6.000000
4 18.00000
5 30.00000
6 42.00000
7 54.00000
8 66.00000
9 78.00000
10 90.00000

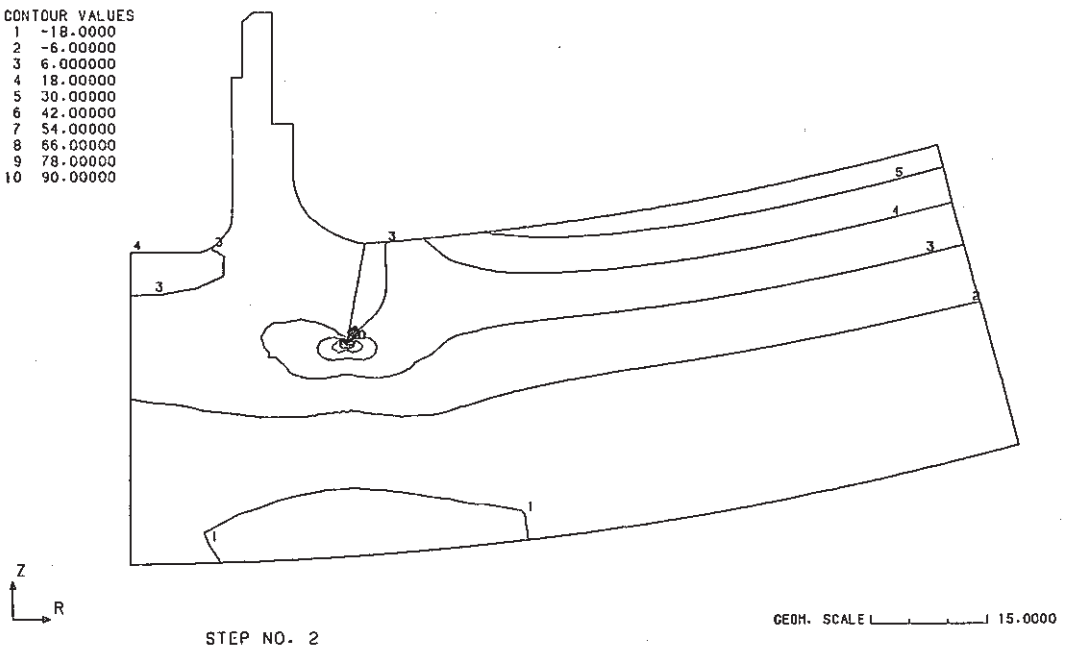


Fig. C.6.6-4 Contour of Radial Stress at Cold Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -12.0000
2 3.000000
3 18.00000
4 33.00000
5 48.00000
6 63.00000
7 78.00000
8 93.00000
9 108.0000
10 123.0000

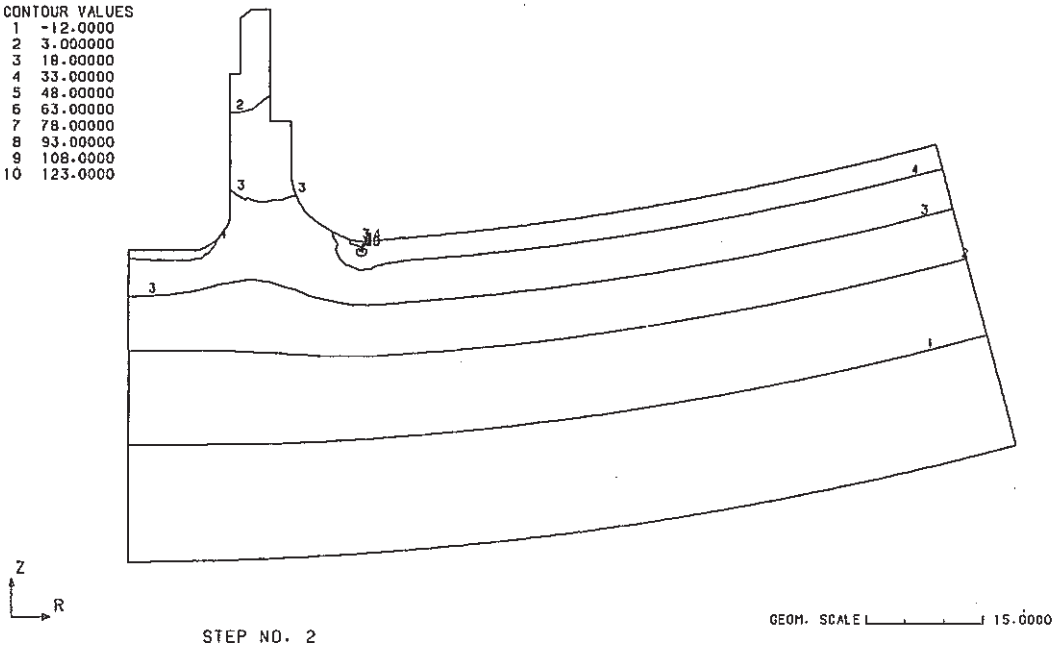


Fig. C.6.7-1 Contour of Hoop Stress at Cold Shock of Stud Bolt
(crack depth $a=1$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -15.0000
2 -4.00000
3 7.000000
4 18.00000
5 29.00000
6 40.00000
7 51.00000
8 62.00000
9 73.00000
10 84.00000

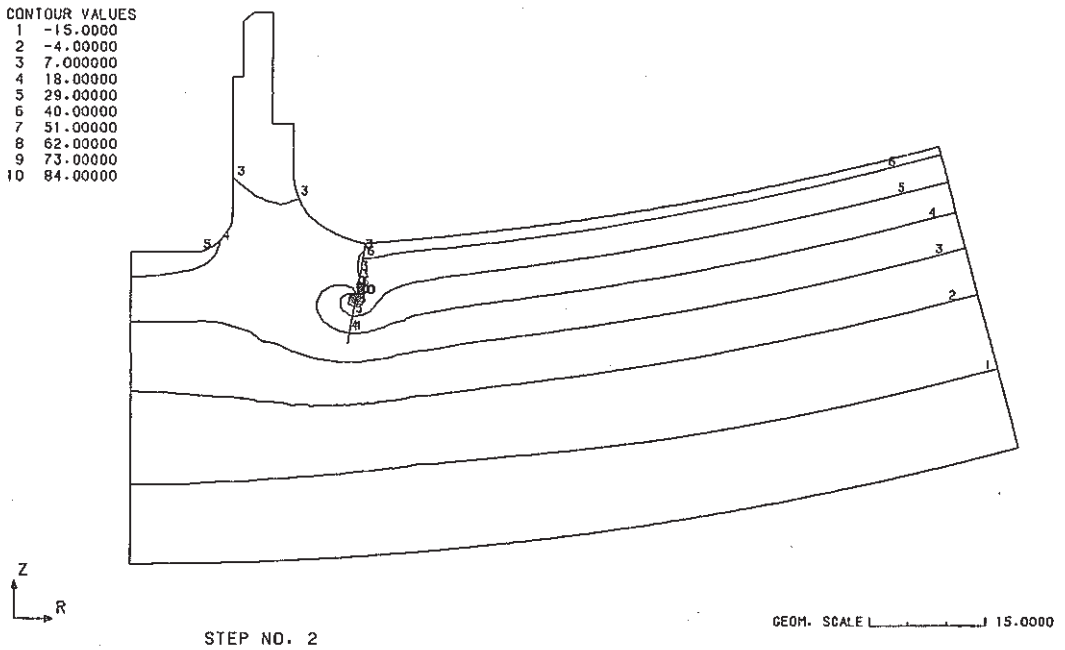


Fig. C.6.7-2 Contour of Hoop Stress at Cold Shock of Stud Bolt
(crack depth $a=7$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -16.0000
2 -6.00000
3 4.000000
4 14.00000
5 24.00000
6 34.00000
7 44.00000
8 54.00000
9 64.00000
10 74.00000

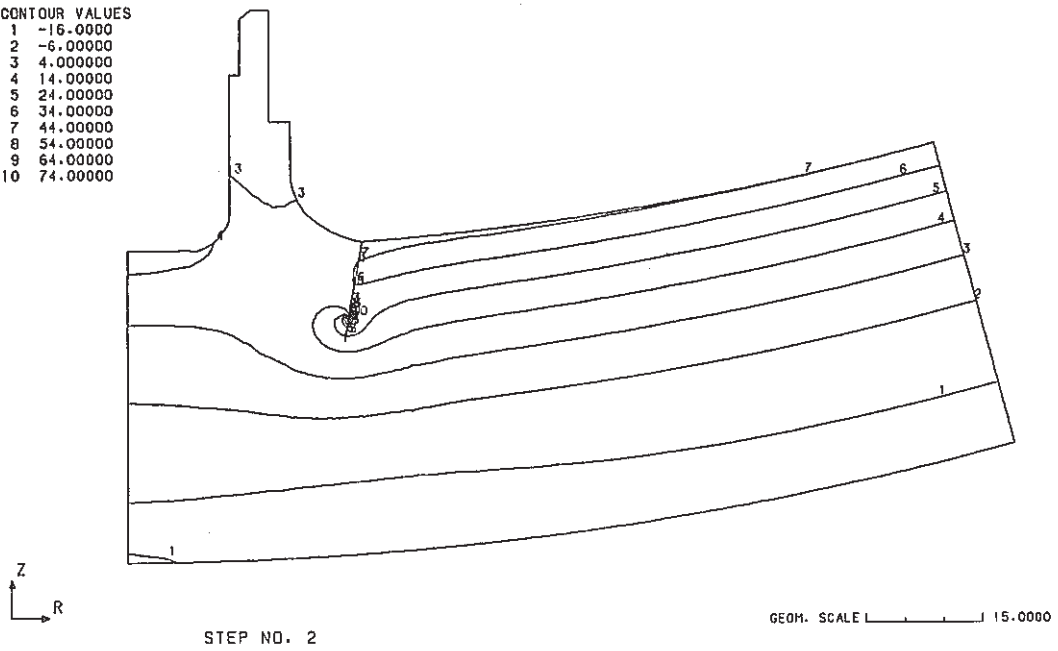


Fig. C.6.7-3 Contour of Hoop Stress at Cold Shock of Stud Bolt
(crack depth $a=10$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -17.6000
2 -9.70000
3 -1.80000
4 6.100000
5 14.00000
6 21.90000
7 29.80000
8 37.70000
9 45.60000
10 53.50000

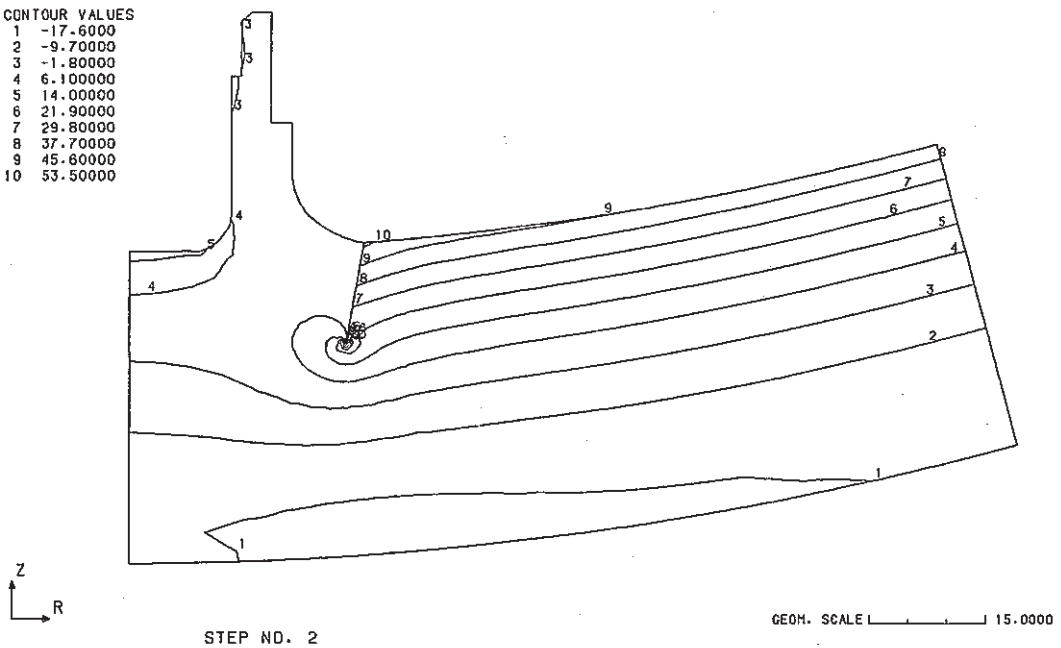


Fig. C.6.7-4 Contour of Hoop Stress at Cold Shock of Stud Bolt
(crack depth $a=13$ mm)

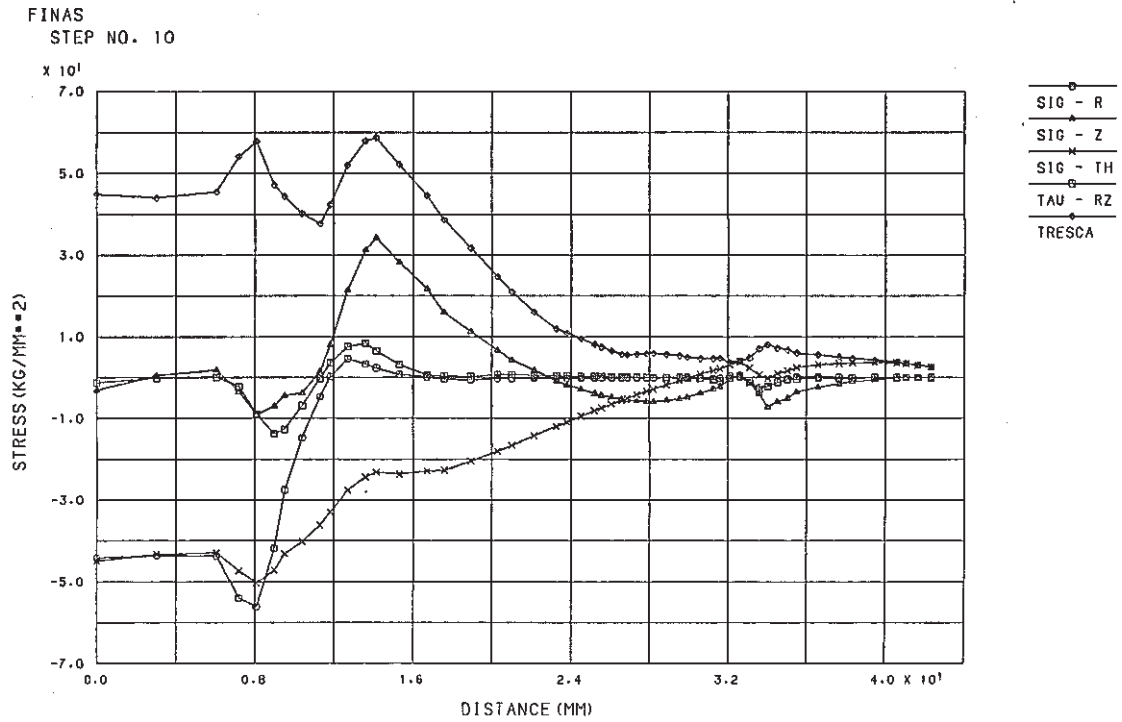


Fig. C.6.8-1 Stress Distribution along Inner-1 Surface at Hot Shock of Stud Bolt (crack depth a=1 mm)

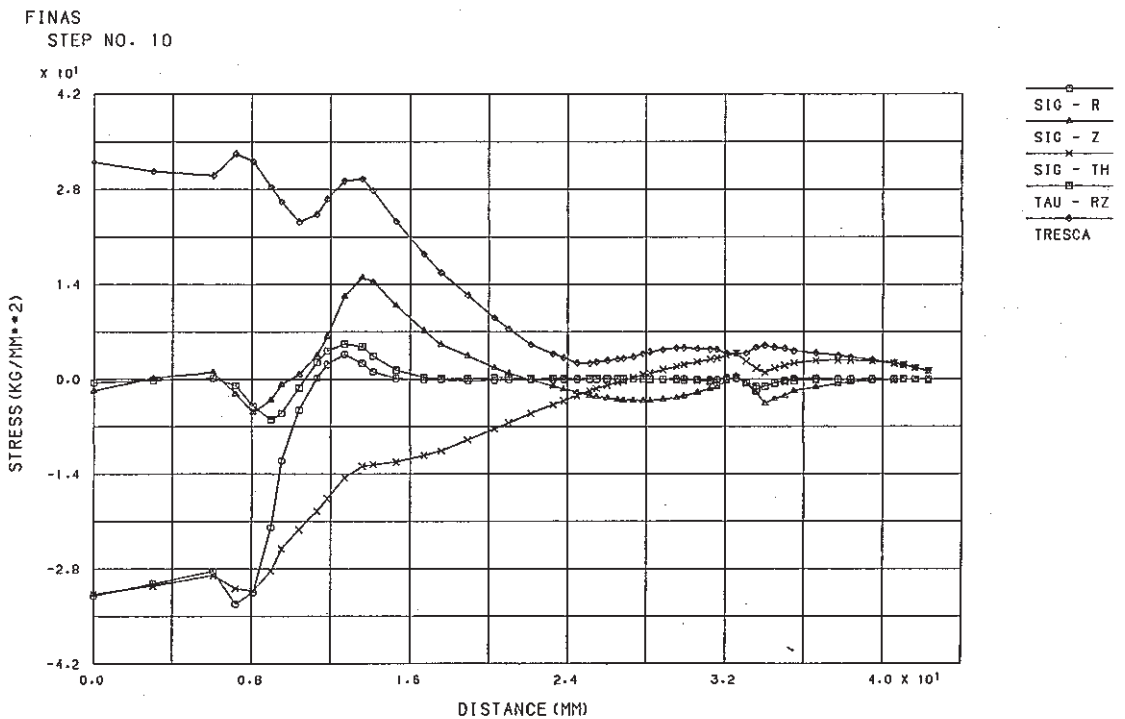


Fig. C.6.8-2 Stress Distribution along Inner-1 Surface at Hot Shock of Stud Bolt (crack depth a=7 mm)

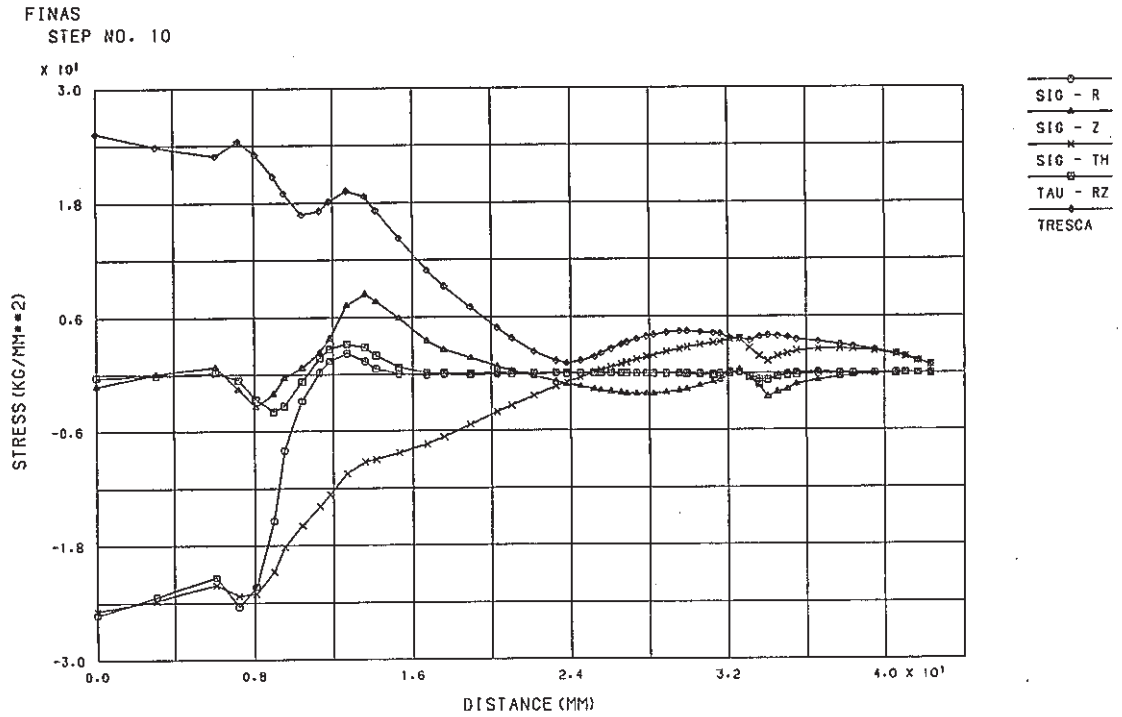


Fig. C.6.8-3 Stress Distribution along Inner-l Surface at Hot Shock of Stud Bolt (crack depth a=10 mm)

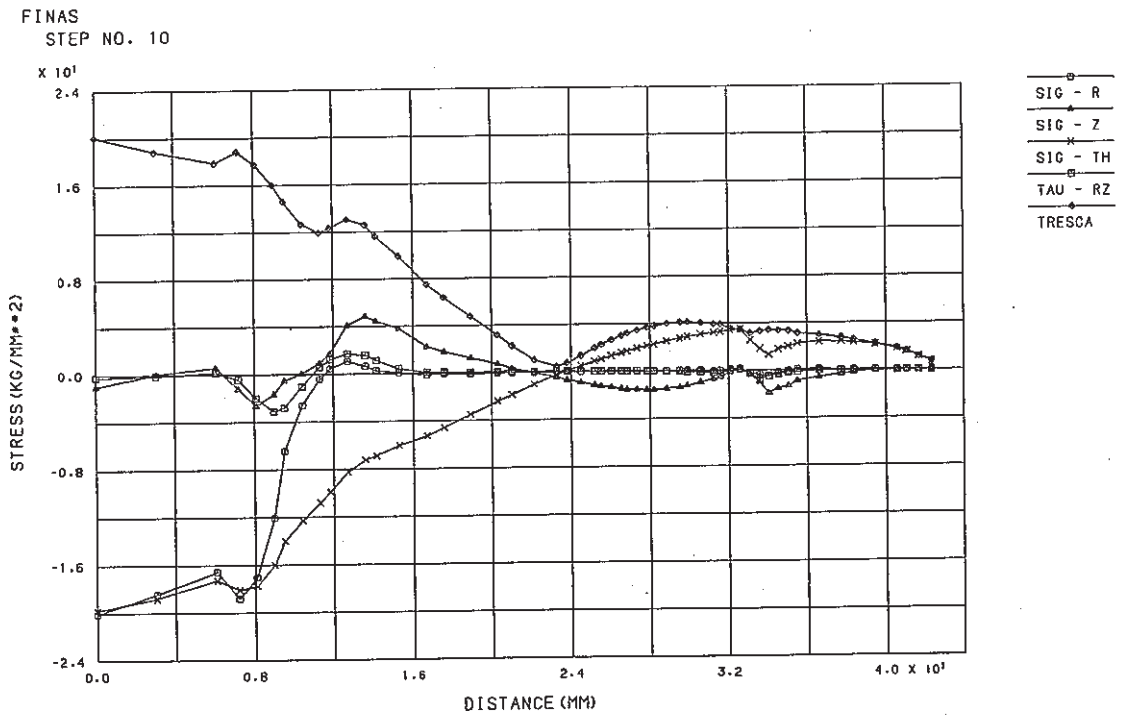


Fig. C.6.8-4 Stress Distribution along Inner-l Surface at Hot Shock of Stud Bolt (crack depth a=13 mm)

FINAS
STEP NO. 10

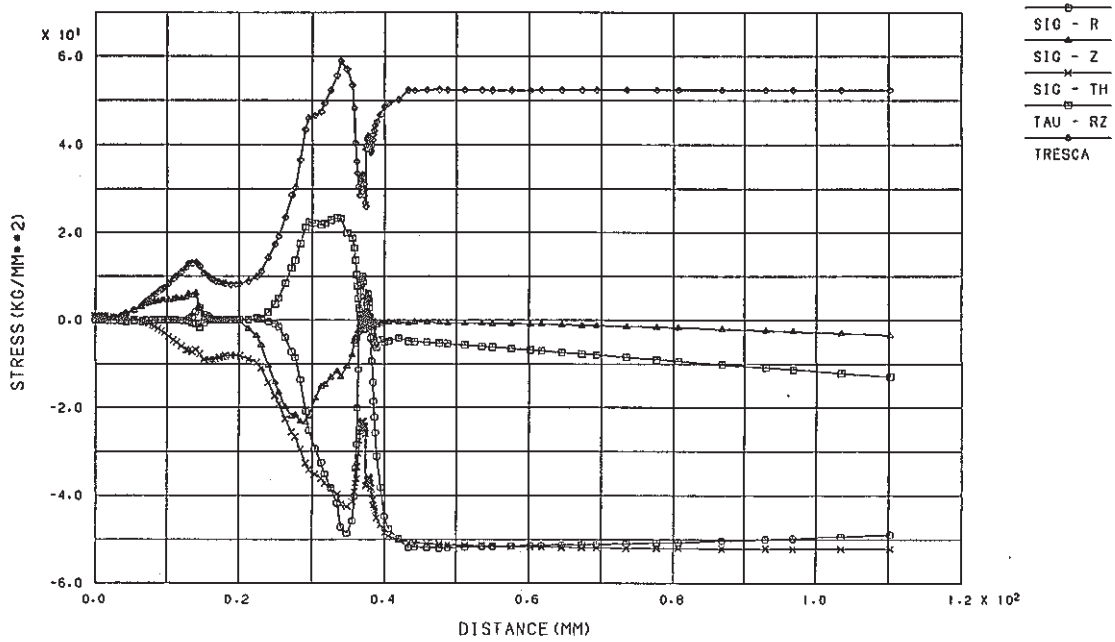


Fig. C.6.9-1 Stress Distribution along Inner-2 Surface at Hot Shock of Stud Bolt (crack depth a=1 mm)

FINAS
STEP NO. 10

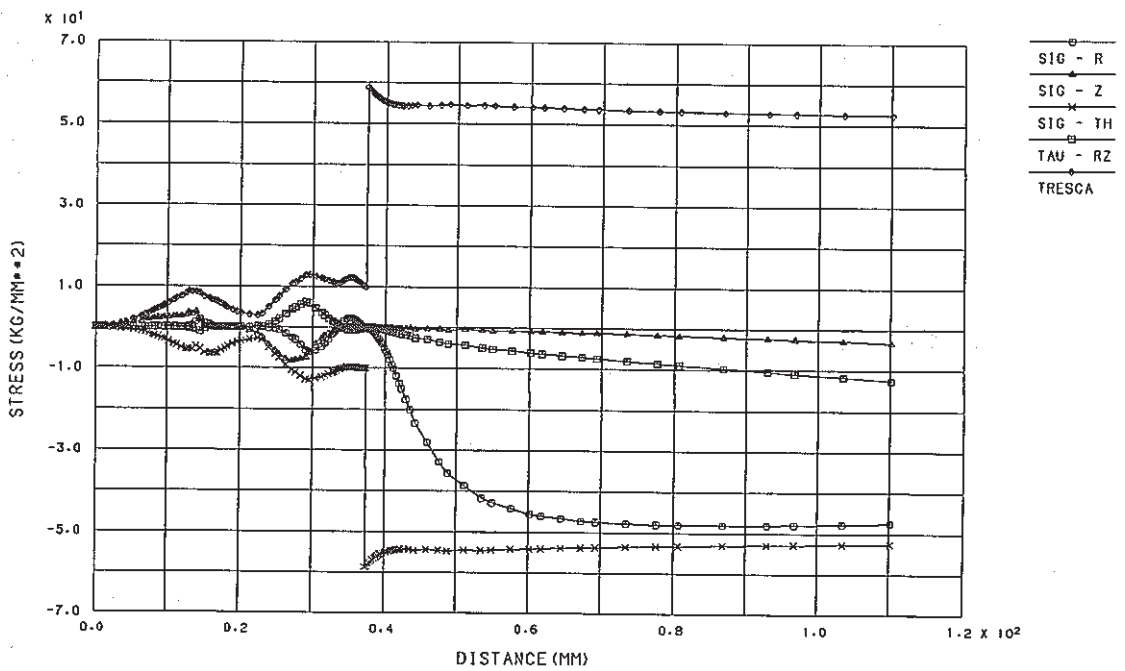


Fig. C.6.9-2 Stress Distribution along Inner-2 Surface at Hot Shock of Stud Bolt (crack depth a=7 mm)

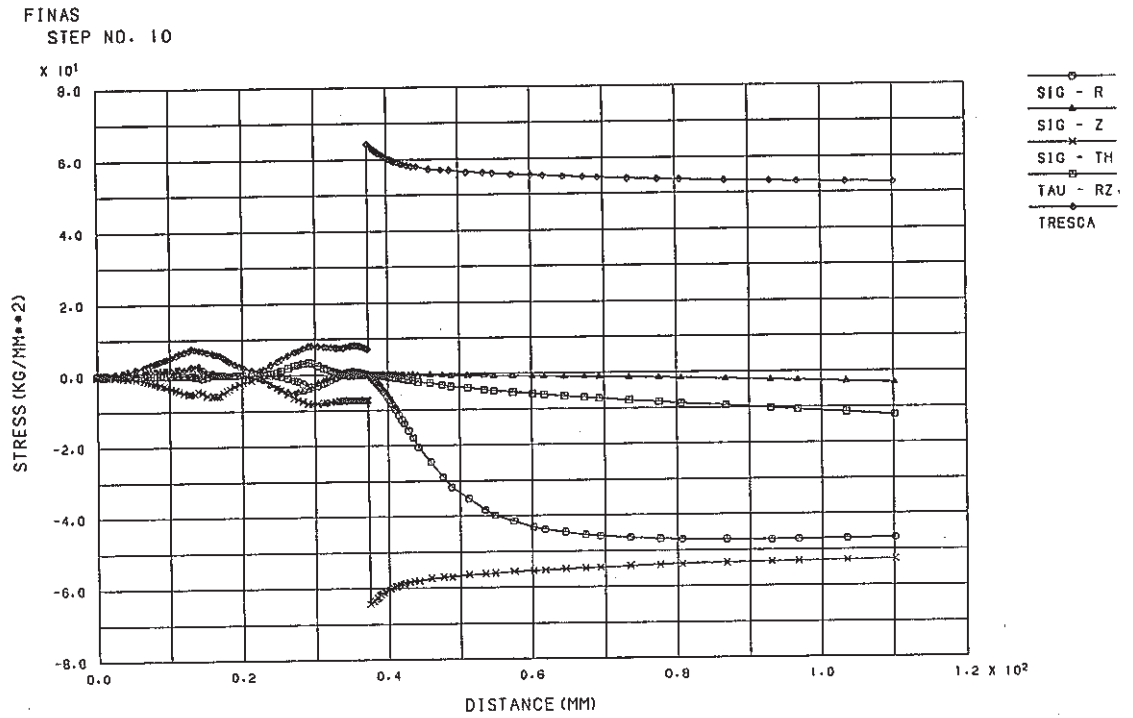


Fig. C.6.9-3 Stress Distribution along Inner-2 Surface at Hot Shock of Stud Bolt (crack depth a=10 mm)

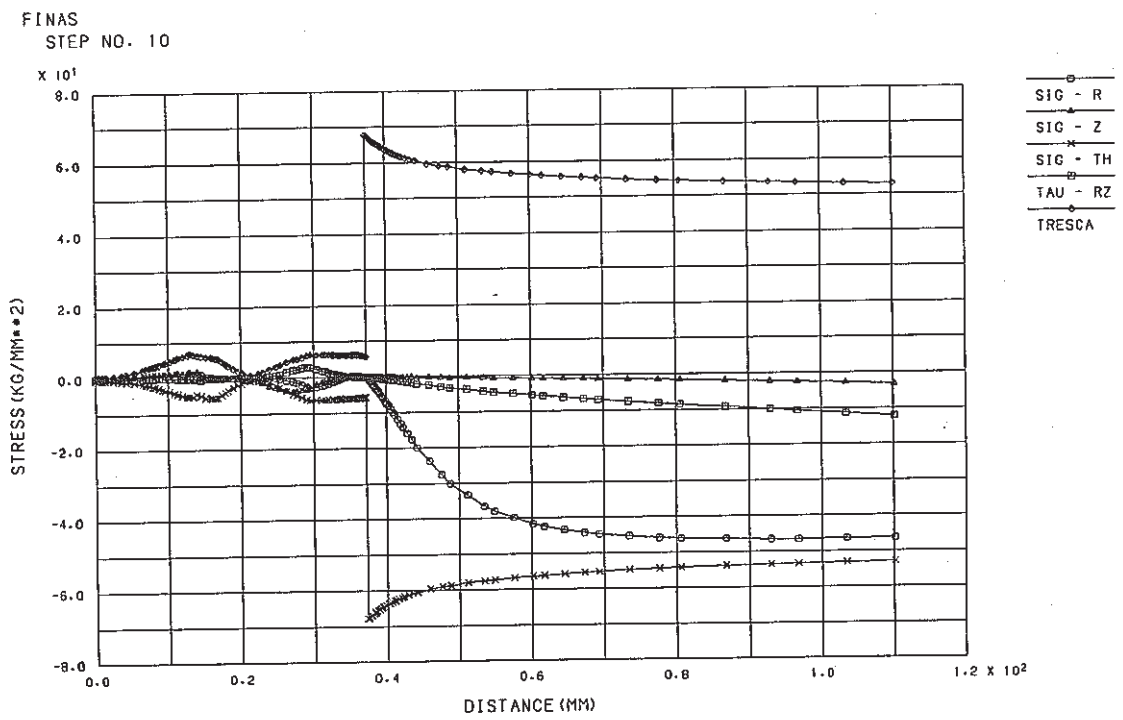


Fig. C.6.9-4 Stress Distribution along Inner-2 Surface at Hot Shock of Stud Bolt (crack depth a=13 mm)

FINAS
STEP NO. 10

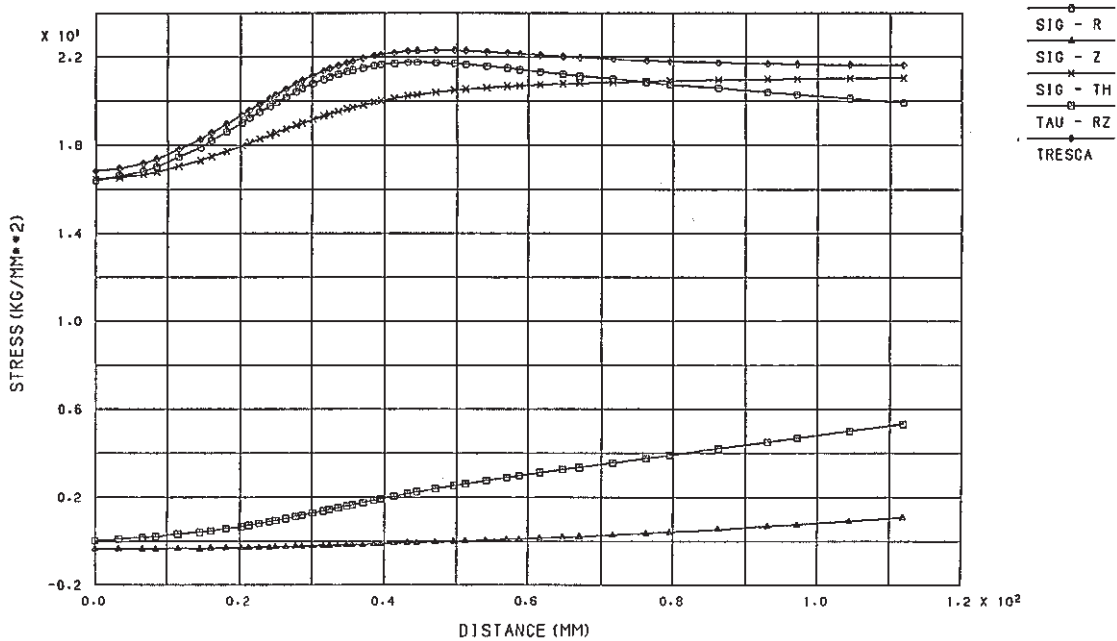


Fig. C.6.10-1 Stress Distribution along Outer Surface at Hot Shock of Stud Bolt (crack depth a=1 mm)

FINAS
STEP NO. 10

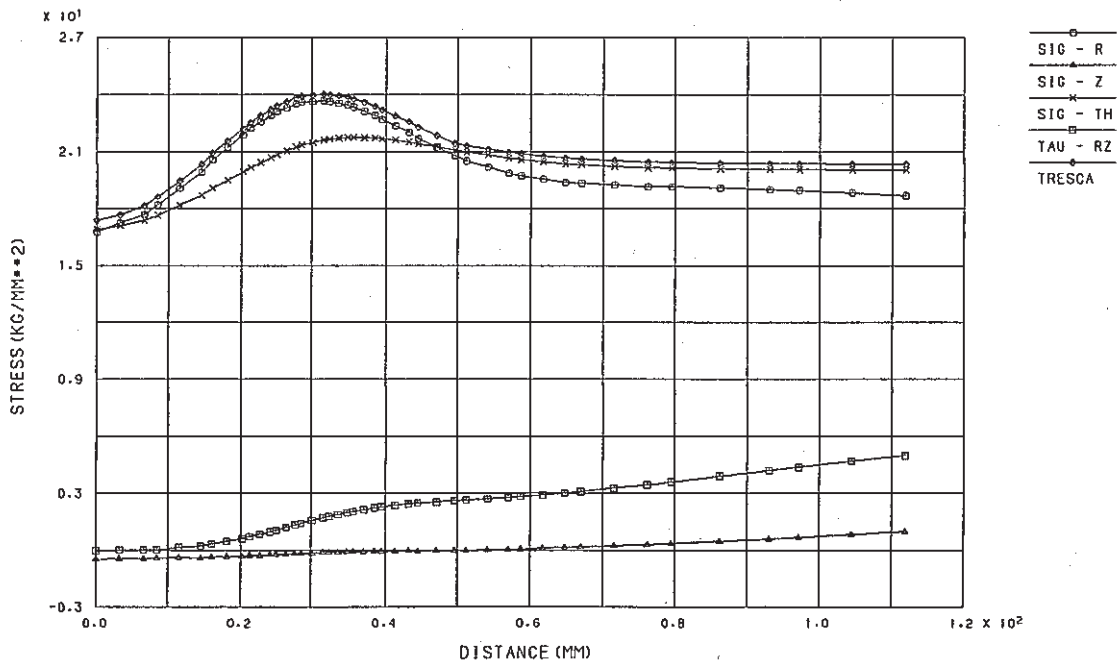


Fig. C.6.10-2 Stress Distribution along Outer Surface at Hot Shock of Stud Bolt (crack depth a=7 mm)

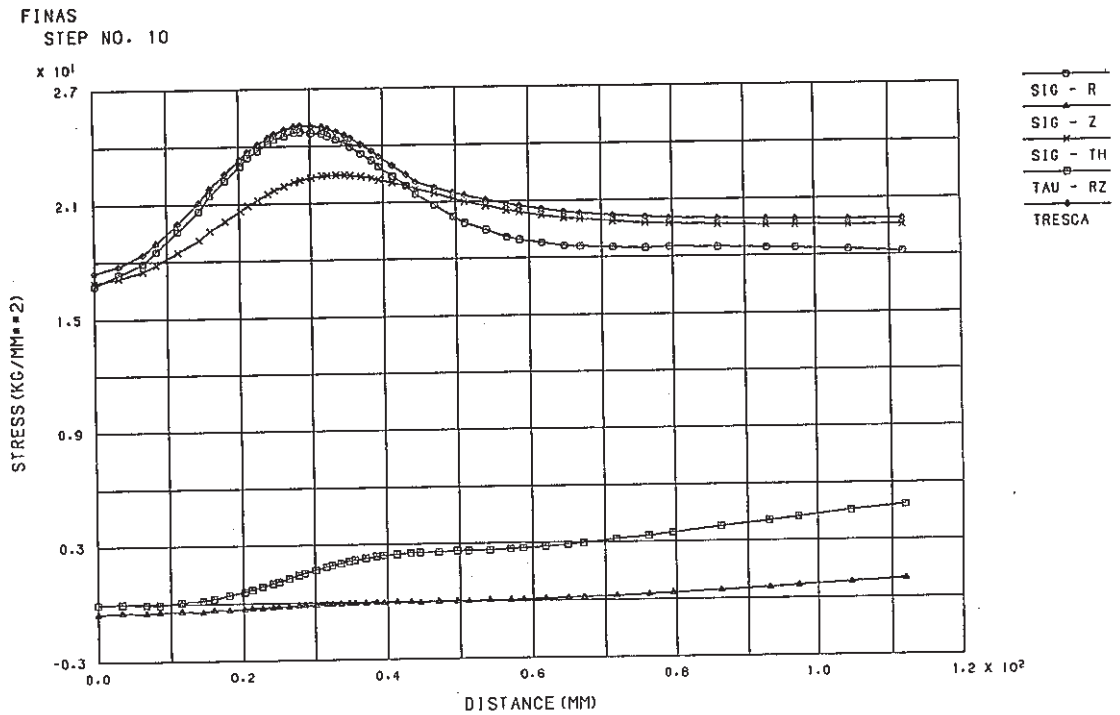


Fig. C.6.10-3 Stress Distribution along Outer Surface at Hot Shock of Stud Bolt (crack depth a=10 mm)

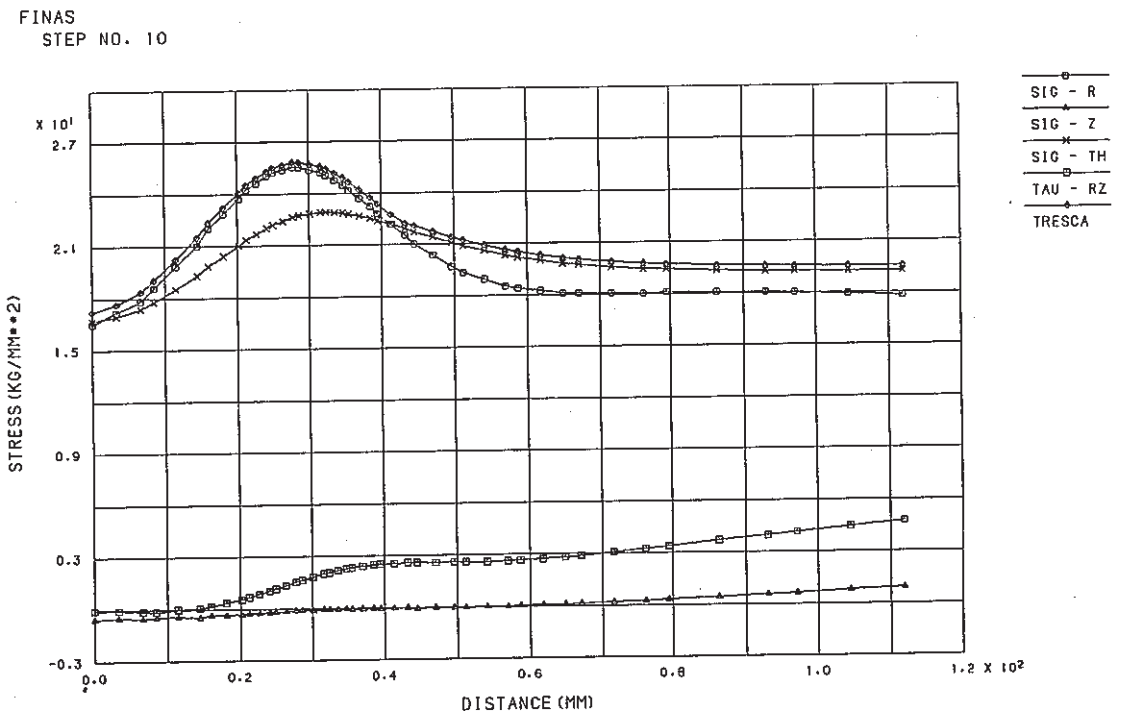


Fig. C.6.10-4 Stress Distribution along Outer Surface at Hot Shock of Stud Bolt (crack depth a=13 mm)

FINAS
STEP NO. 10

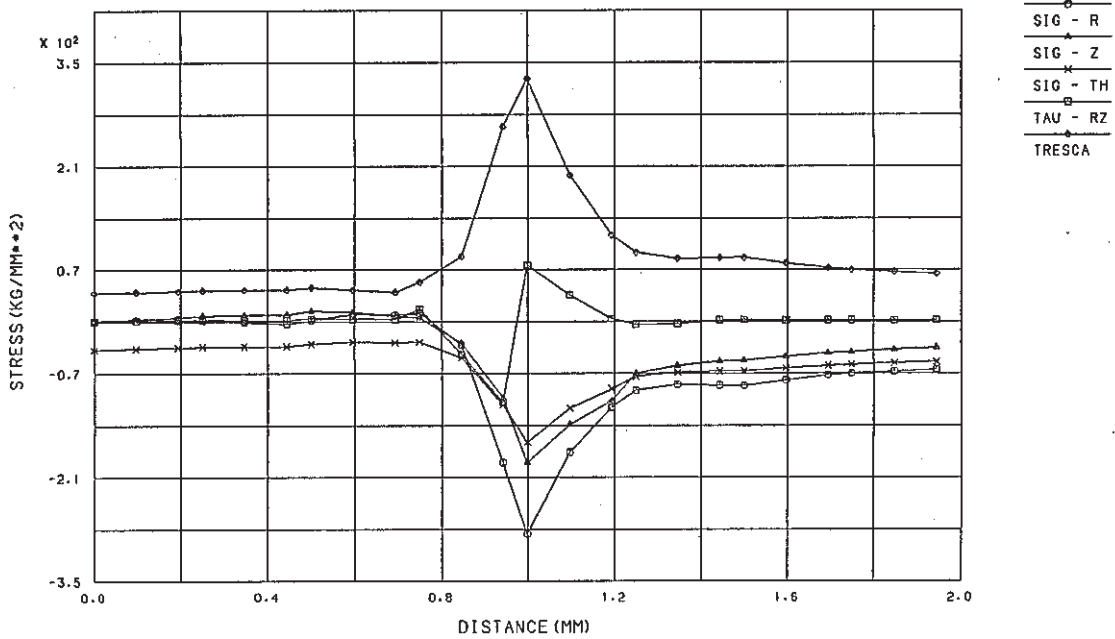


Fig. C.6.11-1 Stress Distribution along Crack Line at Hot Shock of Stud Bolt (crack depth a=1 mm)

FINAS
STEP NO. 10

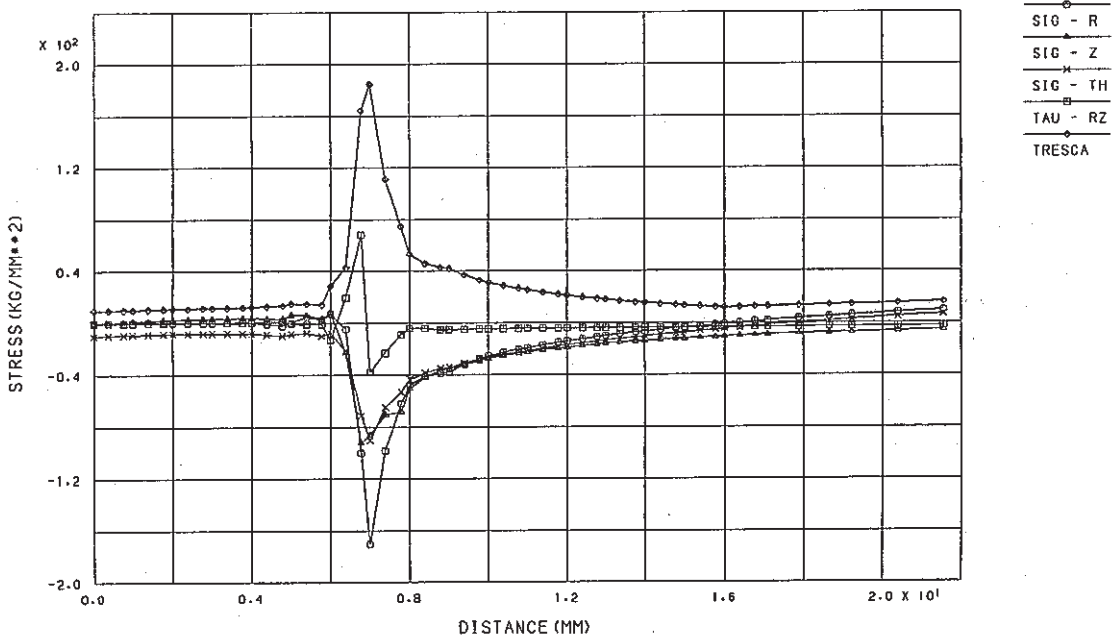


Fig. C.6.11-2 Stress Distribution along Crack Line at Hot Shock of Stud Bolt (crack depth a=7 mm)

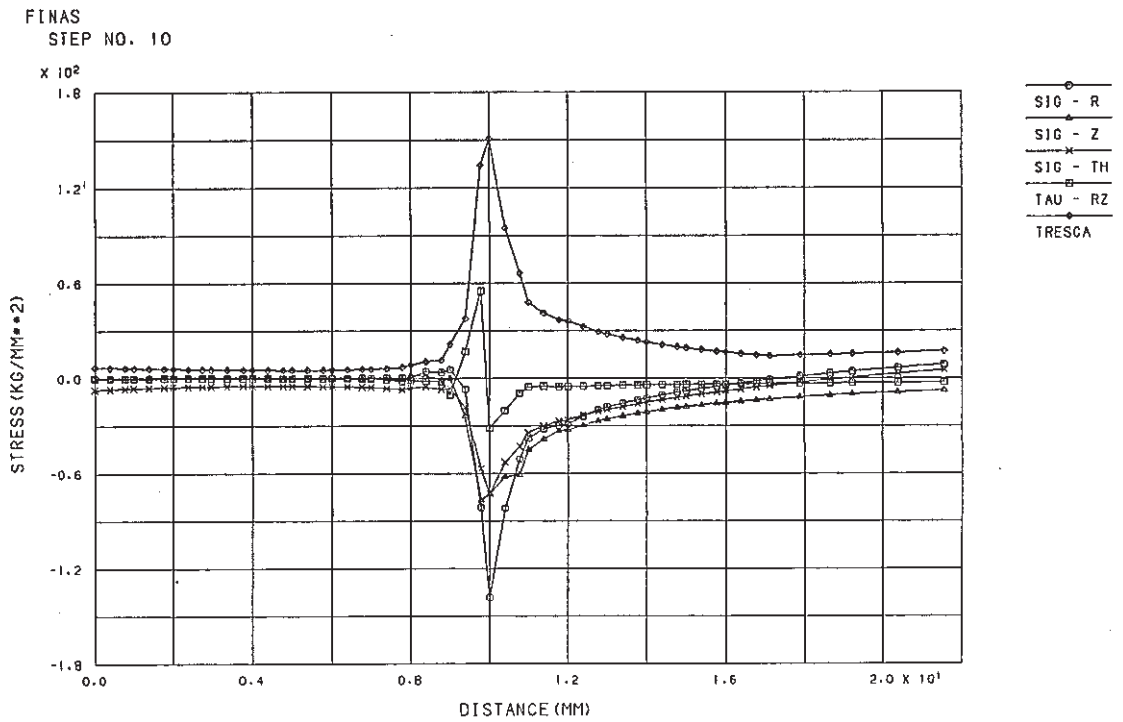


Fig. C.6.11-3 Stress Distribution along Crack Line at Hot Shock of Stud Bolt (crack depth a=10 mm)

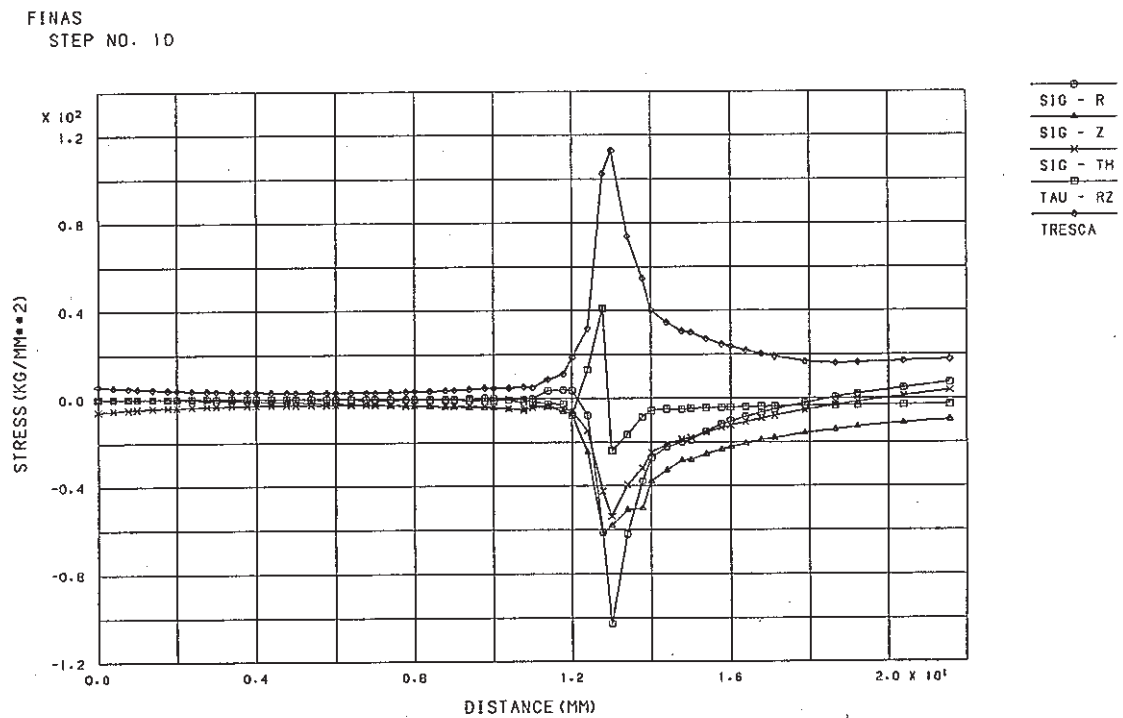


Fig. C.6.11-4 Stress Distribution along Crack Line at Hot Shock of Stud Bolt (crack depth a=13 mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -259.000
2 -229.000
3 -199.000
4 -169.000
5 -139.000
6 -109.000
7 -79.0000
8 -49.0000
9 -19.0000
10 11.00000

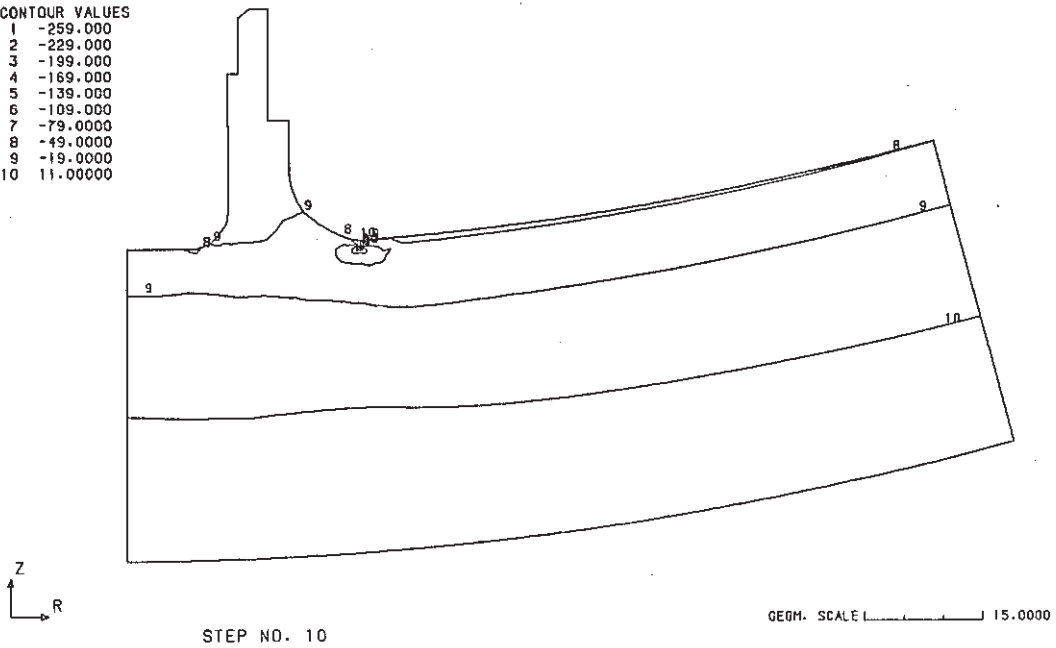


Fig. C.6.12-1 Contour of Radial Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -159.000
2 -140.000
3 -121.000
4 -102.000
5 -83.0000
6 -64.0000
7 -45.0000
8 -26.0000
9 -7.00000
10 12.00000

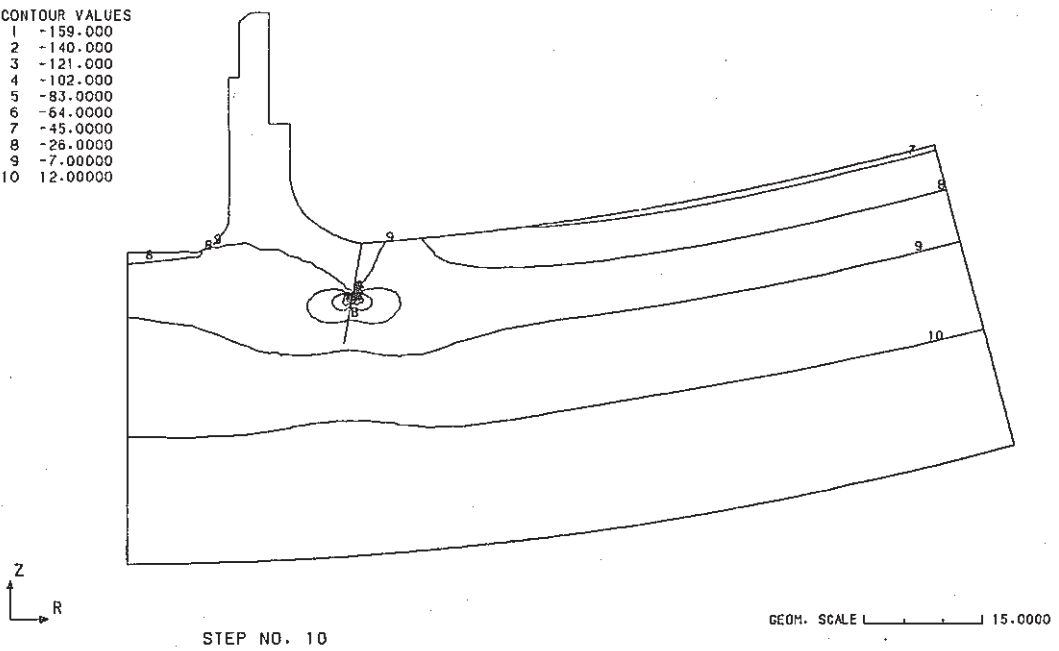


Fig. C.6.12-2 Contour of Radial Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -130.000
2 -114.000
3 -98.0000
4 -82.0000
5 -66.0000
6 -50.0000
7 -34.0000
8 -18.0000
9 -2.00000
10 14.00000

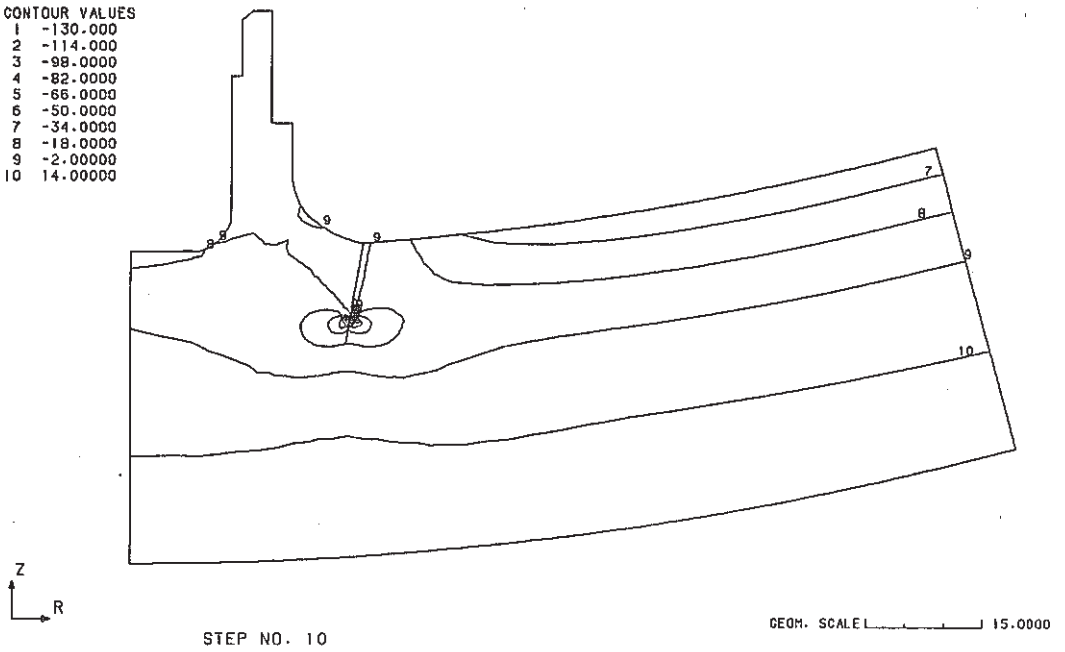


Fig. C.6.12-3 Contour of Radial Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 1

CONTOUR VALUES
1 -95.0000
2 -82.0000
3 -69.0000
4 -56.0000
5 -43.0000
6 -30.0000
7 -17.0000
8 -4.00000
9 9.000000
10 22.00000

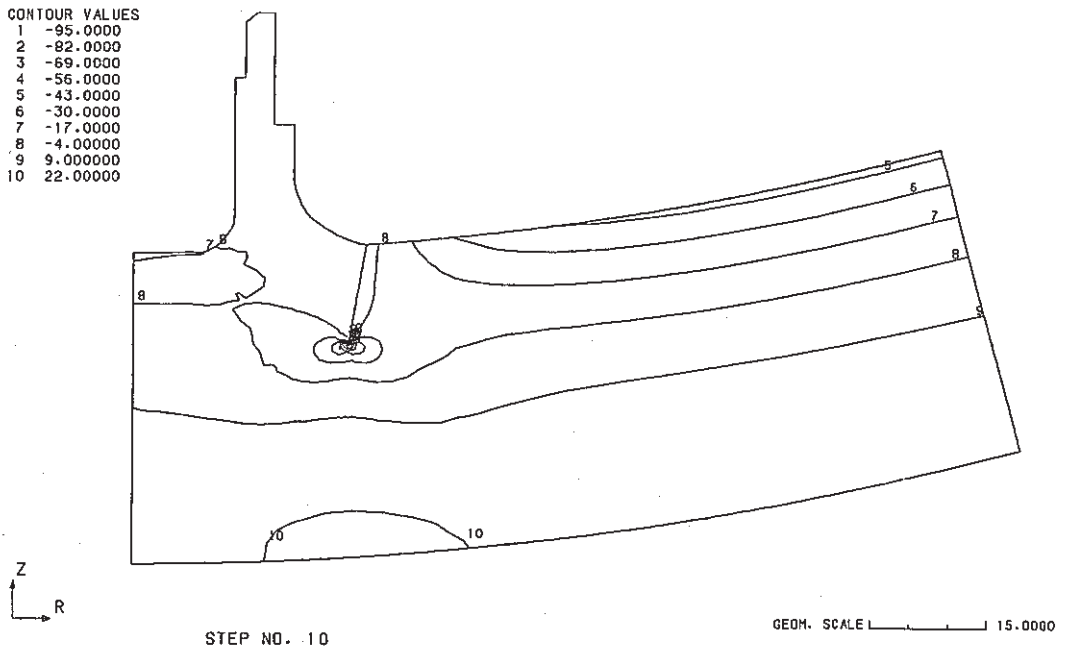


Fig. C.6.12-4 Contour of Radial Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -143.000
2 -126.000
3 -109.000
4 -92.0000
5 -75.0000
6 -58.0000
7 -41.0000
8 -24.0000
9 -7.00000
10 10.00000

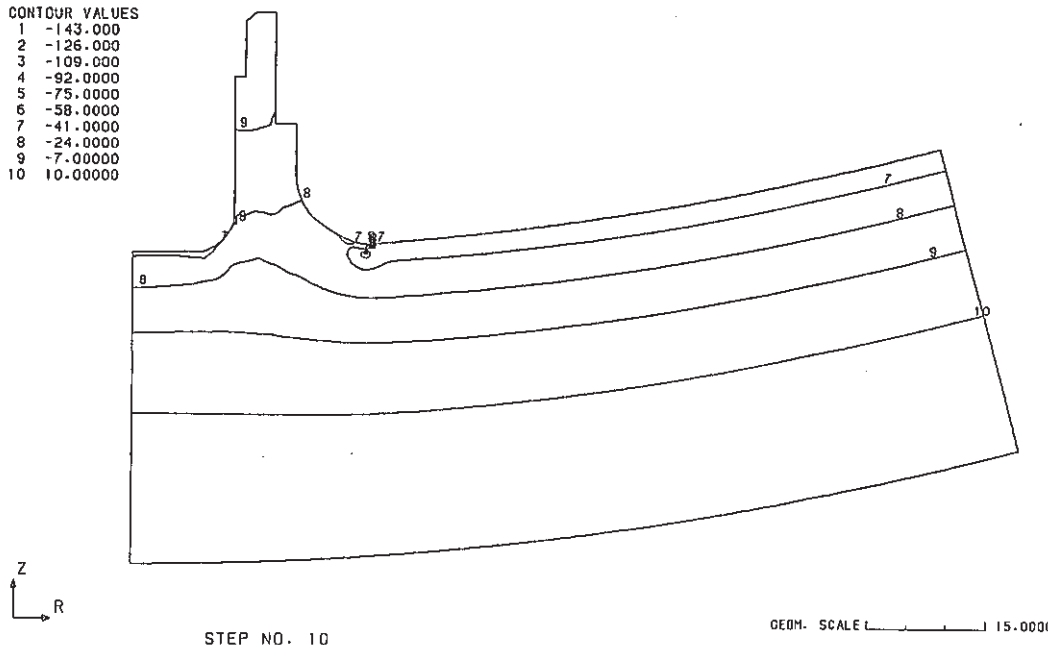


Fig. C.6.13-1 Contour of Hoop Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -96.0000
2 -84.0000
3 -72.0000
4 -60.0000
5 -48.0000
6 -36.0000
7 -24.0000
8 -12.0000
9 0.0
10 12.00000

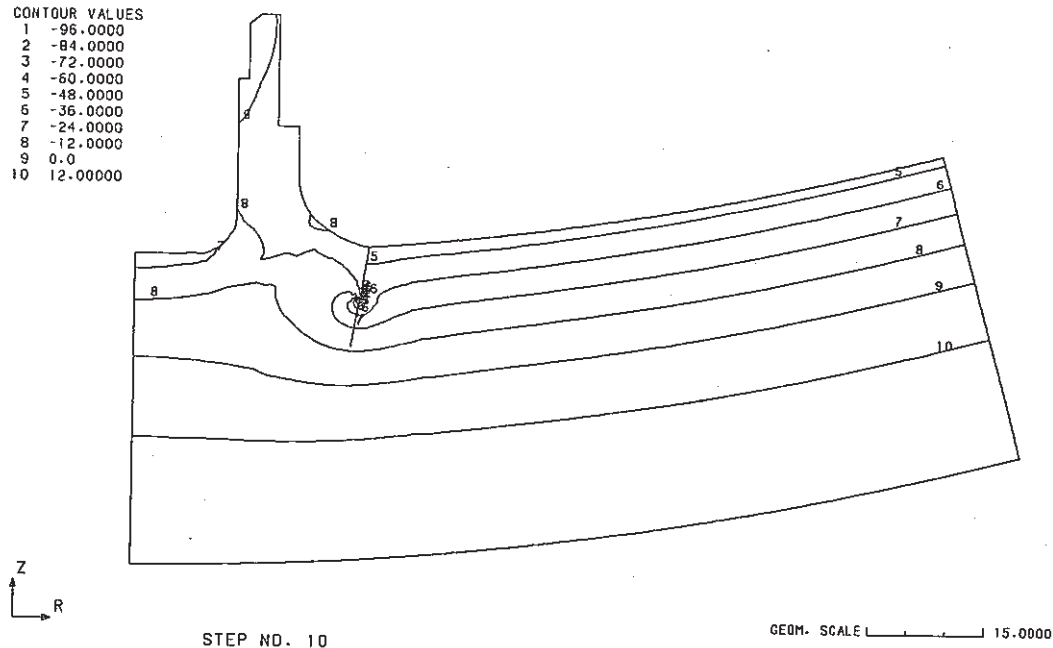


Fig. C.6.13-2 Contour of Hoop Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -78.0000
2 -67.0000
3 -56.0000
4 -45.0000
5 -34.0000
6 -23.0000
7 -12.0000
8 -1.00000
9 10.00000
10 21.00000

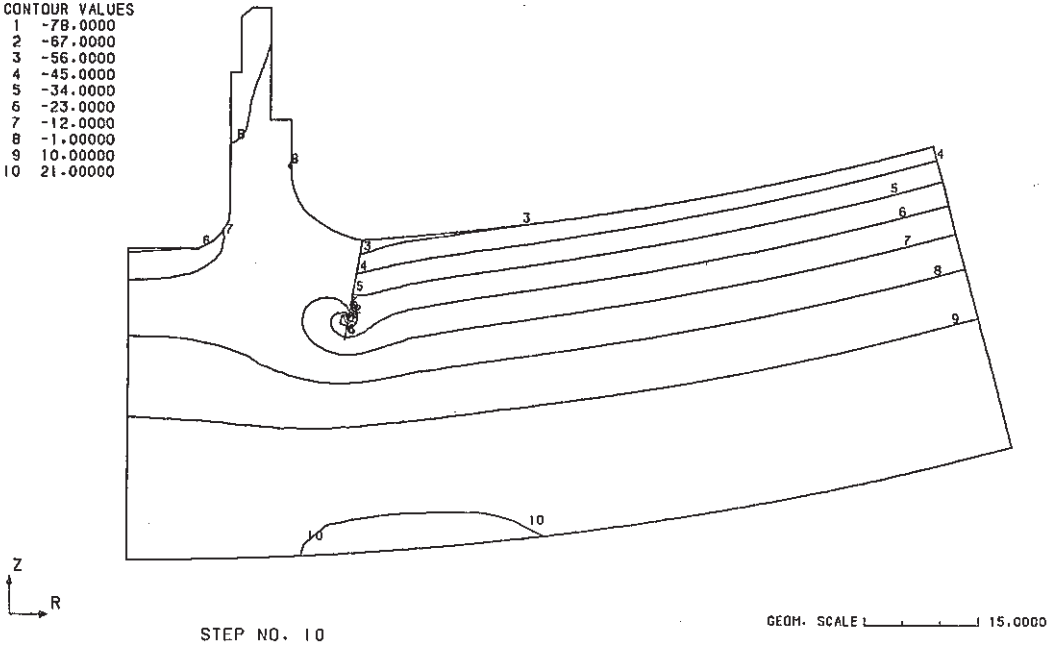


Fig. C.6.13-3 Contour of Hoop Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

FINAS
STRESS COMPONENT 3

CONTOUR VALUES
1 -63.8000
2 -54.6000
3 -45.4000
4 -36.2000
5 -27.0000
6 -17.8000
7 -8.60000
8 0.600000
9 9.800000
10 19.00000

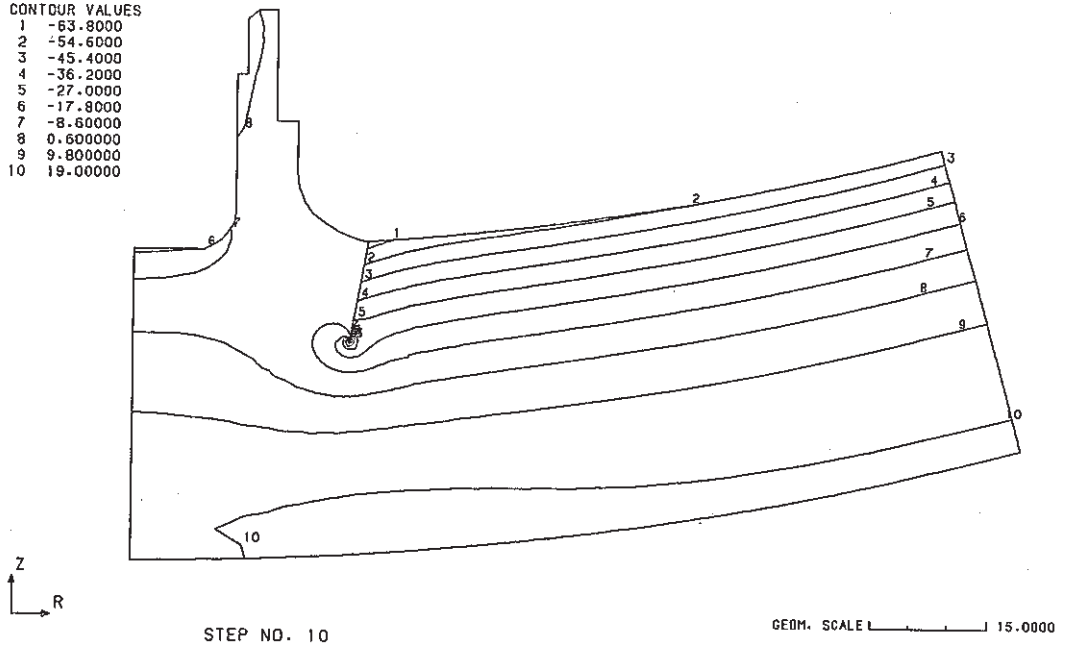


Fig. C.6.13-4 Contour of Hoop Stress at Hot Shock of Stud Bolt
(crack depth $a=13$ mm)

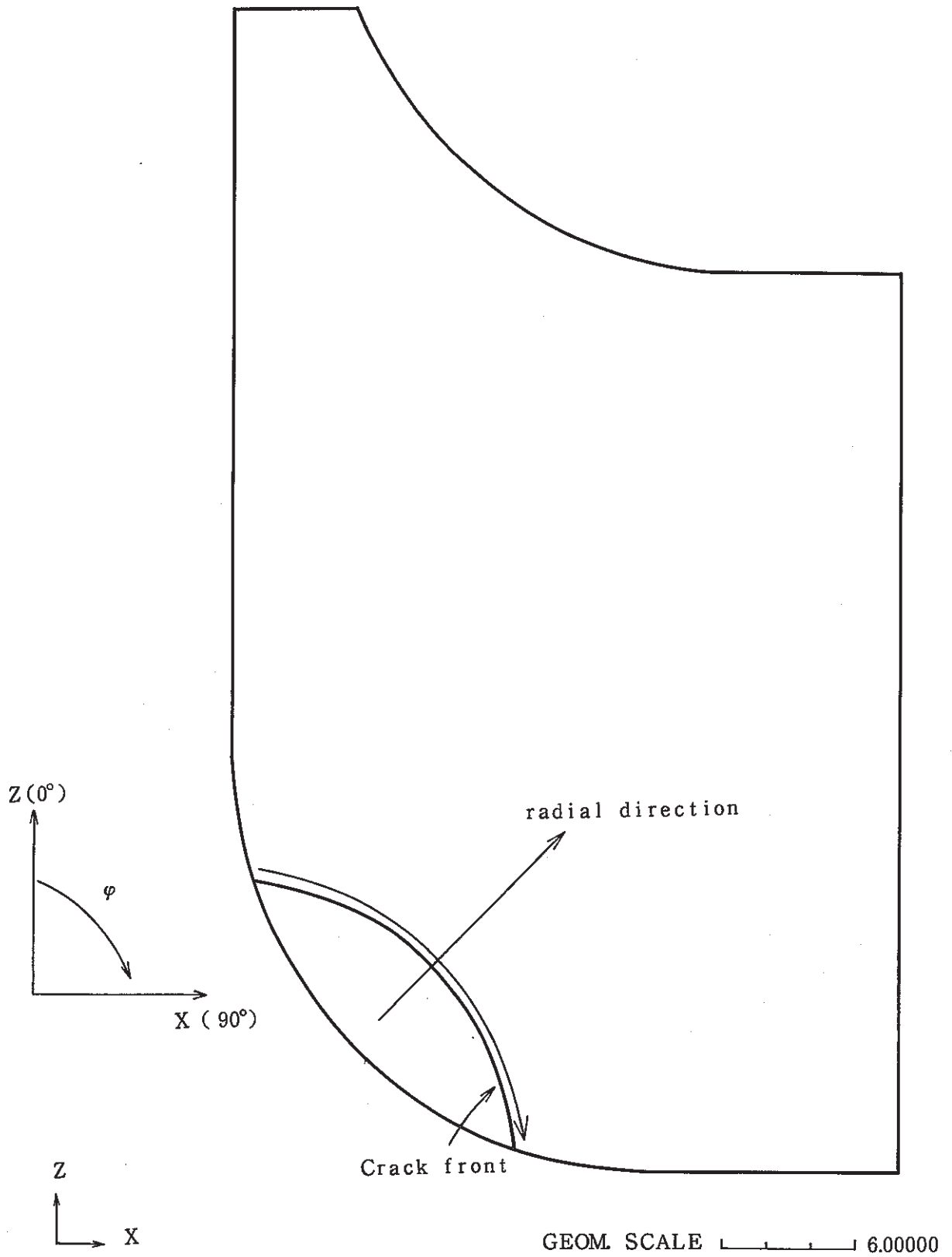


Fig. C.7-1 Evaluation Lines for Stress Distribution of Instrumental Nozzle

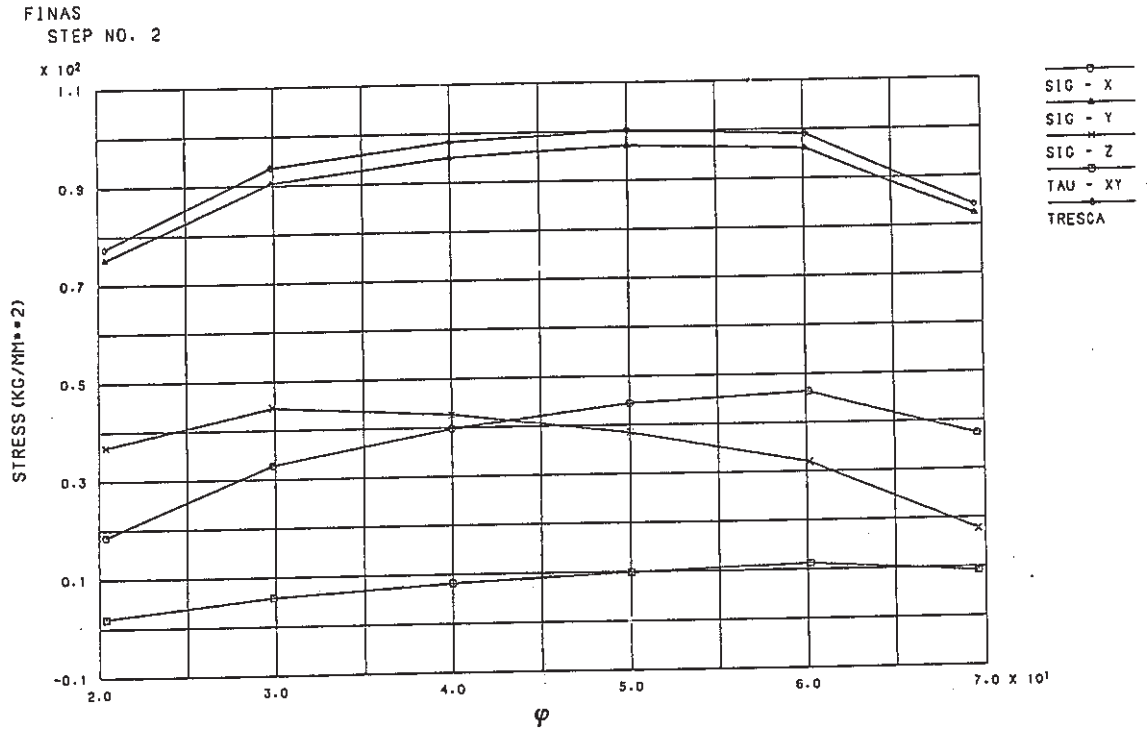


Fig. C.7.1-1 Stress Distribution along Crack Front at Cold Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

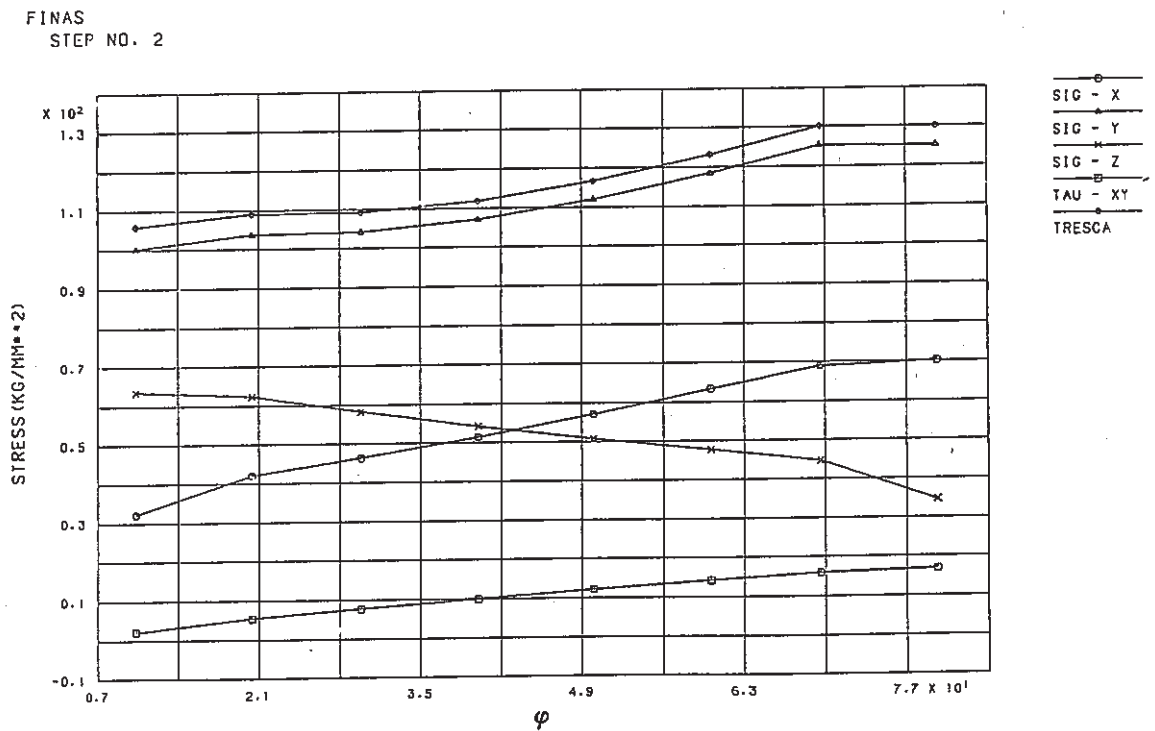


Fig. C.7.1-2 Stress Distribution along Crack Front at Cold Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

FINAS
STEP NO. 2

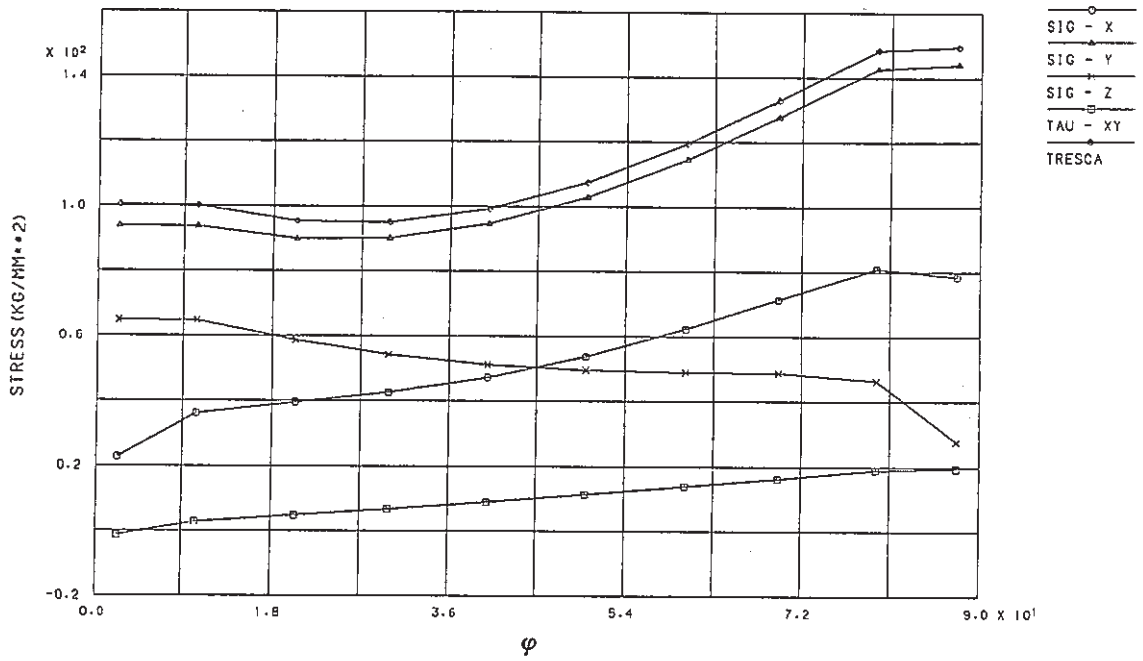


Fig. C.7.1-3 Stress Distribution along Crack Front at Cold Shock of Instrumental Nozzle (crack radius $r=16.0$ mm)

FINAS
STEP NO. 2

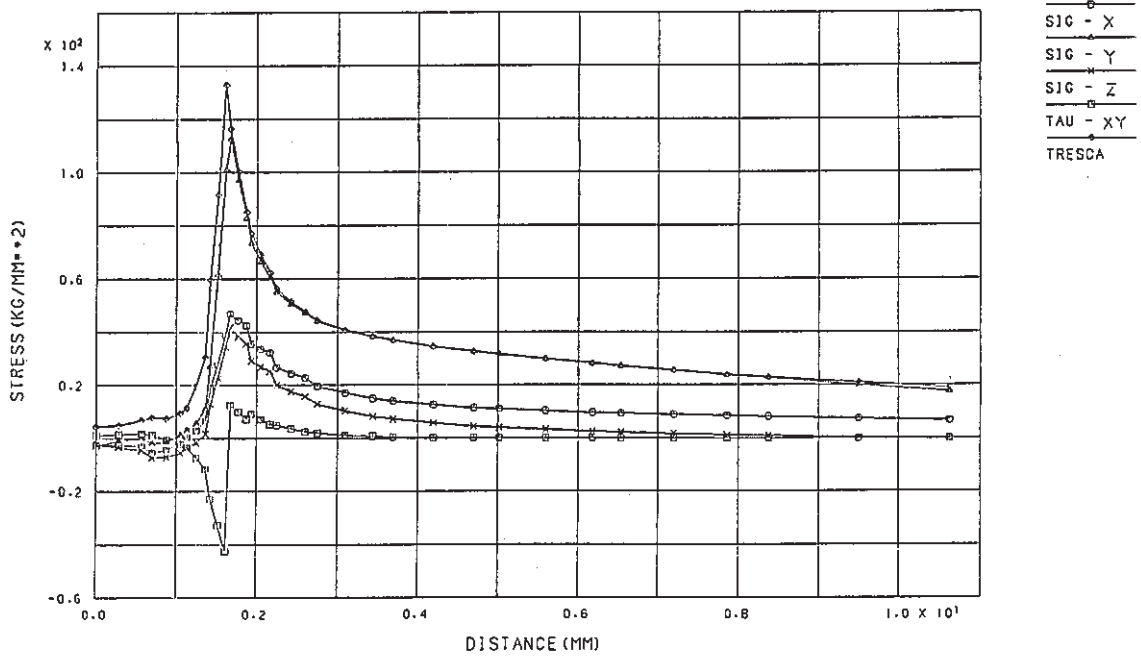


Fig. C.7.2-1 Stress Distribution along $\phi = 50^\circ$ at Cold Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

FINAS
STEP NO. 2

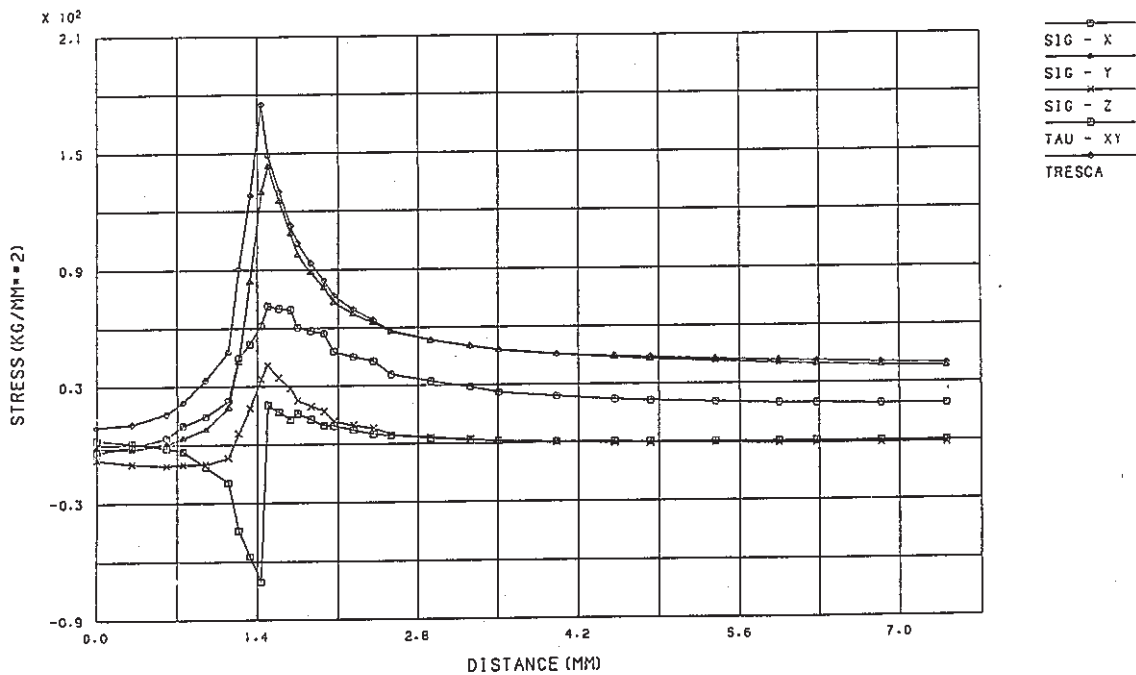


Fig. C.7.2-2 Stress Distribution along $\phi = 80^\circ$ at Cold Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

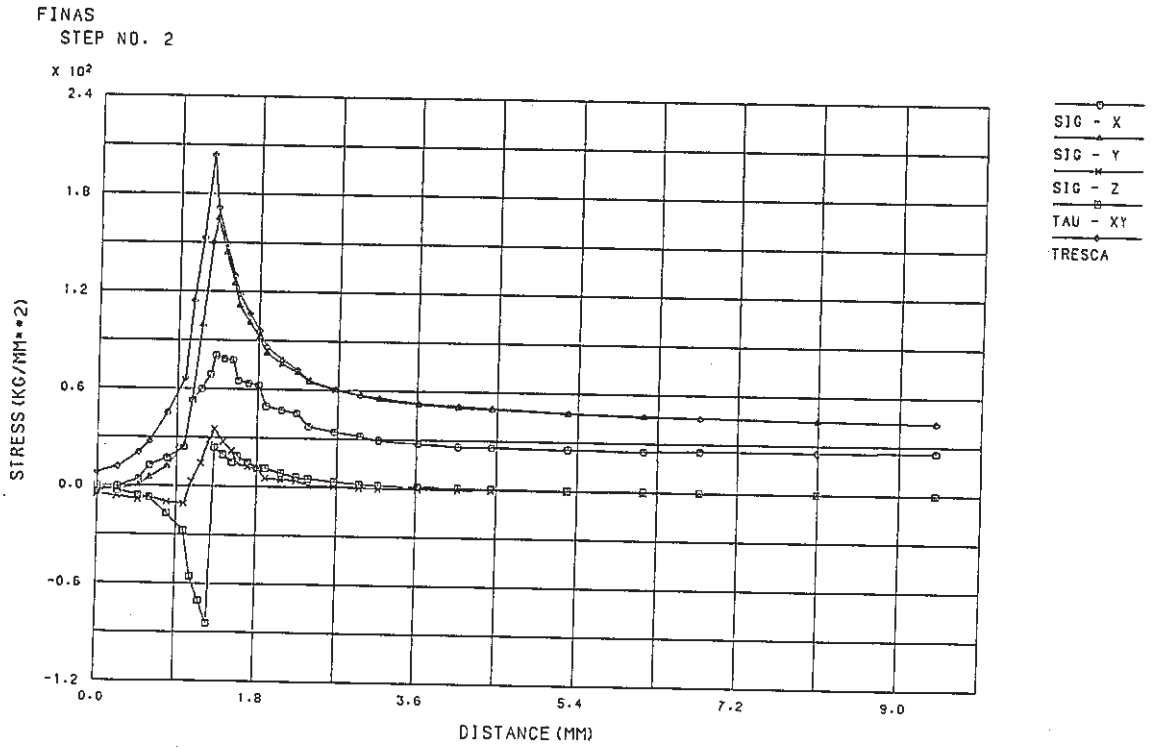
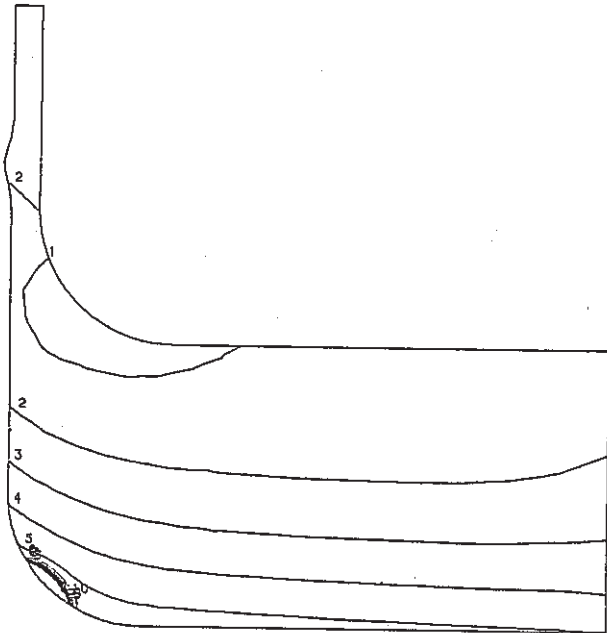


Fig. C.7.2-3 Stress Distribution along $\phi=87.5^\circ$ at Cold Shock of Instrumental Nozzle (crack radius $r=16.0$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -22.0000
2 -7.00000
3 8.000000
4 23.00000
5 38.00000
6 53.00000
7 68.00000
8 83.00000
9 98.00000
10 113.0000

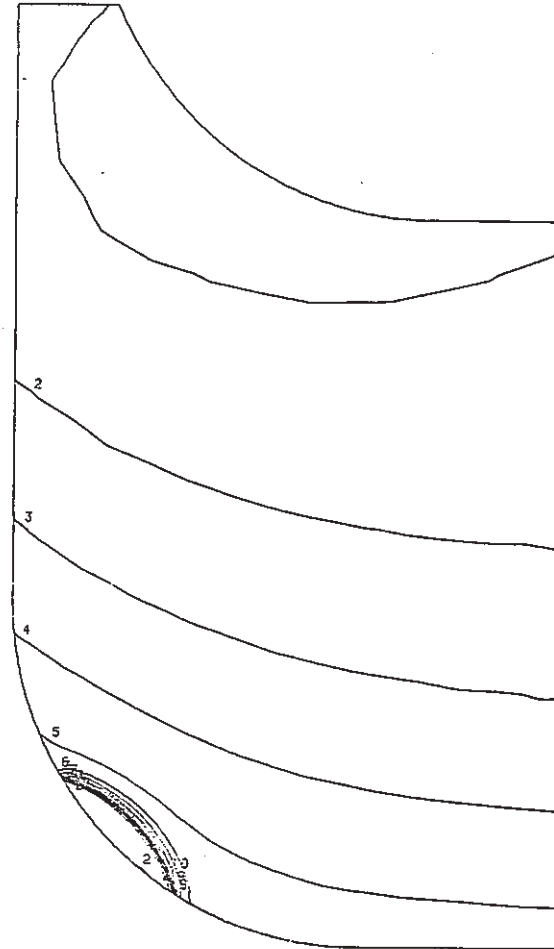


STEP NO. 2

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -22.0000
2 -7.00000
3 8.000000
4 23.00000
5 38.00000
6 53.00000
7 68.00000
8 83.00000
9 98.00000
10 113.0000



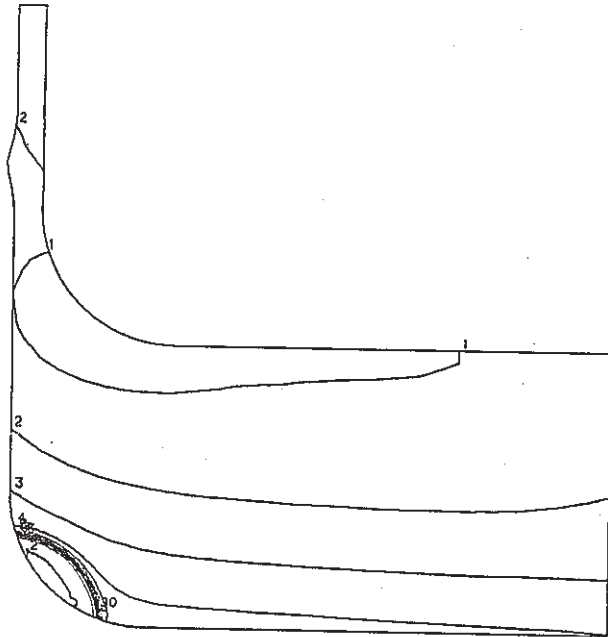
STEP NO. 2

GEOM. SCALE 6.00000

Fig. C.7.3-1 Contour of Hoop Stress at Cold Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -20.0000
2 -1.00000
3 18.00000
4 37.00000
5 56.00000
6 75.00000
7 94.00000
8 113.0000
9 132.0000
10 151.0000

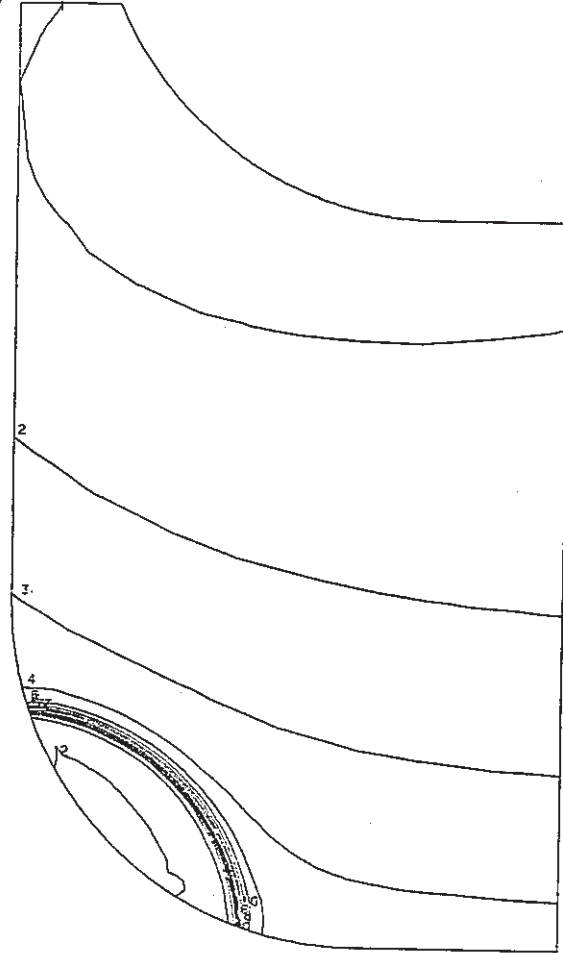


STEP NO. 2

GEOH. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -20.0000
2 -1.00000
3 18.00000
4 37.00000
5 56.00000
6 75.00000
7 94.00000
8 113.0000
9 132.0000
10 151.0000



STEP NO. 2

GEOH. SCALE 6.00000

Fig. C.7.3-2 Contour of Hoop Stress at Cold Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

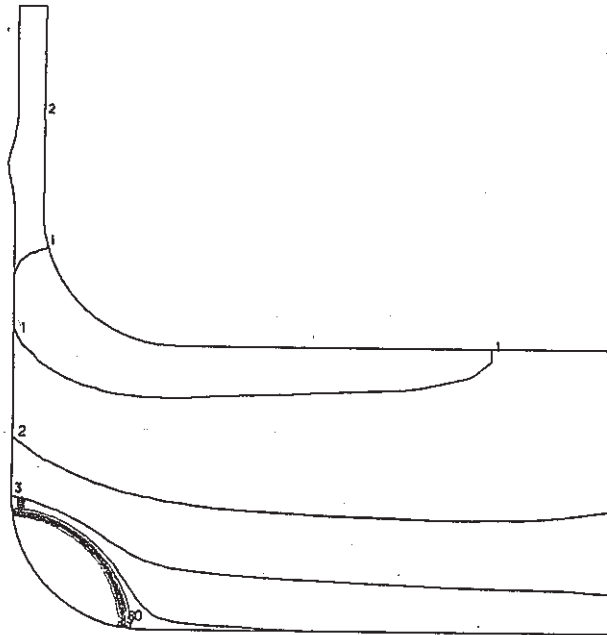
- 335 -

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FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-19.0000
2	2.000000
3	23.00000
4	44.00000
5	65.00000
6	86.00000
7	107.0000
8	128.0000
9	149.0000
10	170.0000



Z
↑
X →

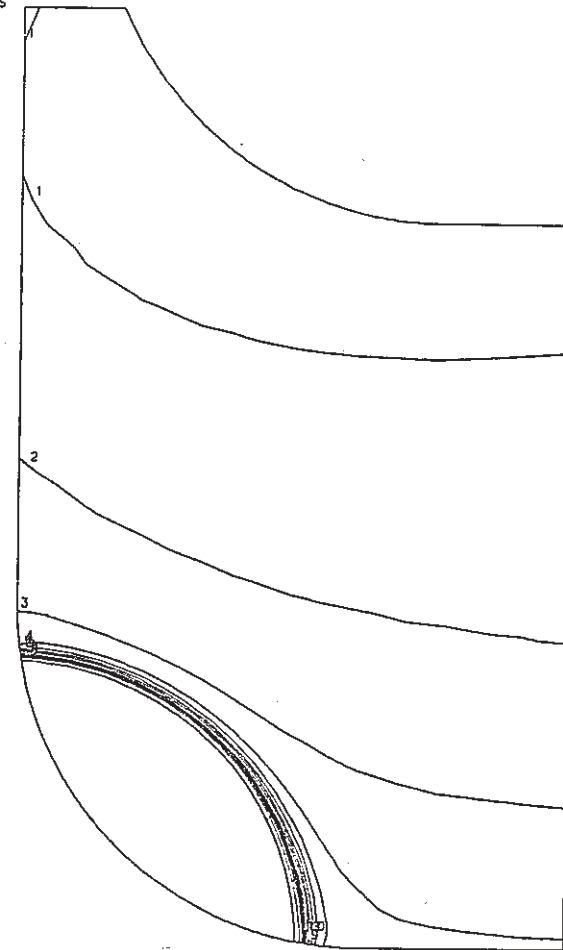
STEP NO. 2

GEO. SCALE |-----| 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES

1	-19.0000
2	2.000000
3	23.00000
4	44.00000
5	65.00000
6	86.00000
7	107.0000
8	128.0000
9	149.0000
10	170.0000



Z
↑
X →

STEP NO. 2

GEO. SCALE |-----| 6.00000

Fig. C.7.3-3 Contour of Hoop Stress at Cold Shock of
Instrumental Nozzle
(crack radius $r=16.0$ mm)

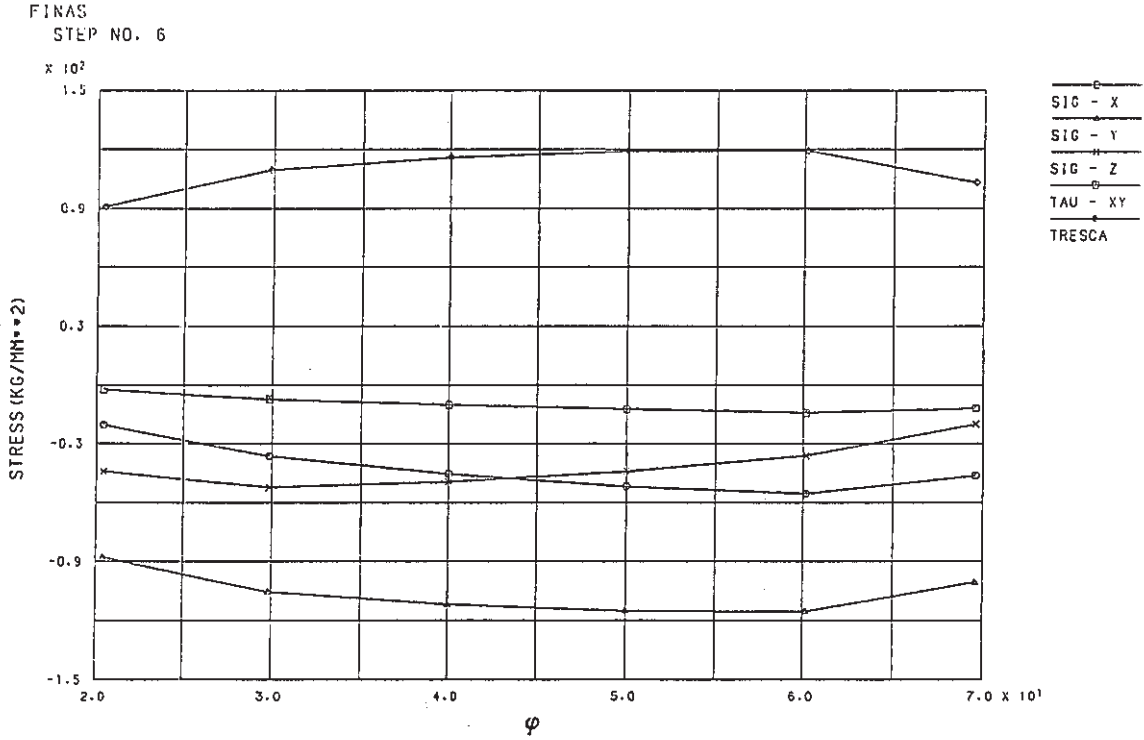


Fig. C.7.4-1 Stress Distribution along Crack Front at Hot Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

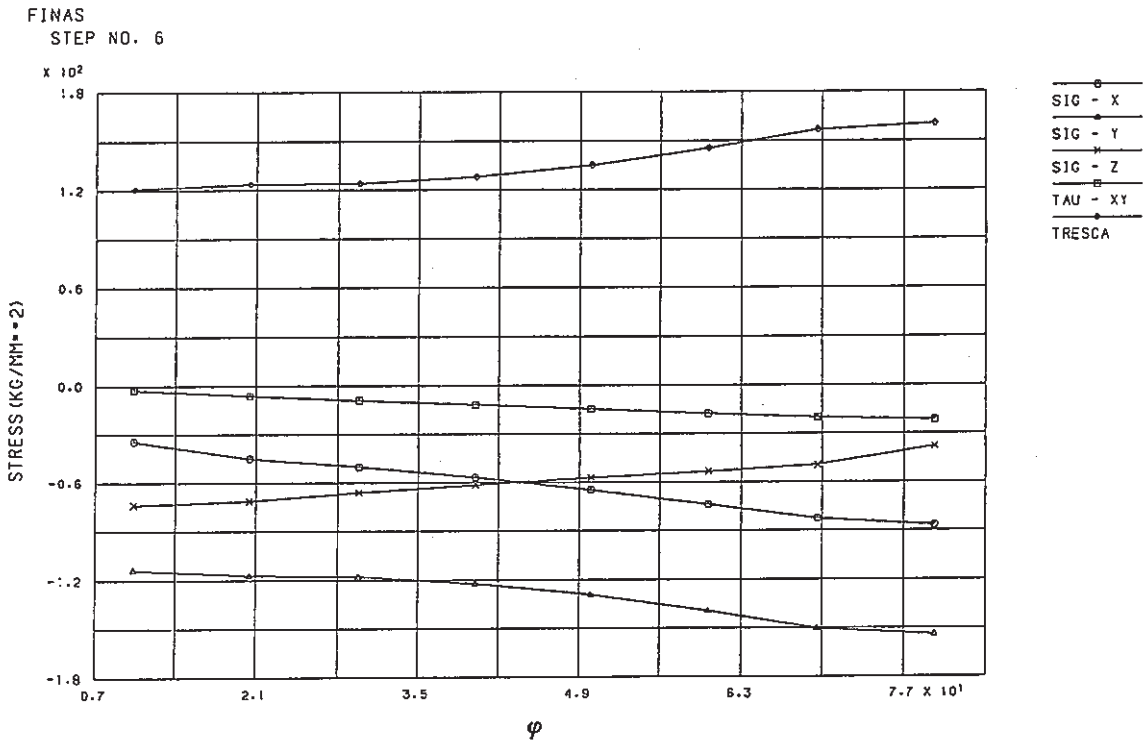


Fig. C.7.4-2 Stress Distribution along Crack Front at Hot Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

FINAS
STEP NO. 6

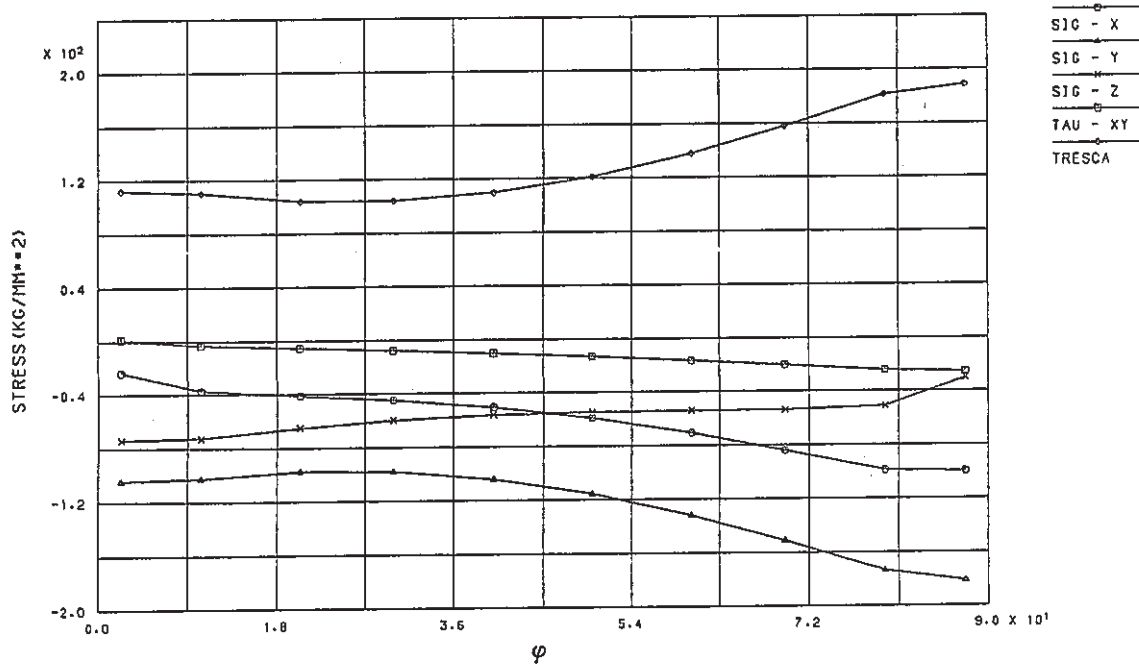


Fig. C.7.4-3 Stress Distribution along Crack Front at Hot Shock of Instrumental Nozzle (crack radius $r=16.0$ mm)

FINAS
STEP NO. 6

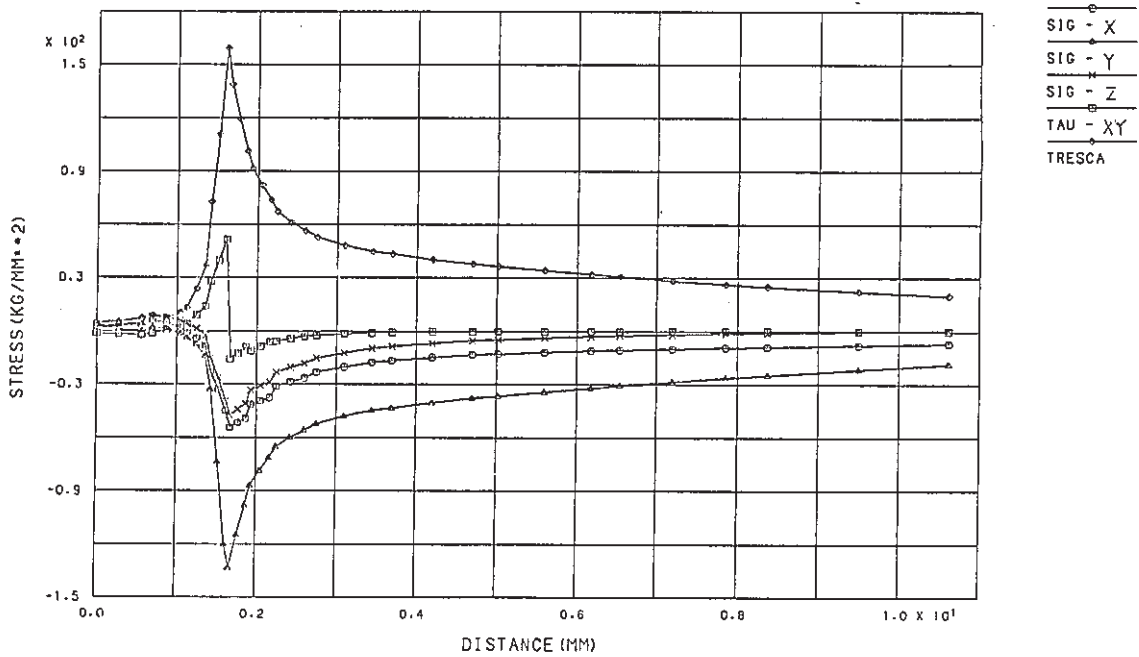


Fig. C.7.5-1 Stress Distribution along $=50^\circ$ at Hot Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

FINAS
STEP NO. 6

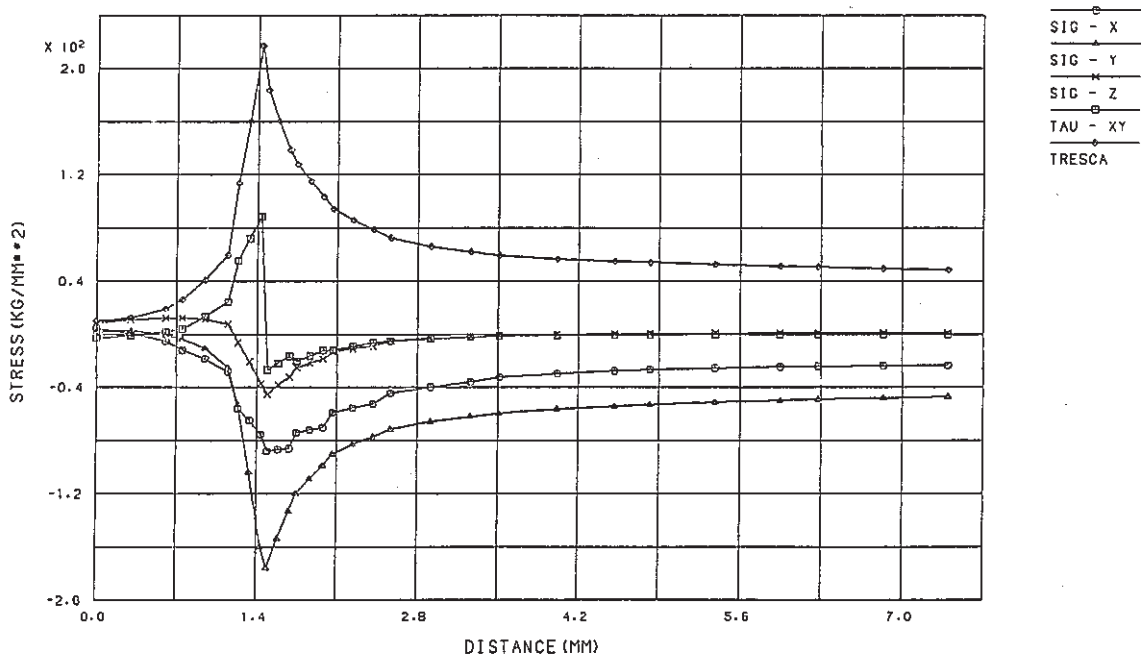


Fig. C.7.5-2 Stress Distribution along $=80^\circ$ at Hot Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

FINAS
STEP NO. 6

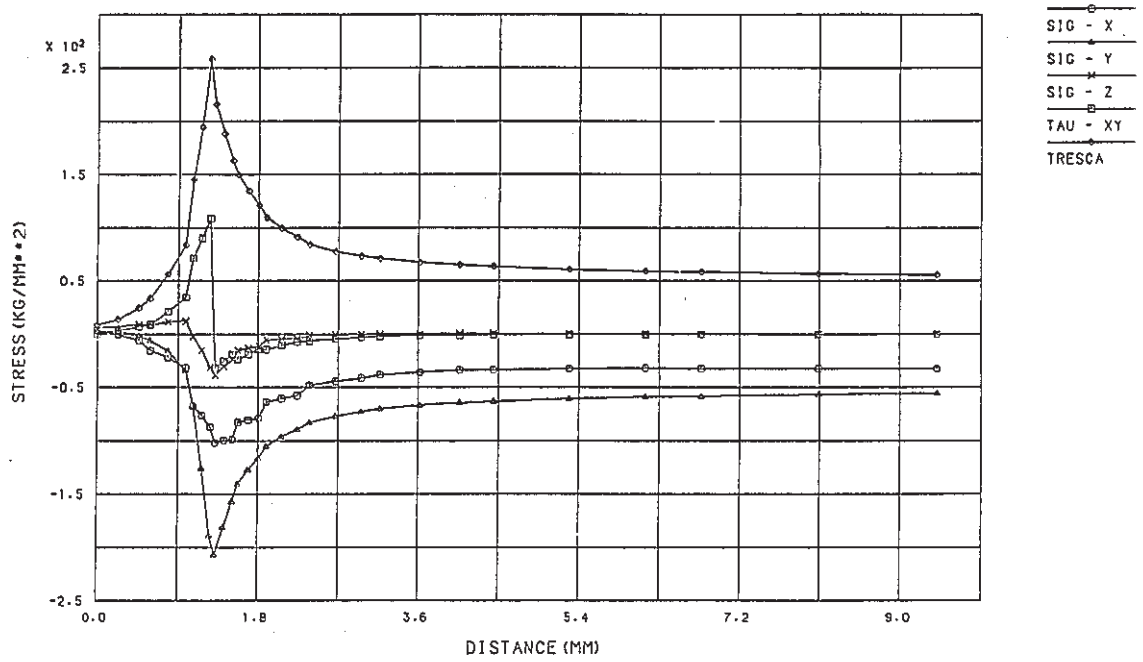
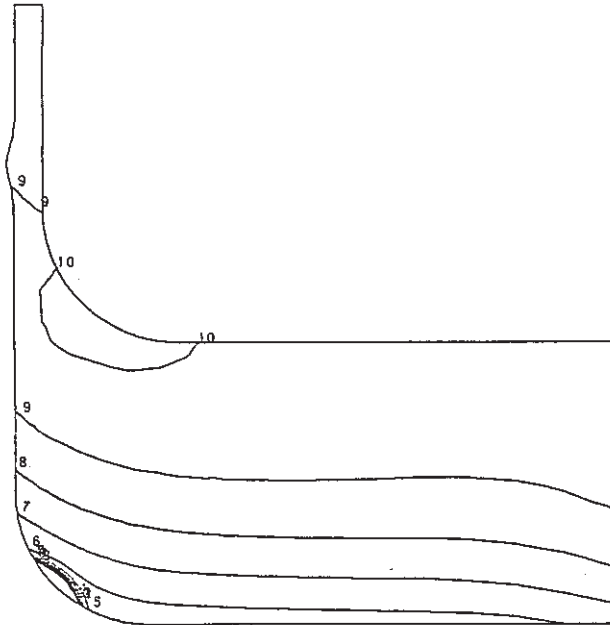


Fig. C.7.5-3 Stress Distribution along $=87.5^\circ$ at Hot Shock of Instrumental Nozzle (crack radius $r=16.0$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -136.000
 2 -118.000
 3 -100.000
 4 -82.0000
 5 -64.0000
 6 -46.0000
 7 -28.0000
 8 -10.0000
 9 8.000000
 10 26.00000



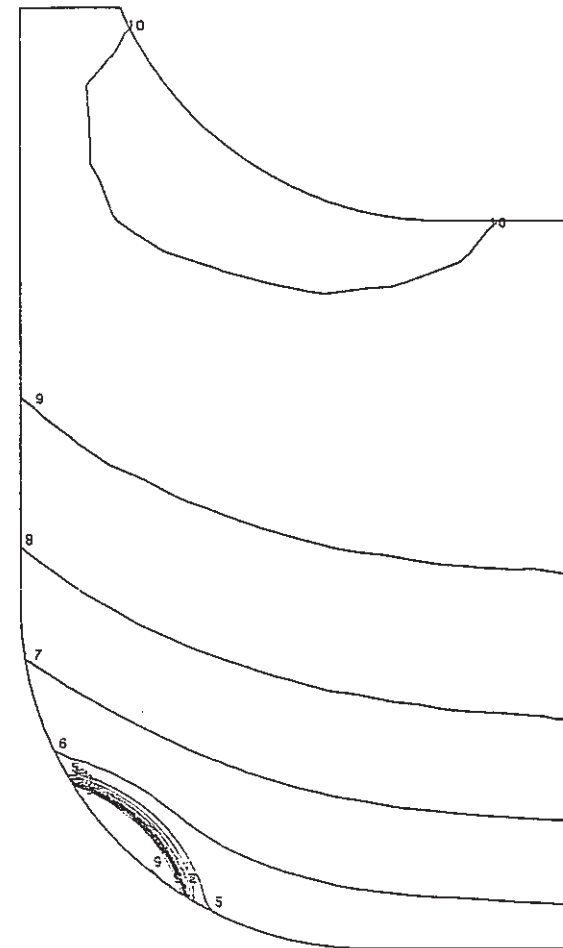
Z
↑
X

STEP NO. 6

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -136.000
 2 -118.000
 3 -100.000
 4 -82.0000
 5 -64.0000
 6 -46.0000
 7 -28.0000
 8 -10.0000
 9 8.000000
 10 26.00000



Z
↑
X

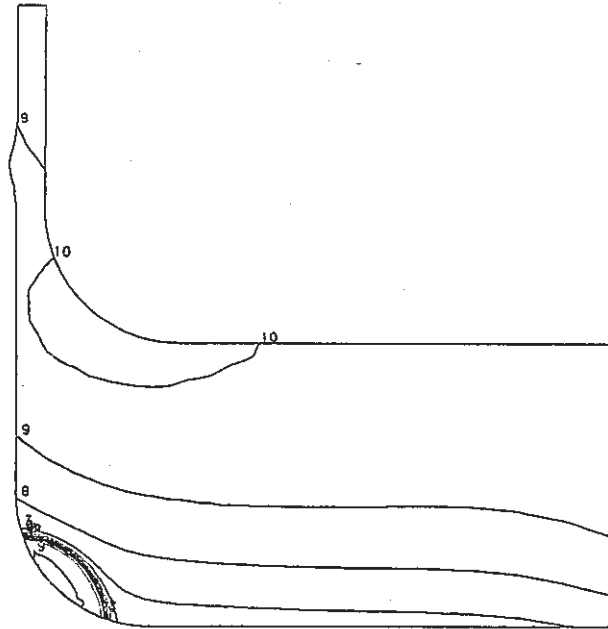
STEP NO. 6

GEOM. SCALE 6.00000

Fig. C.7.7-1 Contour of Hoop Stress at Hot Shock of Instrumental Nozzle (crack radius $r=9.6$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -183.000
 2 -160.000
 3 -137.000
 4 -114.000
 5 -91.0000
 6 -68.0000
 7 -45.0000
 8 -22.0000
 9 1.000000
 10 24.00000

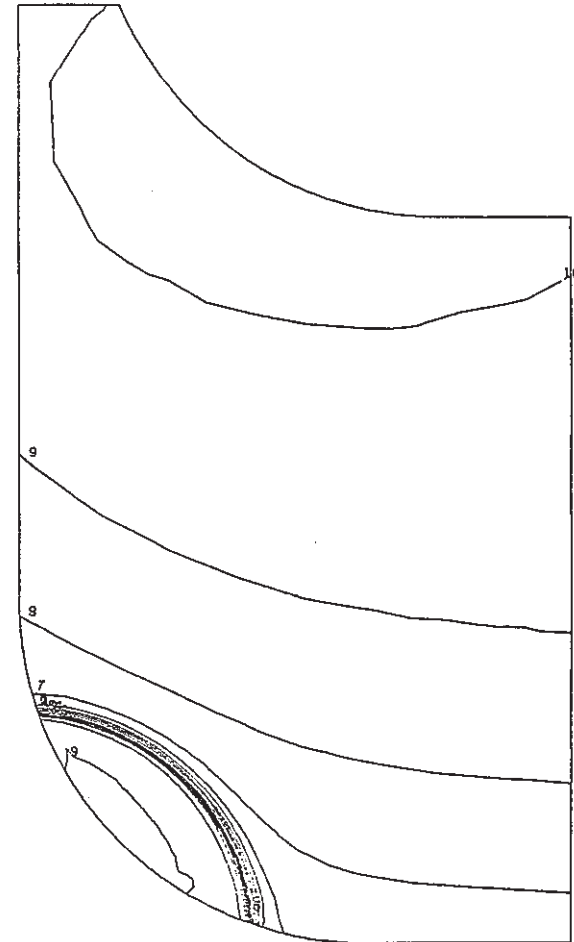


STEP NO. 6

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -183.000
 2 -160.000
 3 -137.000
 4 -114.000
 5 -91.0000
 6 -68.0000
 7 -45.0000
 8 -22.0000
 9 1.000000
 10 24.00000



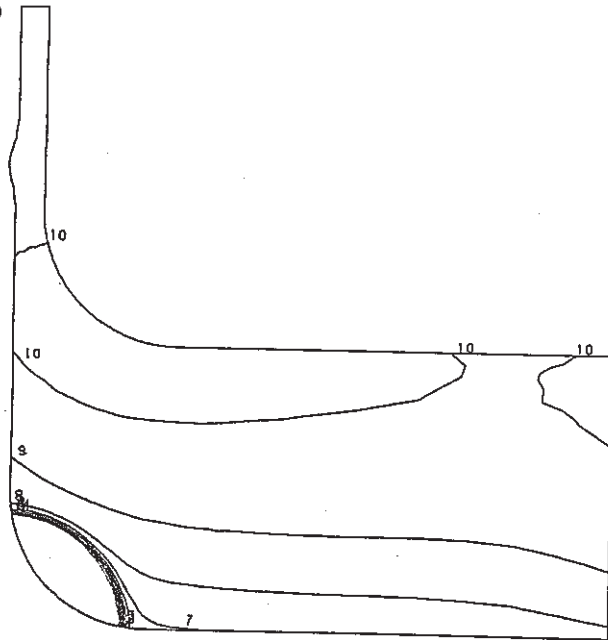
STEP NO. 6

GEOM. SCALE 8.00000

Fig. C.7.7-2 Contour of Hoop Stress at Hot Shock of Instrumental Nozzle (crack radius $r=12.8$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -215.000
2 -189.000
3 -163.000
4 -137.000
5 -111.000
6 -85.0000
7 -59.0000
8 -33.0000
9 -7.00000
10 19.00000

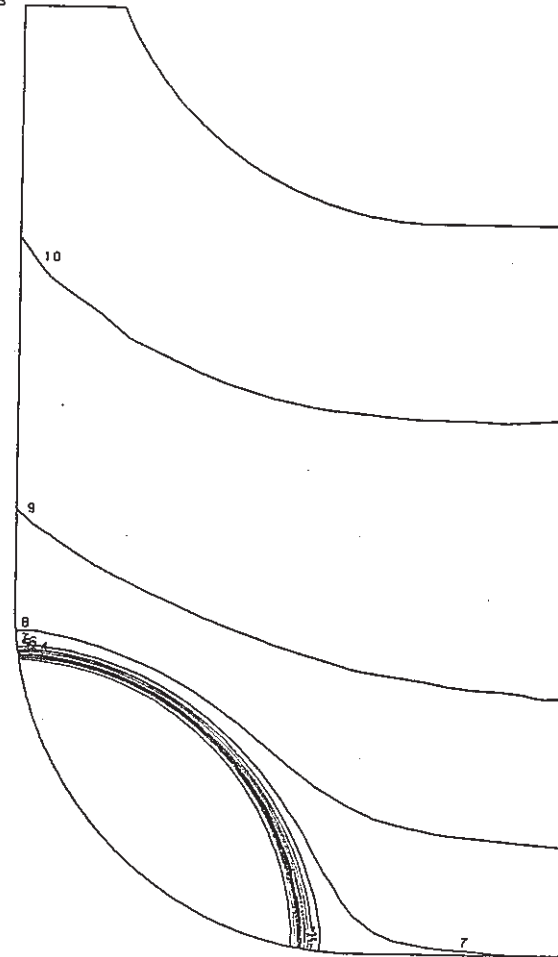


STEP NO. 6

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -215.000
2 -189.000
3 -163.000
4 -137.000
5 -111.000
6 -85.0000
7 -59.0000
8 -33.0000
9 -7.00000
10 19.00000



STEP NO. 6

GEOM. SCALE 6.00000

Fig. C.7.7-3 Contour of Hoop Stress at Hot Shock of Instrumental Nozzle (crack radius $r=16.0$ mm)

附錄 D 彈塑性応力解析結果

附録D 弾塑性応力解析結果

最終溶接部に発生したき裂についてのみ弾塑性解析を実施した。想定したき裂深さは、1 mm、15 mm及び27 mmであり、その有限要素分割は弾性解析に用いたものと同一である（Fig.3.1-2）。計算で用いた物理定数は、弾性解析と同一であるが、塑性についてはMisesの塑性ポテンシャル、Misesの降伏条件及びORNL推奨の硬化則を適用した。二直線近似での最大想定ひずみレベルは1.0%とした。この場合、定常降伏応力は31.20（450℃～550℃）、24.33（600℃）kg/mm²、加工硬化係数は509.5（350℃）～429.2（600℃）kg/mm²である。使用コードは、FINAS V-9.0である。

Fig.D-1に、各き裂モデルのき裂先端近傍における応力の時刻歴を示す。同図にはき裂のないモデルの結果も含んでいるが、これはき裂面の内表面に最も近い積分点の応力時刻歴である。熱過渡解析はコールド、ホット及びコールドショックの1.5サイクルについて実施した。ホットショック中にホットショック初期の圧縮応力の発生に続いて引張応力が発生する。Table.D-1に各き裂モデルにおけるこの応力 σ_z を示すが、き裂深さ1mmと15mmでは、軸方向応力 σ_z がかなり大きい。実際には、温度が600℃でありクリープが進行している領域である。

Fig.D-2～Fig.D-4に、ホットショックにおいて圧縮の応力が最大を示す時点（1020sec）の内外表面及びき裂面に沿った応力分布を示す。また、Fig.D-5、Fig.D-6に、同時点での軸方向応力 σ_z 、及びせん断応力 τ_{rz} 成分のコンター図を示す。

Fig.D-7～Fig.D-9は、コールドショックにおいて引張の応力が最大を示す時点（7352sec）の内外表面及びき裂面に沿った応力分布である。また、Fig.D-10、Fig.D-11は、同時点での軸方向応力 σ_z 、及びせん断応力 τ_{rz} 成分のコンター図である。

Fig.D-12～Fig.D-14は、ホットショックにおいて引張の応力を示す時点（4200sec）の内外表面及びき裂面に沿った応力分布である。また、Fig.D-15は、同時点での軸方向応力 σ_z 成分の応力コンターである。

Fig.D-7(a)にみられるように、この最終溶接部モデルでは、軸方向応力の極値が2ヶ所にある。この2ヶ所は供試体を解体検査して判明したき裂の位置と一致しており、今回のき裂を想定した解析は、このうちの下部胴側の一本を対象としている。内表面では、軸方向応力が、き裂の進展とともに減少している。周方向応力は、き裂発生位置でかなりの減少がみられるが、ある範囲を超えるとき裂のないモデルの結果と同程度もしくは大きくなっている。外表面では、Fig.D-3でみられるように、ホットショック時に、き裂面上で軸方向応力 σ_z の極値が発生する。き裂が深いほどその大きさも大きくなり、外表面からき裂が発生する可能性を示している。これはPT検査で外表面に全周欠陥指示があったことに対応する。

ホットショック時において、クリープき裂が進展するような時点は、4200～7200sec付近であると思われる（Fig.D-1）。この時点での引張応力はFig.D-15にみられるように、き裂先端の狭い

領域に限られており、さらにき裂先端から離れると圧縮応力、さらにその最大値が現われる (Fig. D-14)。このような応力状態下では、き裂先端の応力場を特徴づけるために極値を持って外挿する形となり、き裂先端近傍の要素分割及び応力場を計算する積分点位置の取り方が大きく影響する。

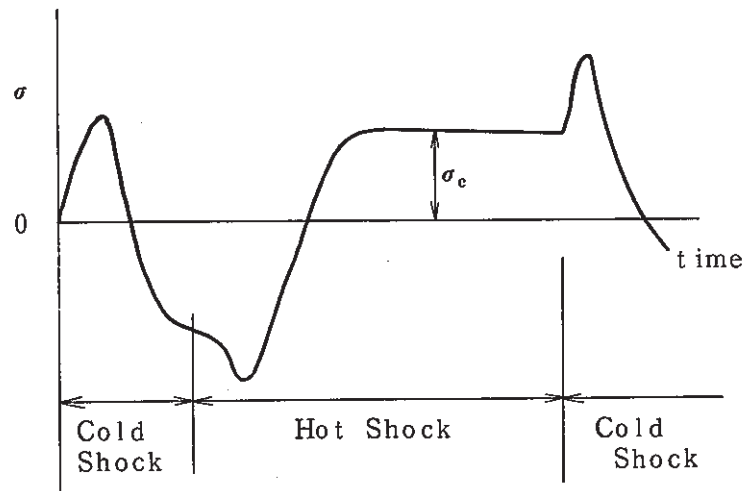
List of Figures and Table

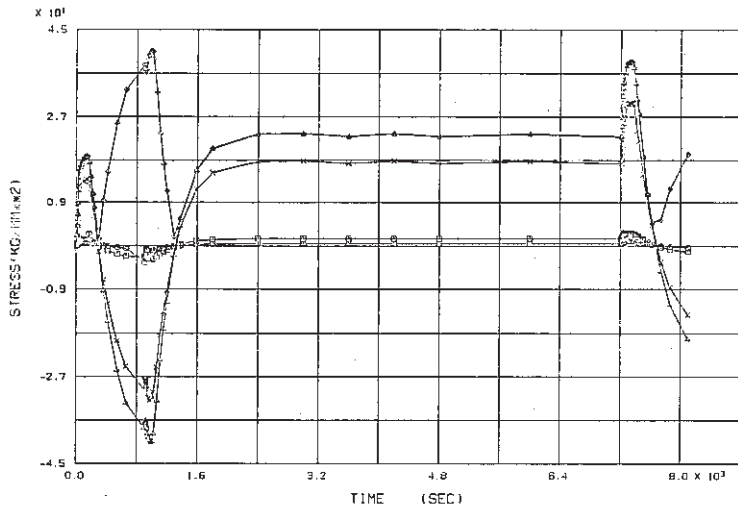
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Table D-1	Core Stress at Hot Shock	348

Table D-1 Core Stress at Hot Shock

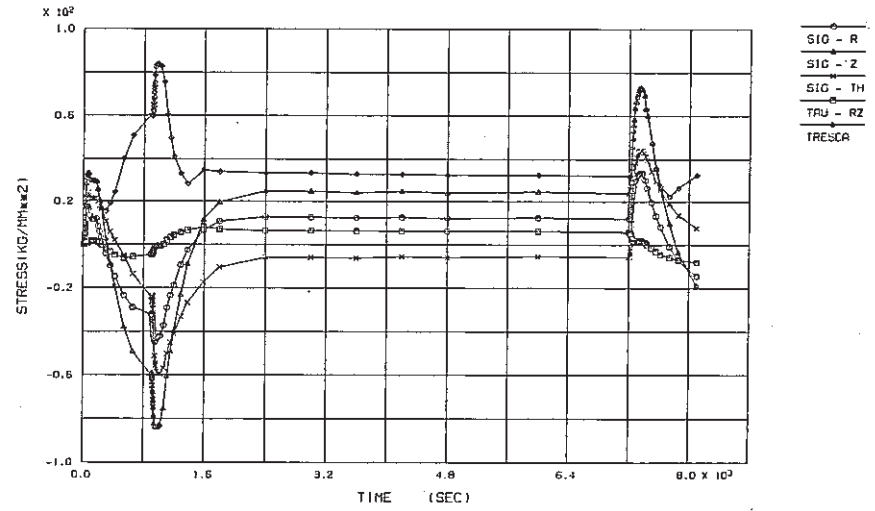
Crack Depth (mm)	σ_c (kgf / mm^2)				time (sec)	from crack tip (mm)
	$\sigma_{c,r}$	$\sigma_{c,z}$	$\sigma_{c,\theta}$	Mises		
0	0.5	16.0	12.7	14.2	4200	-
1	4.2	31.4	20.9	23.8	4200	0.6
15	12.5	24.7	-5.6	28.6	4200	2.92
27	12.1	6.07	-16.6	27.9	4200	3.0

Typical Thermal Stress History

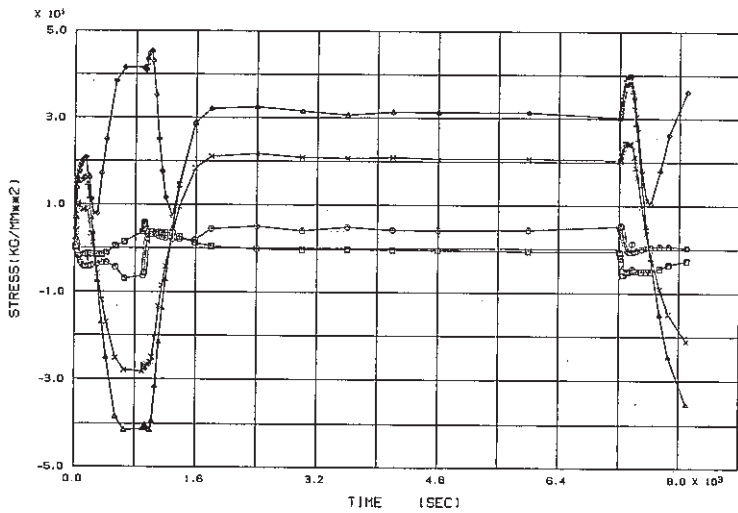




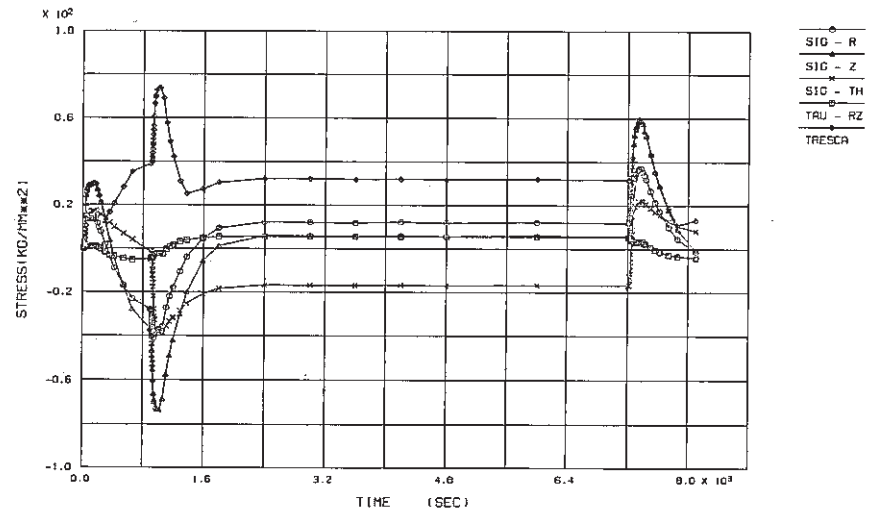
(a) No crack



(c) Crack depth a=15mm

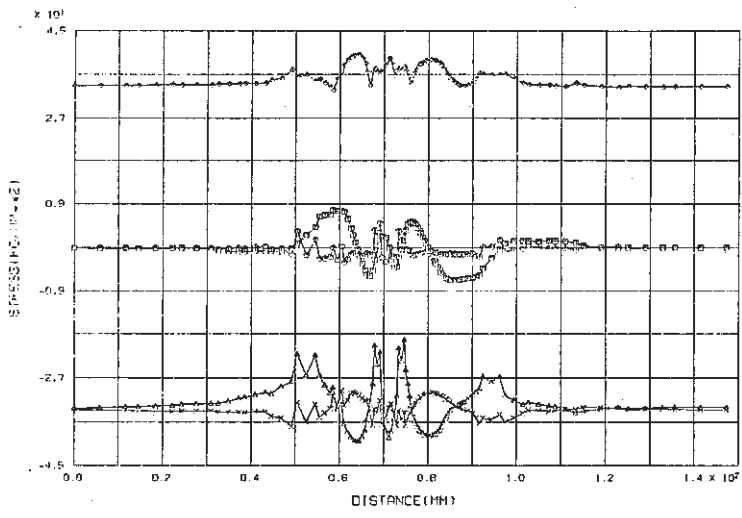


(b) Crack depth a=1mm

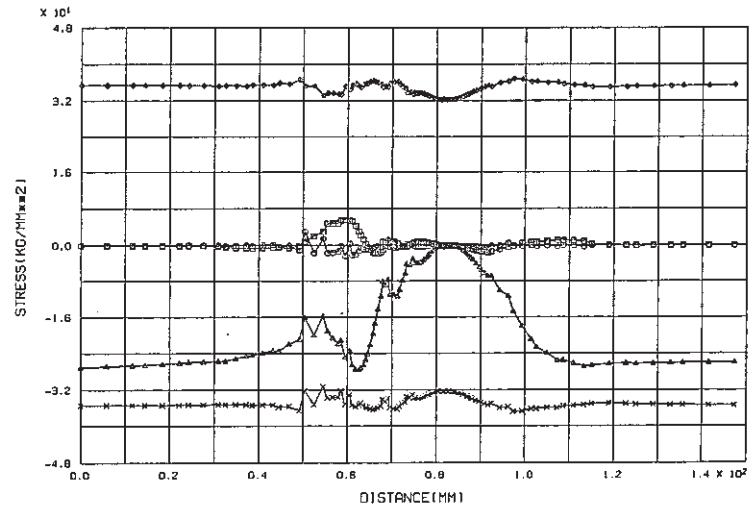


(d) Crack depth a=27mm

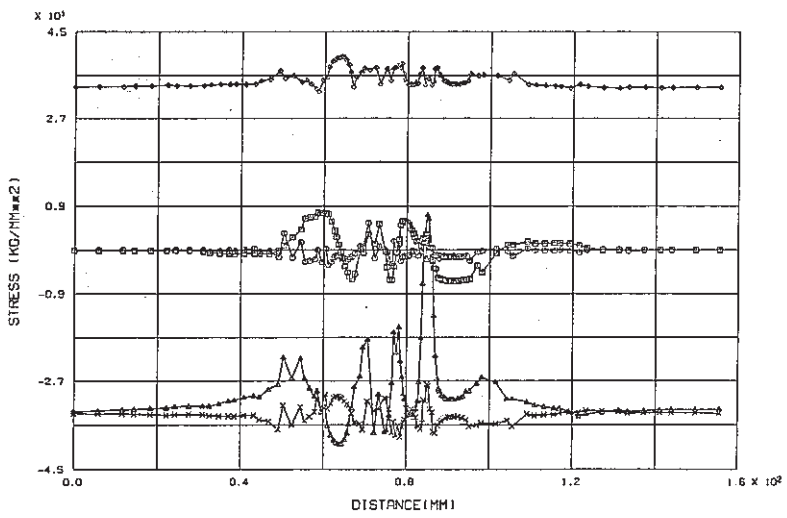
Fig. D-1 Stress History ahead of Crack Tip of Finally Welded Joint



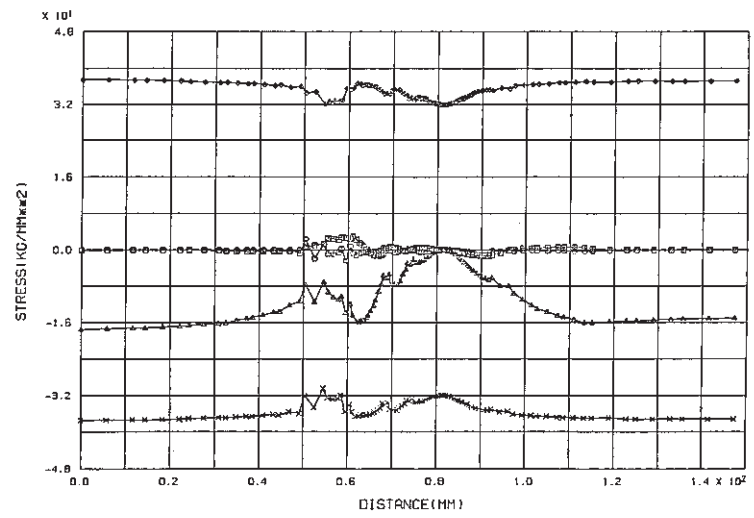
(a) No crack



(c) Crack depth a=15mm

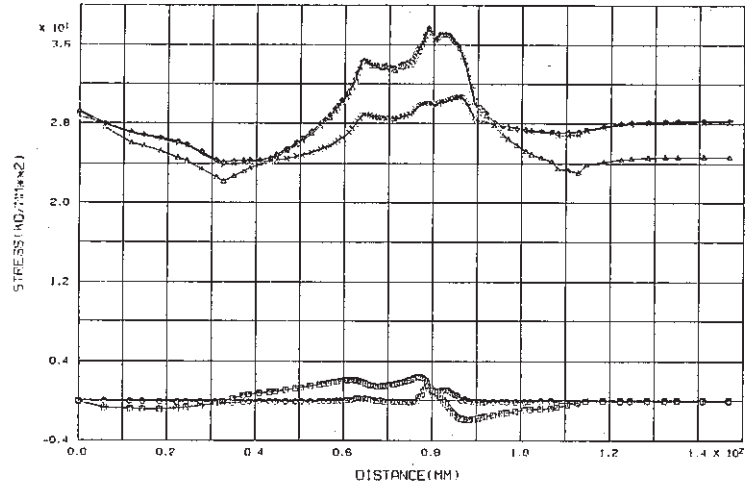


(b) Crack depth a=1mm

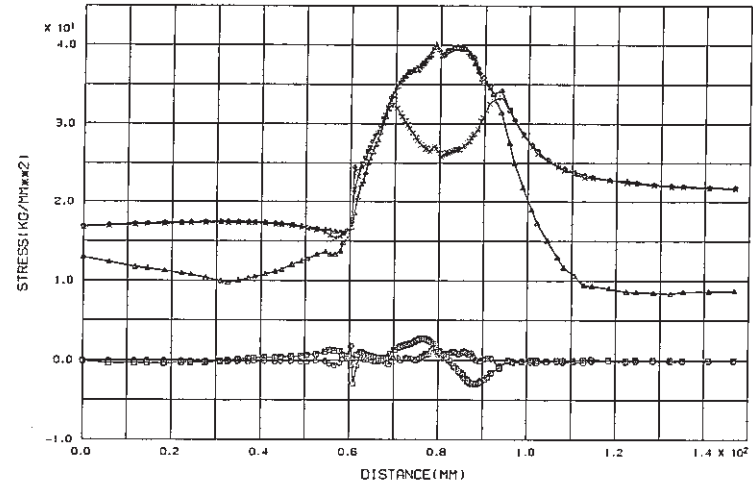


(d) Crack depth a=27mm

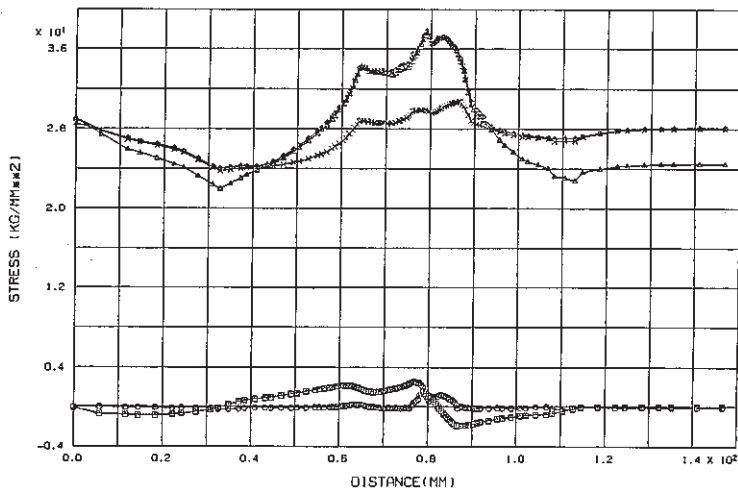
Fig. D-2 Stress Distribution along Inner Surface at Hot Shock (Time=1020 sec) of Finally Welded Joint



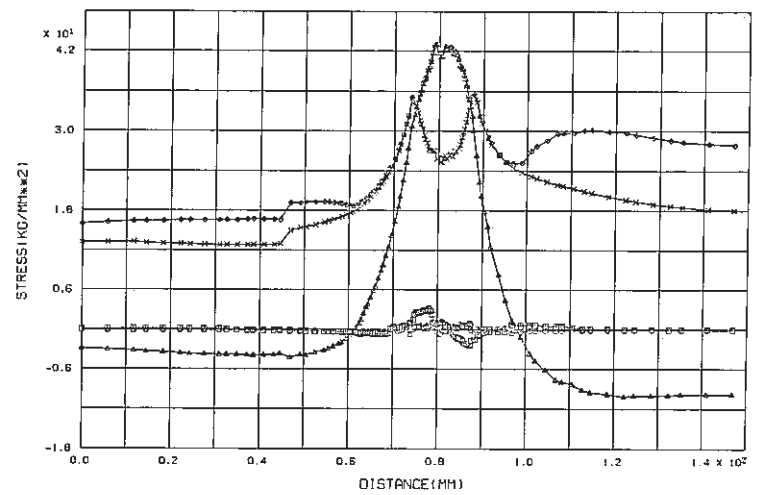
(a) No crack



(c) Crack depth a=15mm

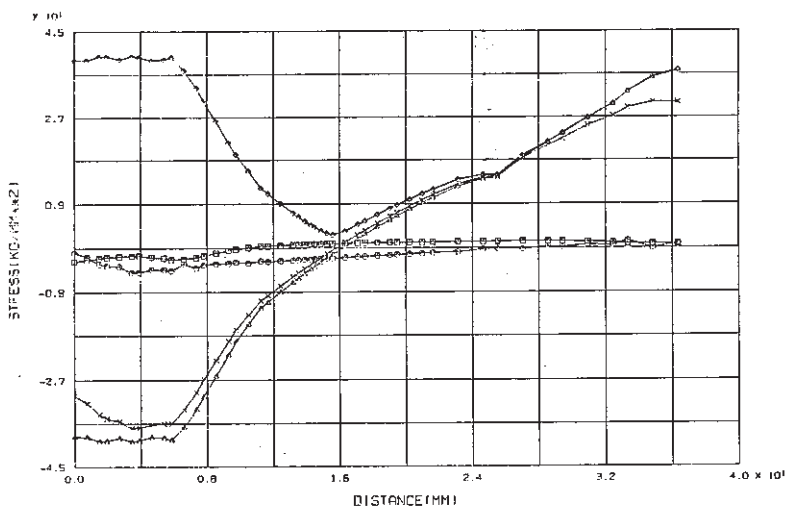


(b) Crack depth a=1mm

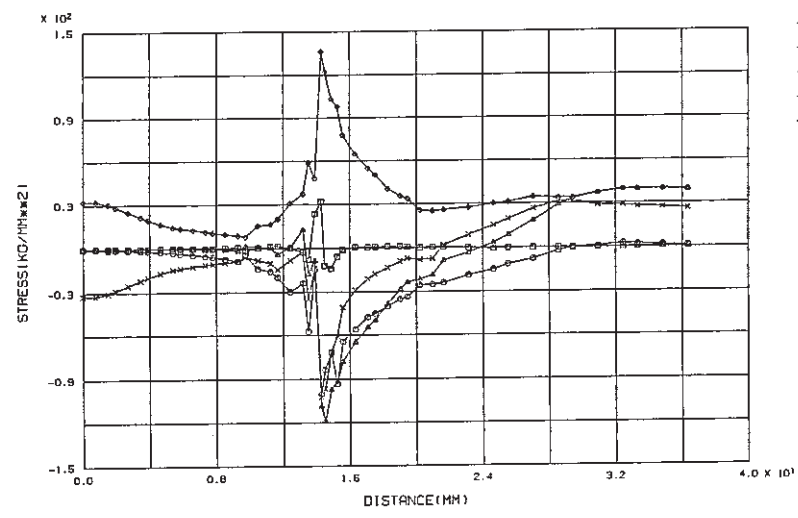


(d) Crack depth a=27mm

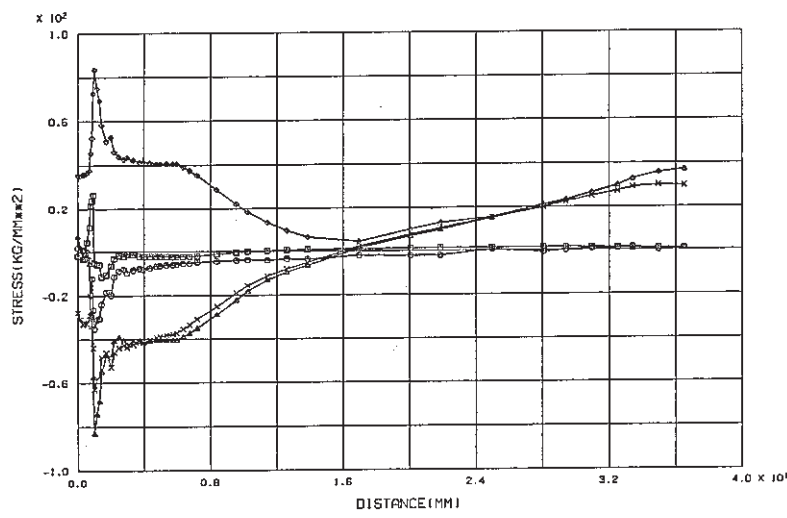
Fig. D-3 Stress Distribution along Outer Surface at Hot Shock (Time=1020 sec) of Finally Welded Joint



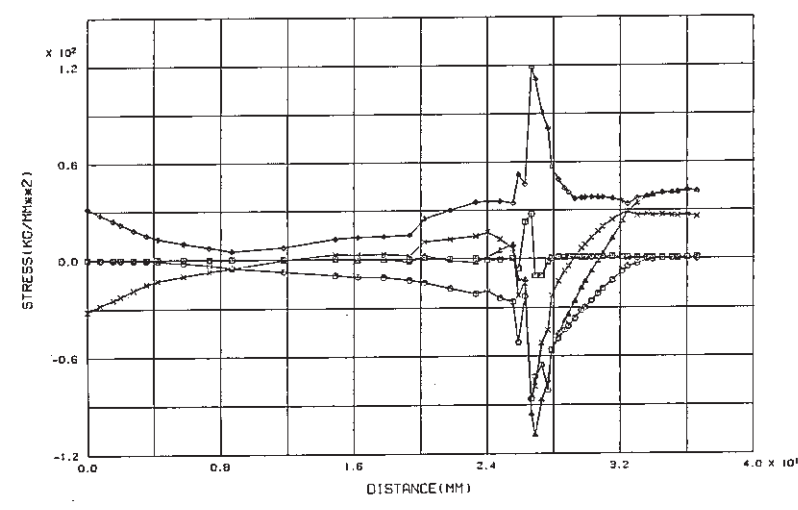
(a) No crack



(c) Crack depth a=15mm



(b) Crack depth a=1mm



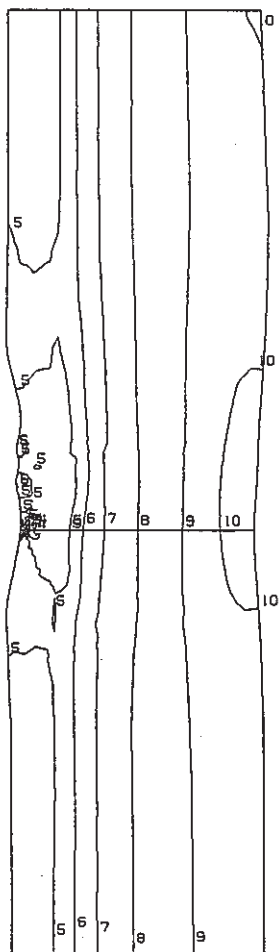
(d) Crack depth a=27mm

Fig. D-4 Stress Distribution along Crack Line at Hot Shock (Time=1020 sec) of Finally Welded Joint

- 3 5 2 -

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -80.0000
2 -68.0000
3 -56.0000
4 -44.0000
5 -32.0000
6 -20.0000
7 -8.00000
8 4.000000
9 16.00000
10 28.00000

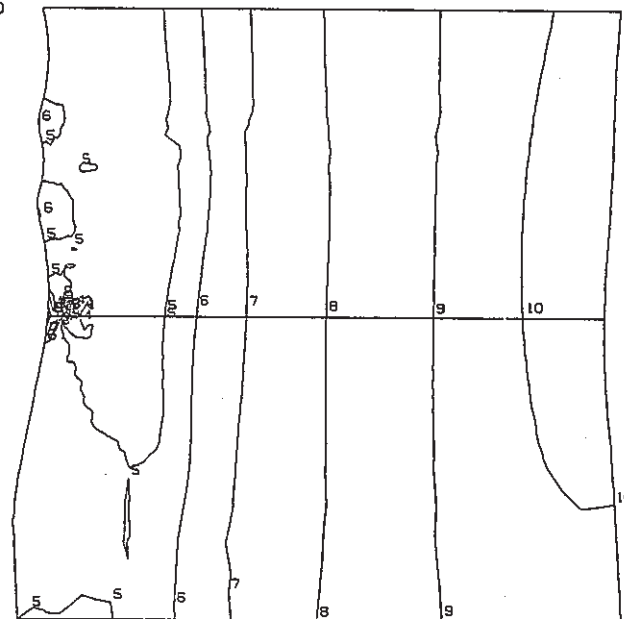


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -80.0000
2 -68.0000
3 -56.0000
4 -44.0000
5 -32.0000
6 -20.0000
7 -8.00000
8 4.000000
9 16.00000
10 28.00000



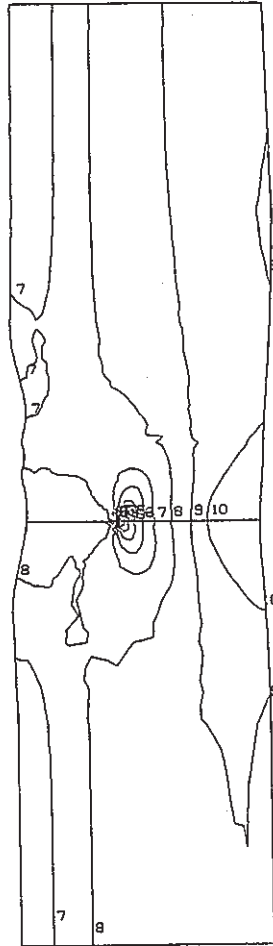
STEP NO. 61

GEOM. SCALE 8.00000

Fig. D-5(a) Contour of Axial Stress at Hot Shock (Time=1020 sec) of Finally Welded Joint (crack depth $a=1$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -125.000
 2 -108.000
 3 -91.0000
 4 -74.0000
 5 -57.0000
 6 -40.0000
 7 -23.0000
 8 -6.00000
 9 10.99999
 10 28.00000

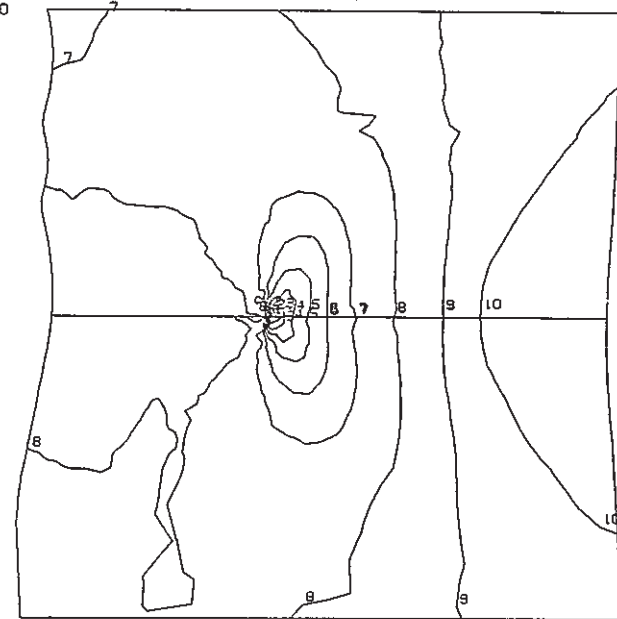


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -125.000
 2 -108.000
 3 -91.0000
 4 -74.0000
 5 -57.0000
 6 -40.0000
 7 -23.0000
 8 -6.00000
 9 10.99999
 10 28.00000



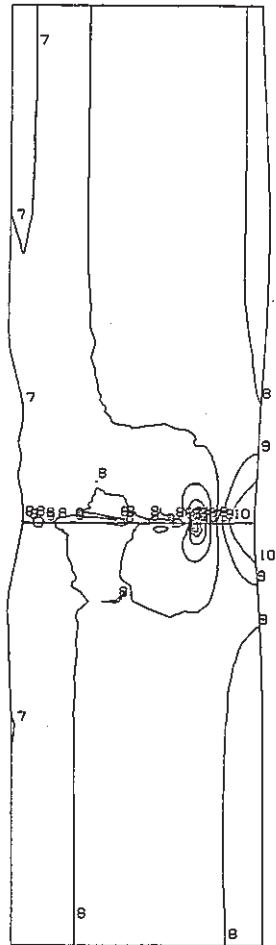
STEP NO. 61

GEOM. SCALE 8.00000

Fig. D-5(b) Contour of Axial Stress at Hot Shock (Time= 1020 sec) of Finally Welded Joint (crack depth a=15 mm)

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -112.000
 - 2 -96.0000
 - 3 -80.0000
 - 4 -64.0000
 - 5 -48.0000
 - 6 -32.0000
 - 7 -16.0000
 - 8 0.0
 - 9 16.00000
 - 10 32.00000

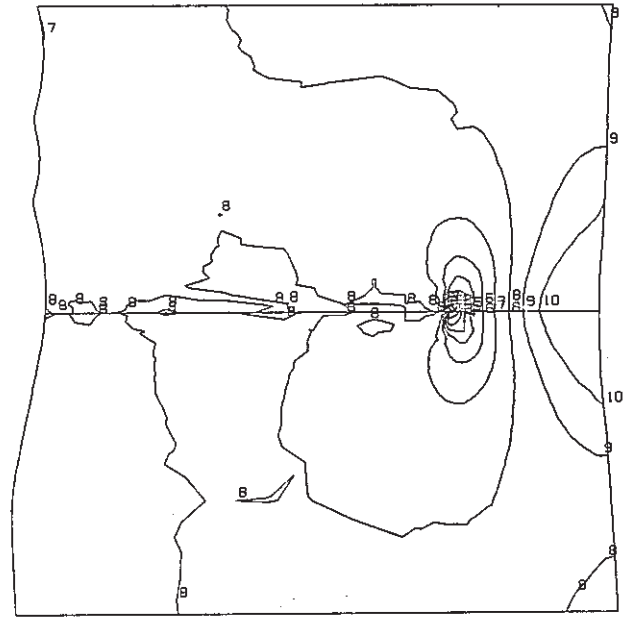


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -112.000
 - 2 -96.0000
 - 3 -80.0000
 - 4 -64.0000
 - 5 -48.0000
 - 6 -32.0000
 - 7 -16.0000
 - 8 0.0
 - 9 16.00000
 - 10 32.00000



STEP NO. 61

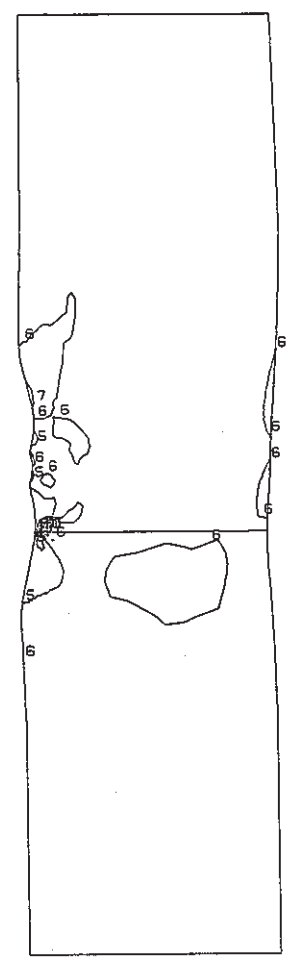
GEOM. SCALE 8.00000

- 355 -

Fig. D-5(c) Contour of Axial Stress at Hot shock (Time= 1020 sec) of Finally Welded Joint (crack depth a=27 mm)

FINAS
STRESS COMPONENT 4

- CONTOUR VALUES
- 1 -25.4000
 - 2 -20.0000
 - 3 -14.6000
 - 4 -9.19996
 - 5 -3.79996
 - 6 1.600036
 - 7 7.000034
 - 8 12.40002
 - 9 17.80001
 - 10 23.20001

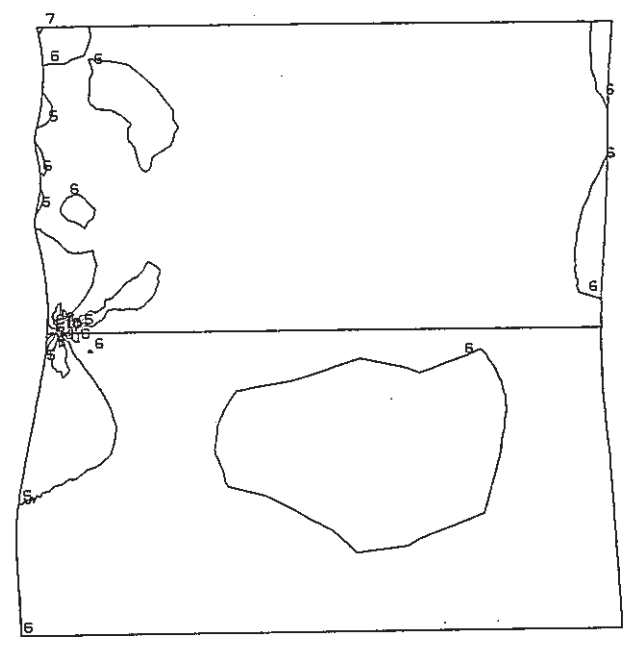


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

- CONTOUR VALUES
- 1 -25.4000
 - 2 -20.0000
 - 3 -14.6000
 - 4 -9.19996
 - 5 -3.79996
 - 6 1.600036
 - 7 7.000034
 - 8 12.40002
 - 9 17.80001
 - 10 23.20001



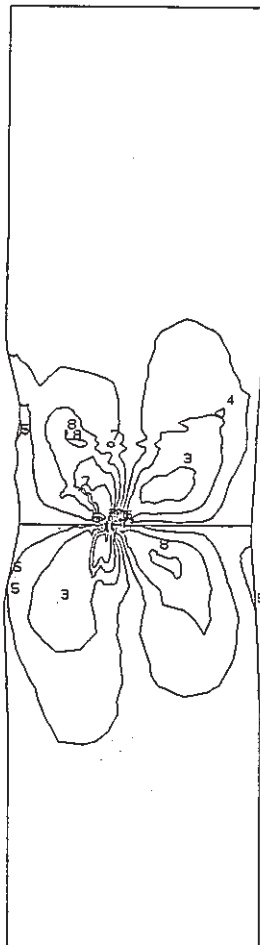
STEP NO. 61

GEOM. SCALE 8.00000

Fig. D-6(a) Contour of Shear Stress at Hot Shock (Time= 1020 sec) of Finally Welded Joint (crack depth a=1 mm)

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
1 -19.7000
2 -15.1000
3 -10.5000
4 -5.89997
5 -1.29998
6 3.300021
7 7.900018
8 12.50001
9 17.10000
10 21.70000

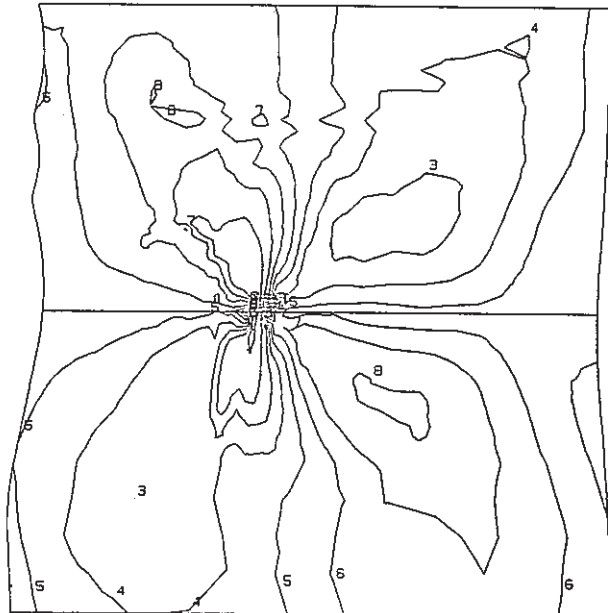


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
1 -19.7000
2 -15.1000
3 -10.5000
4 -5.89997
5 -1.29998
6 3.300021
7 7.900018
8 12.50001
9 17.10000
10 21.70000



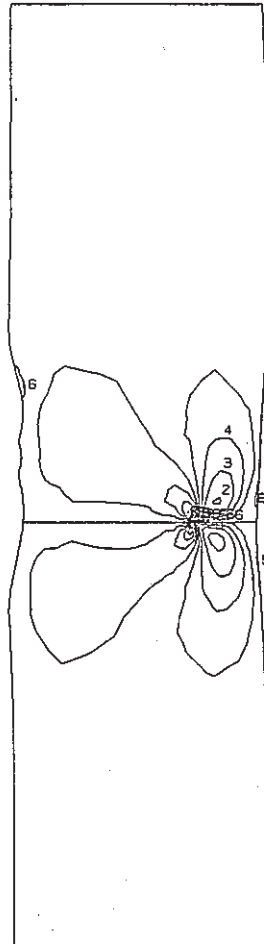
STEP NO 61

GEOM. SCALE 8.00000

Fig. D-6(b) Contour of Shear Stress at Hot Shock (Time=1020 sec) of Finally Welded Joint (crack depth a=15 mm)

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -20.1000
 2 -15.6000
 3 -11.1000
 4 -6.59998
 5 -2.09998
 6 2.400014
 7 6.900012
 8 11.40001
 9 15.90001
 10 20.39999

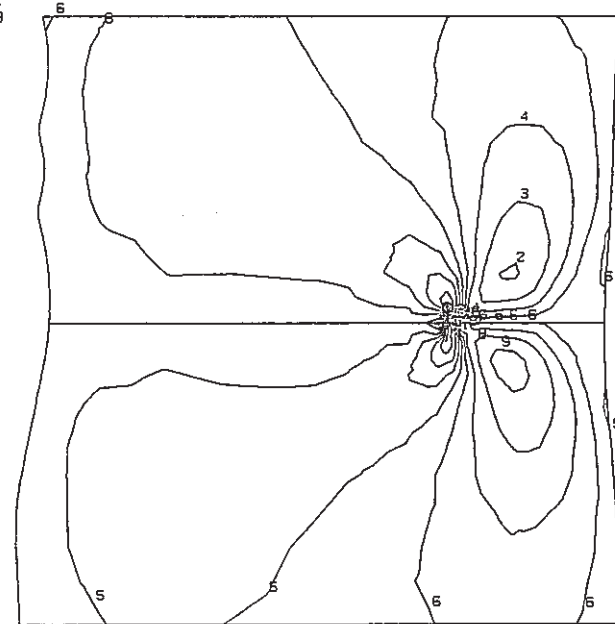


STEP NO. 61

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

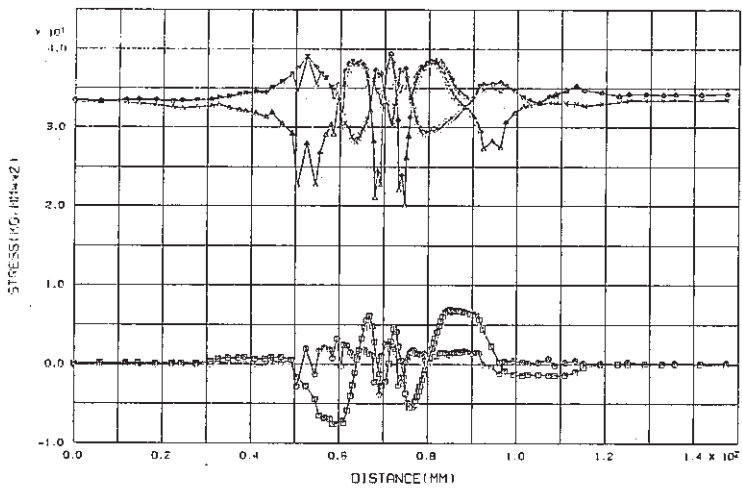
CONTOUR VALUES
 1 -20.1000
 2 -15.6000
 3 -11.1000
 4 -6.59998
 5 -2.09998
 6 2.400014
 7 6.900012
 8 11.40001
 9 15.90001
 10 20.39999



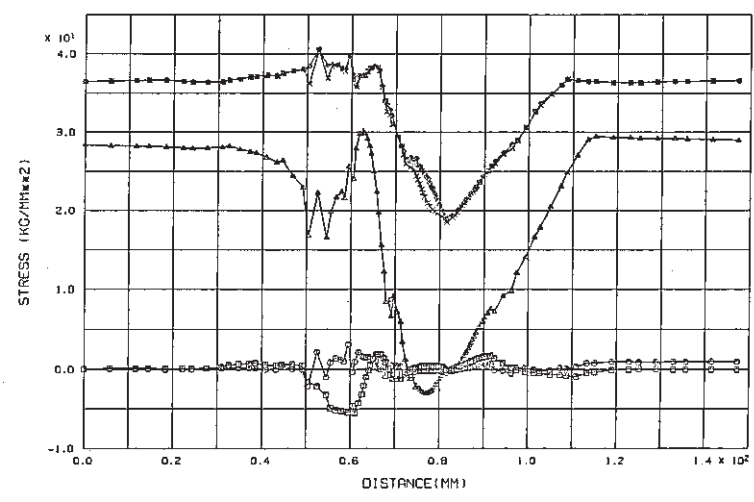
STEP NO. 61

GEOM. SCALE 8.00000

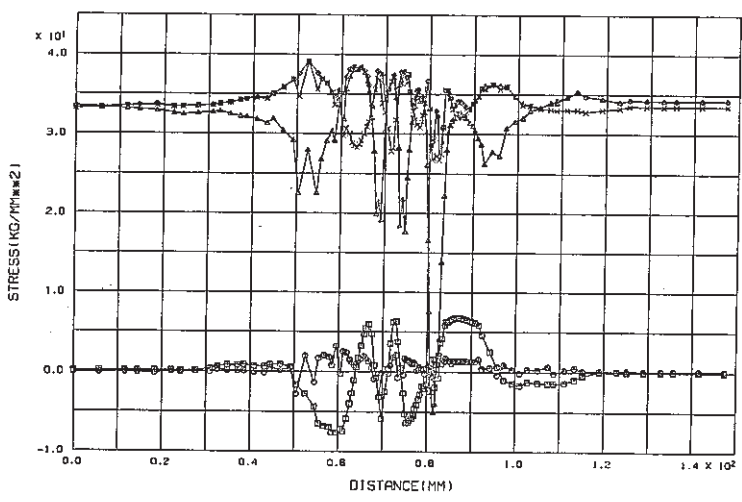
Fig. D-6(c) Contour of Shear Stress at Hot Shock (Time= 1020 sec) of Finally Welded Joint (crack depth a=27 mm)



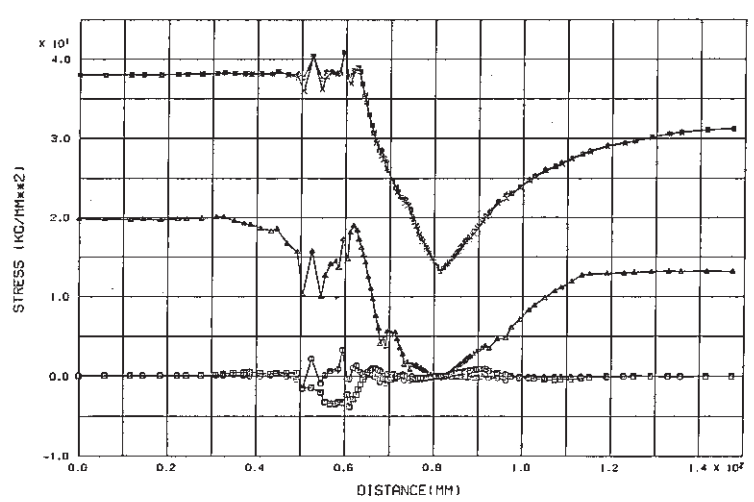
(a) No crack



(c) Crack depth a=15mm



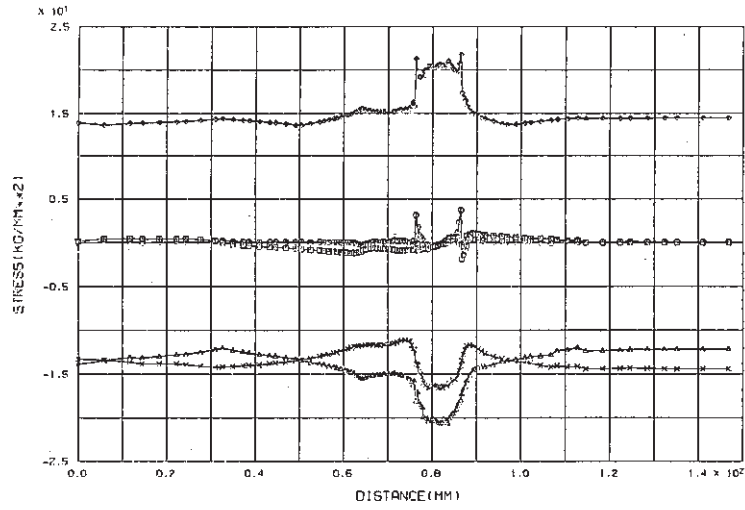
(b) Crack depth a=1mm



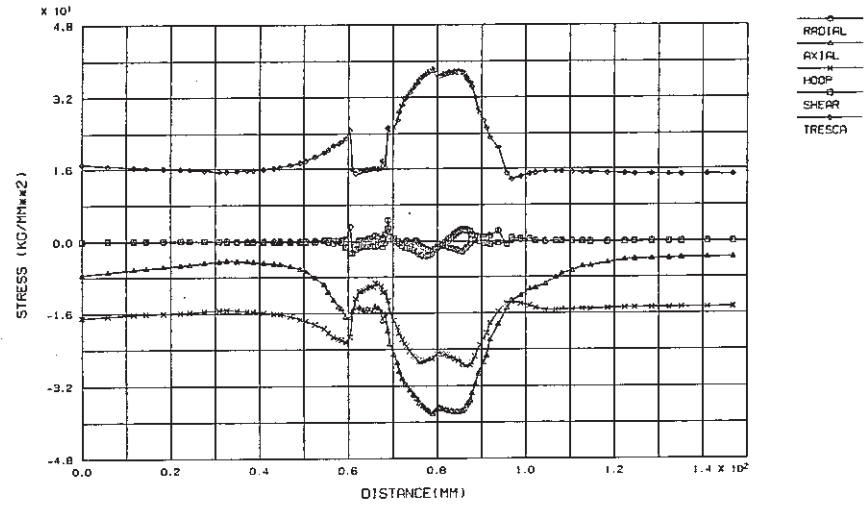
(d) Crack depth a=27mm

Fig. D-7 Stress Distribution along Inner Surface at Cold Shock (Time=7352 sec) of Finally Welded Joint

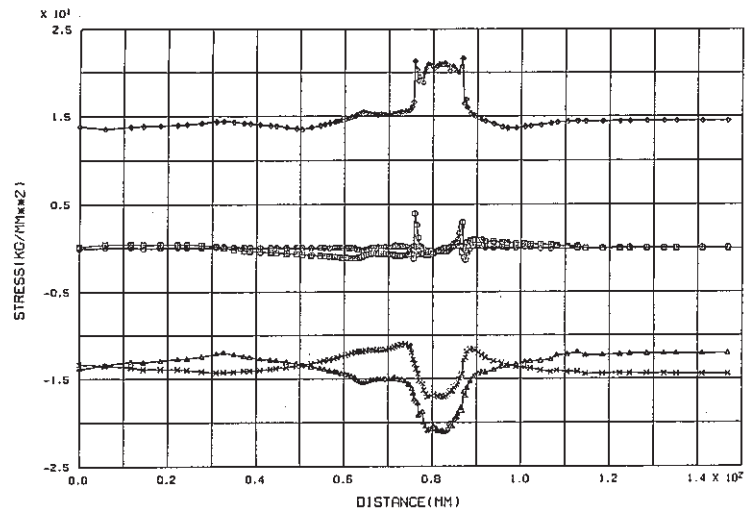
- 359 -



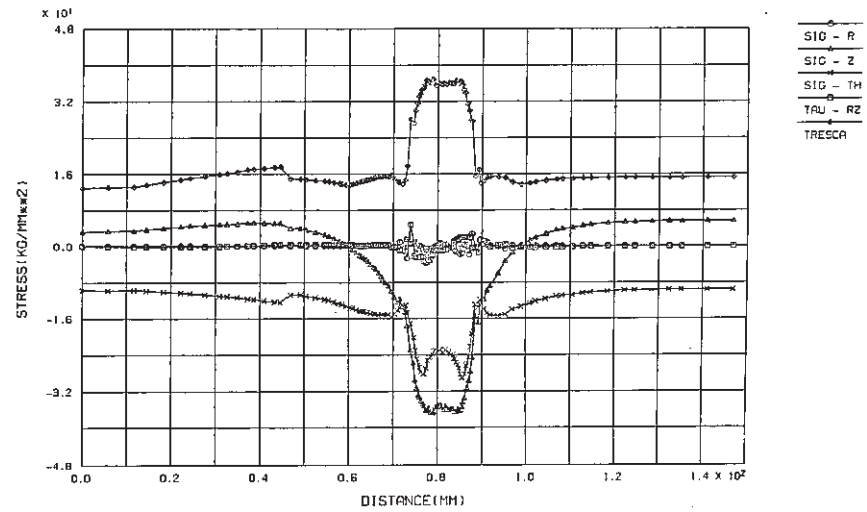
(a) No crack



(c) Crack depth a=15mm

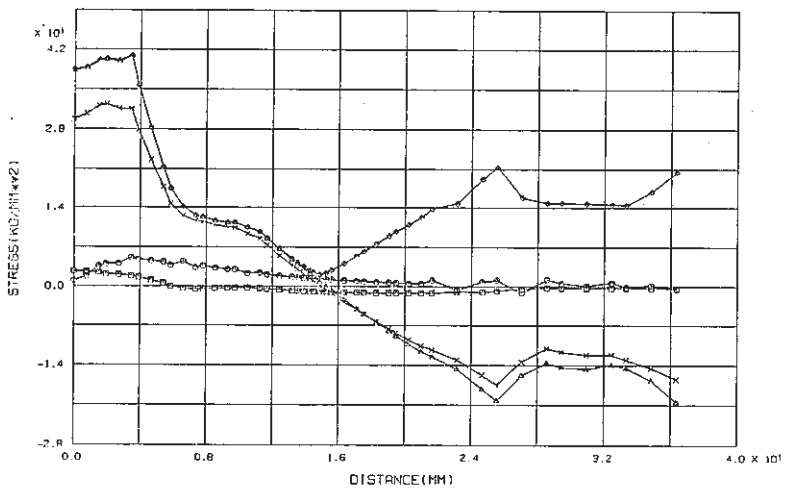


(b) Crack depth a=1mm

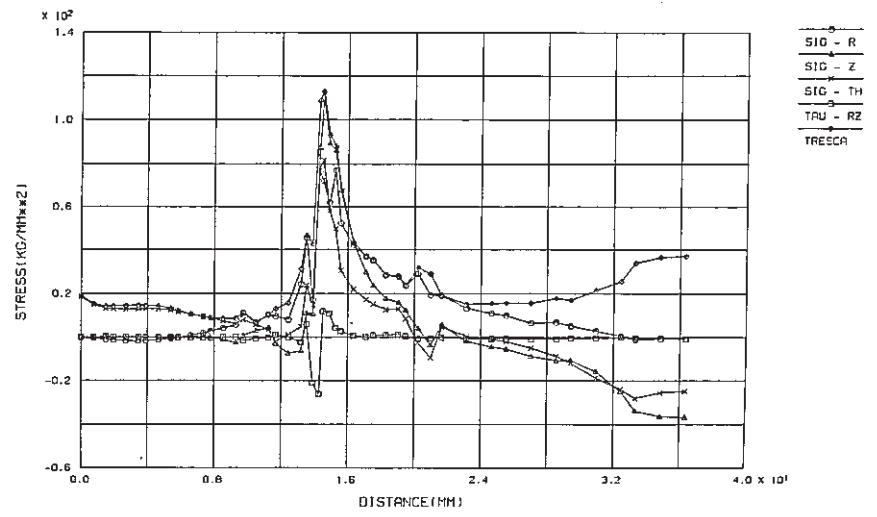


(d) Crack depth a=27mm

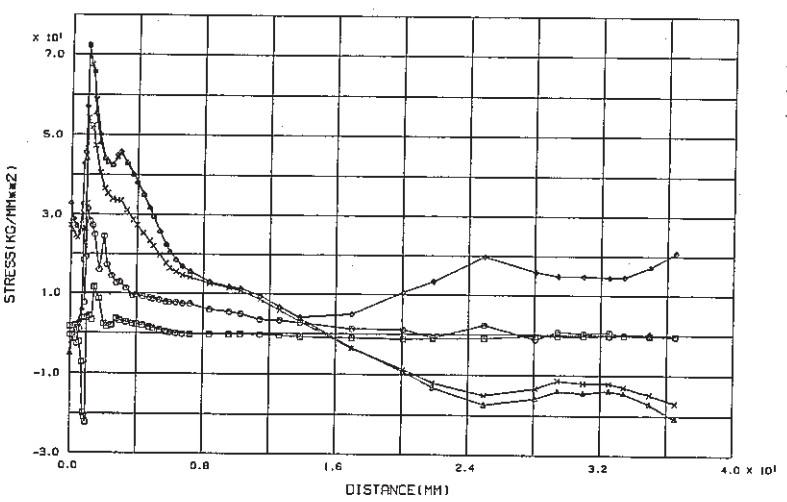
Fig. D-8 Stress Distribution along Outer Surface at Cold Shock (Time=7352 sec) of Finally Welded Joint



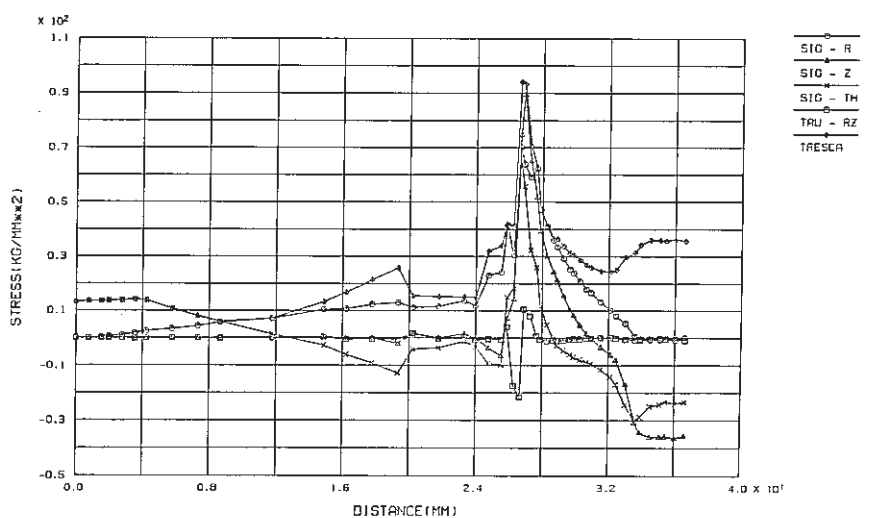
(a) No crack



(c) Crack depth a=15mm



(b) Crack depth a=1mm



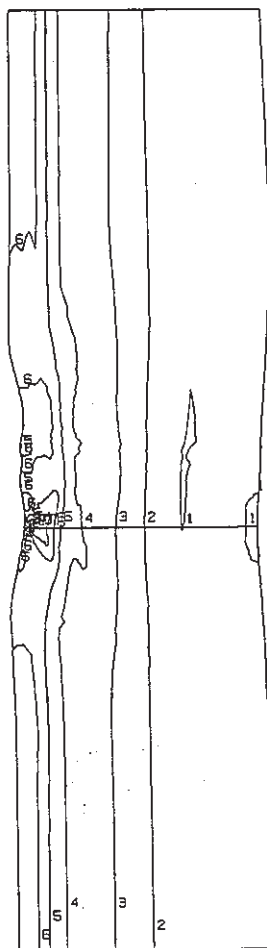
(d) Crack depth a=27mm

Fig. D-9 Stress Distribution along Crack Line at Cold Shock (Time=7352 sec) of Finally Welded Joint

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FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -17.3000
 2 -7.39998
 3 2.500019
 4 12.40001
 5 22.30000
 6 32.20000
 7 42.10000
 8 51.99998
 9 61.89998
 10 71.79998

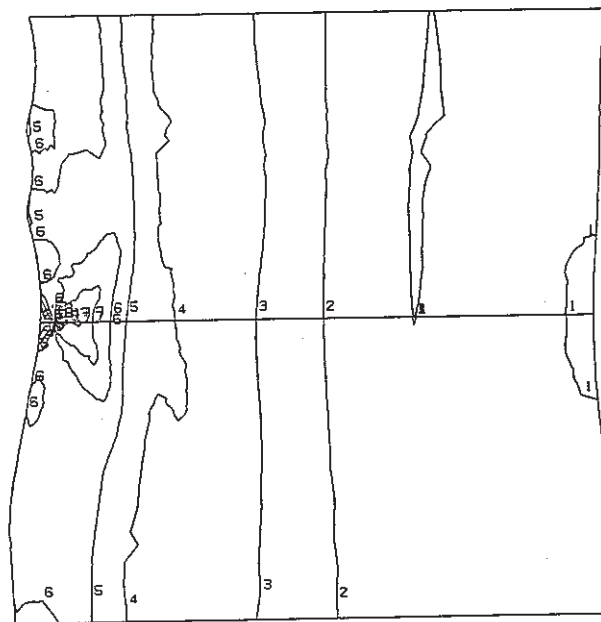


STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -17.3000
 2 -7.39998
 3 2.500019
 4 12.40001
 5 22.30000
 6 32.20000
 7 42.10000
 8 51.99998
 9 61.89998
 10 71.79998



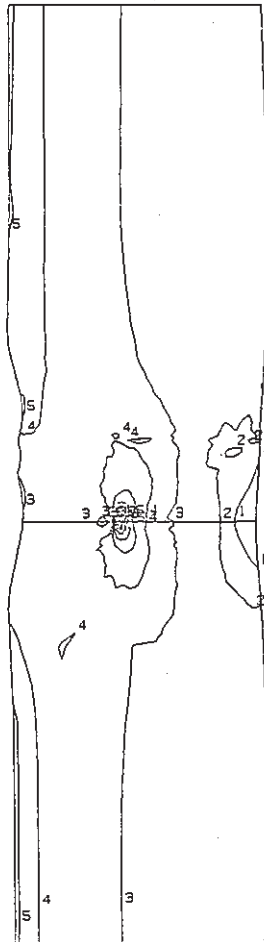
STEP NO. 102

GEOM. SCALE 8.00000

Fig. D-10(a) Contour of Axial Stress at Cold Shock
(Time=7352 sec) of Finally Welded Joint
(crack depth a=1 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -32.0000
 2 -17.0000
 3 -2.00000
 4 13.00000
 5 28.00000
 6 43.00000
 7 58.00001
 8 73.00001
 9 88.00002
 10 102.9999

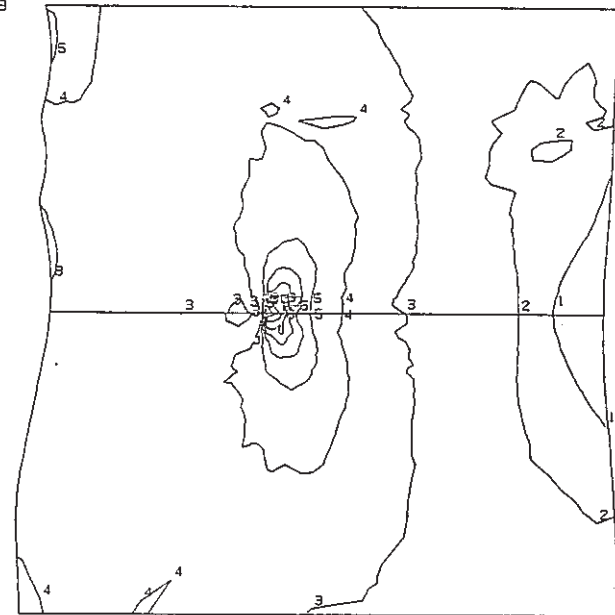


STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -32.0000
 2 -17.0000
 3 -2.00000
 4 13.00000
 5 28.00000
 6 43.00000
 7 58.00001
 8 73.00001
 9 88.00002
 10 102.9999



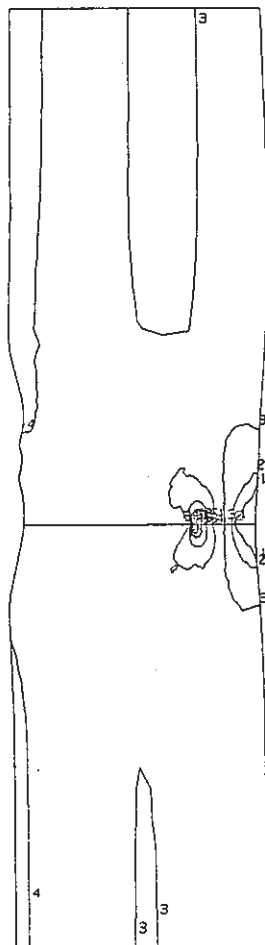
STEP NO. 102

GEOM. SCALE 8.00000

Fig. D-10(b) Contour of Axial Stress at Cold Shock
 (Time=7352 sec) of Finally Welded Joint.
 (crack depth $a=15$ mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -31.0000
 2 -18.0000
 3 -5.00000
 4 8.000000
 5 21.00000
 6 34.00000
 7 47.00000
 8 60.00000
 9 73.00001
 10 86.00001

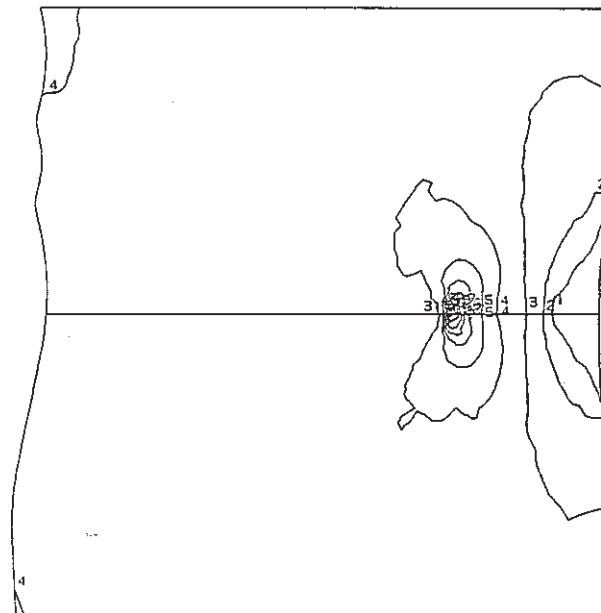


STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -31.0000
 2 -18.0000
 3 -5.00000
 4 8.000000
 5 21.00000
 6 34.00000
 7 47.00000
 8 60.00000
 9 73.00001
 10 86.00001



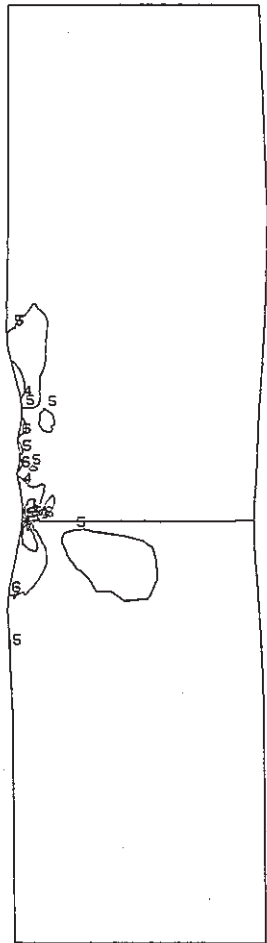
STEP NO. 102

GEOM. SCALE 8.00000

Fig. D-10(c) Contour of Axial Stress at Cold Shock
 (Time=7352 sec) of Finally Welded Joint
 (crack depth a=27 mm)

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -19.9000
 2 -15.3000
 3 -10.7000
 4 -6.09997
 5 -1.49997
 6 3.100024
 7 7.700021
 8 12.30001
 9 16.90000
 10 21.49999

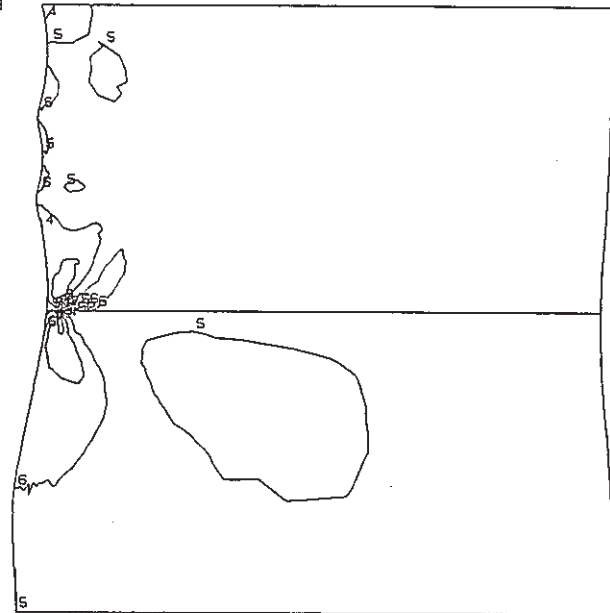


STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -19.9000
 2 -15.3000
 3 -10.7000
 4 -6.09997
 5 -1.49997
 6 3.100024
 7 7.700021
 8 12.30001
 9 16.90000
 10 21.49999



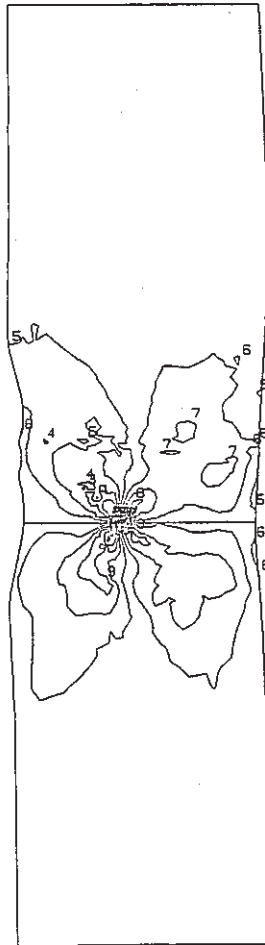
STEP NO. 102

GEOM. SCALE 8.00000

Fig. D-11(a) Contour of Shear Stress at Cold Shock
(Time=7352 sec) of Finally Welded Joint.
(crack depth a=1 mm)

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -19.1000
 2 -14.9000
 3 -10.7000
 4 -6.49998
 5 -2.29998
 6 1.900013
 7 6.100011
 8 10.30000
 9 14.50000
 10 18.69999



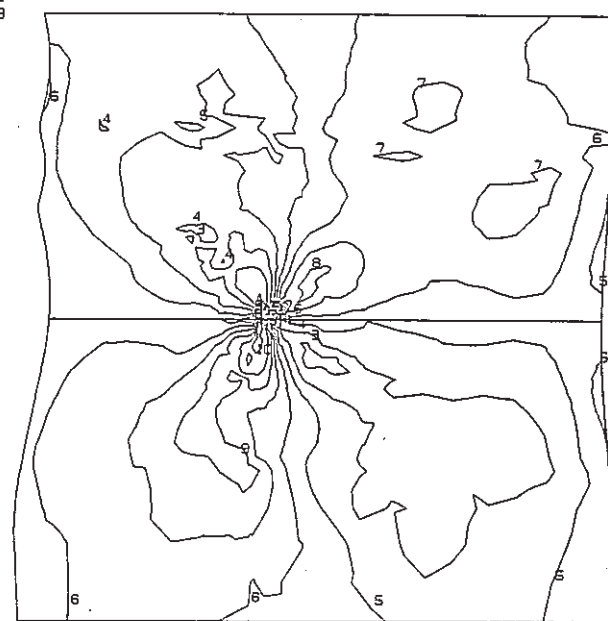
Z
↑
R →

STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -19.1000
 2 -14.9000
 3 -10.7000
 4 -6.49998
 5 -2.29998
 6 1.900013
 7 6.100011
 8 10.30000
 9 14.50000
 10 18.69999



Z
↑
R →

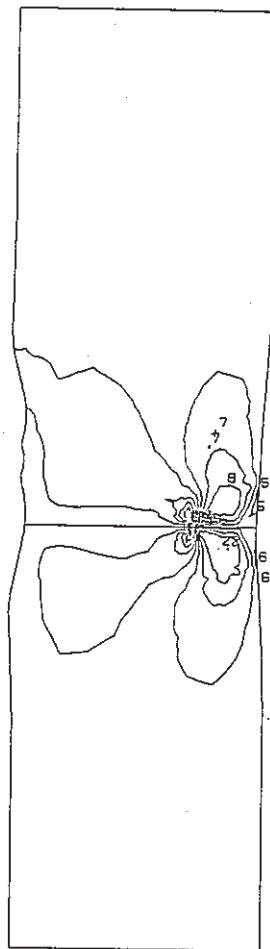
STEP NO. 102

GEOM. SCALE 8.00000

Fig. D-11(b) Contour of Shear Stress at Cold Shock
(Time=7352 sec) of Finally Welded Joint
(crack depth a=15 mm)

FINAS
STRESS COMPONENT 4

CONTOUR VALUES
 1 -15.8000
 2 -12.3000
 3 -8.79999
 4 -5.30000
 5 -1.80000
 6 1.70000
 7 5.199998
 8 8.699996
 9 12.19999
 10 15.69998

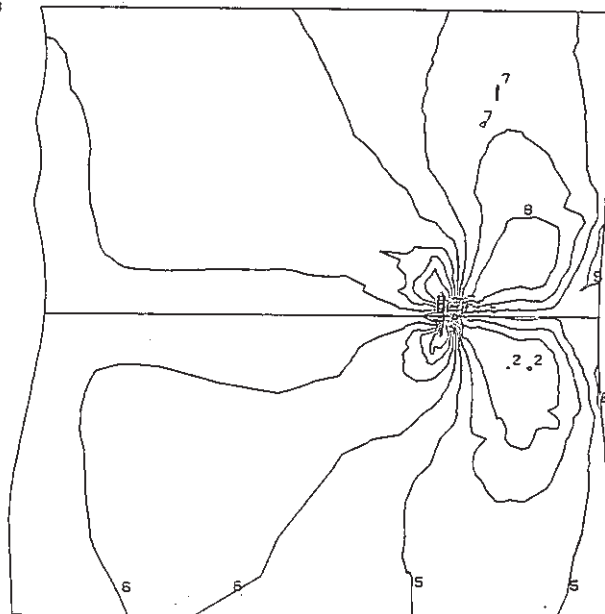


STEP NO. 102

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 4

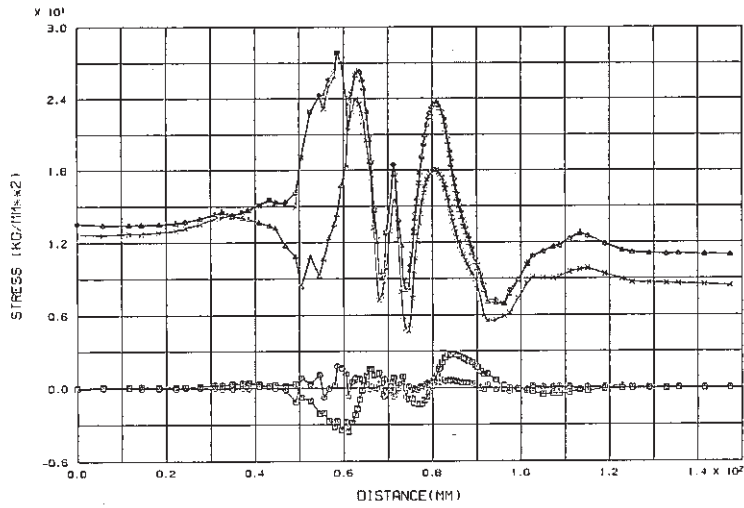
CONTOUR VALUES
 1 -15.8000
 2 -12.3000
 3 -8.79999
 4 -5.30000
 5 -1.80000
 6 1.70000
 7 5.199998
 8 8.699996
 9 12.19999
 10 15.69998



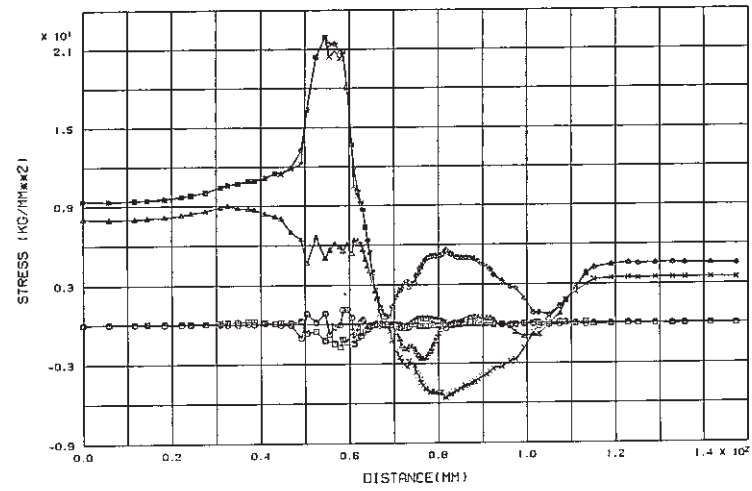
STEP NO. 102

GEOM. SCALE 8.00000

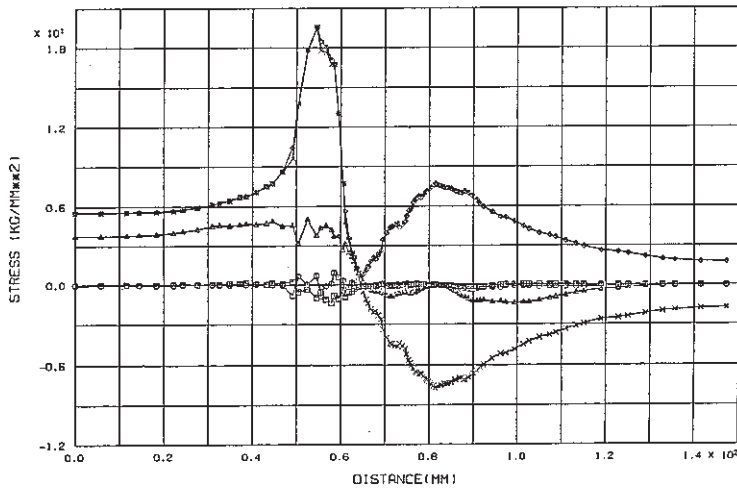
Fig. D-11(c) Contour of Shear Stress at Cold Shock
(Time=7352 sec) of Finally Welded Joint
(crack depth a=27 mm)



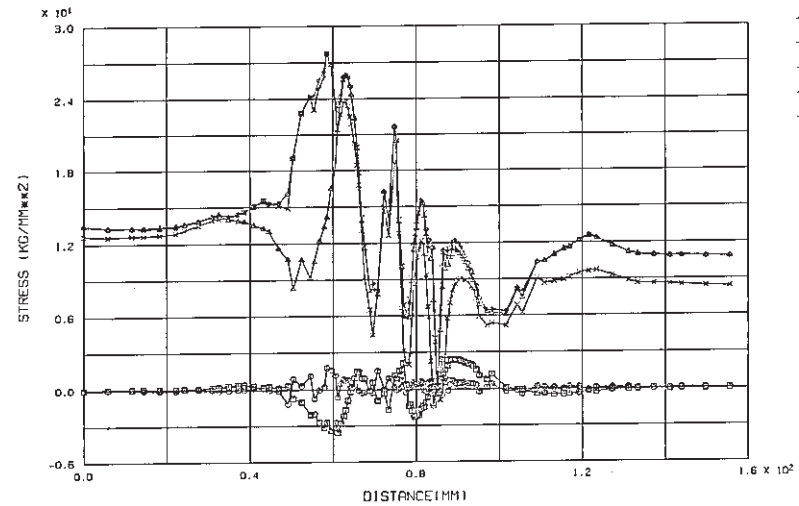
(a) No crack



(c) Crack depth a=15mm

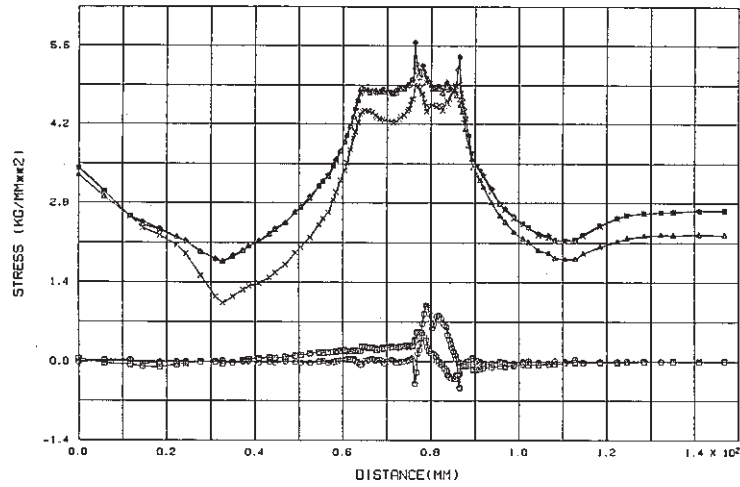


(b) Crack depth a=1mm

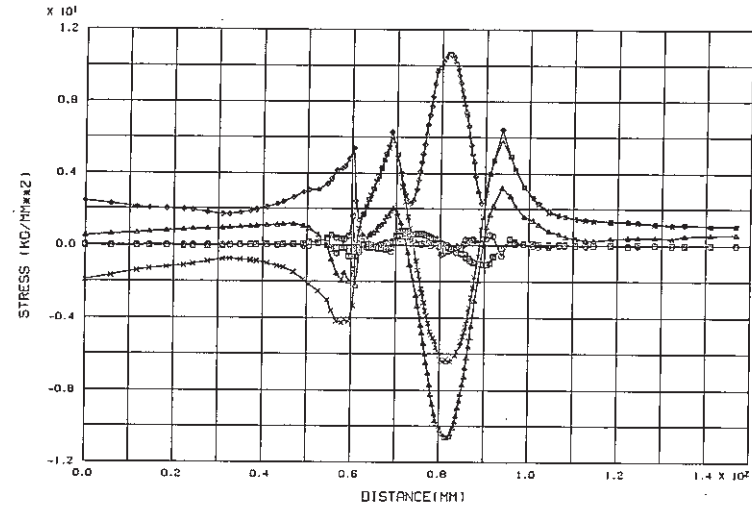


(d) Crack depth a=27mm

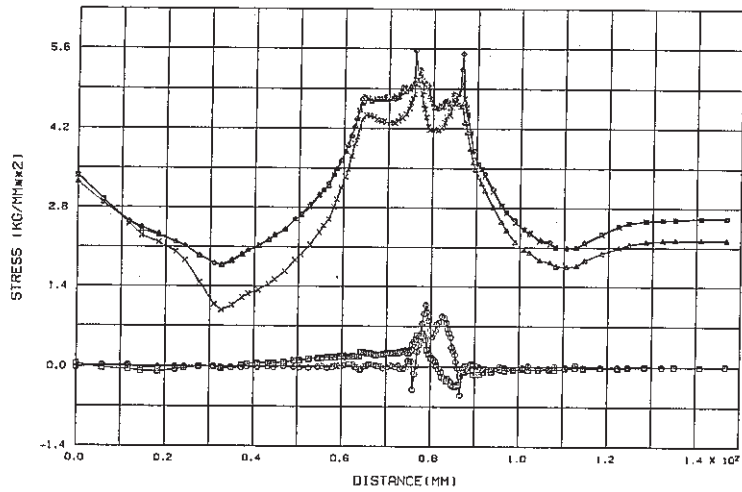
Fig. D-12 Stress Distribution along Inner Surface at Hot Shock (Time=4200 sec) of Finally Welded Joint



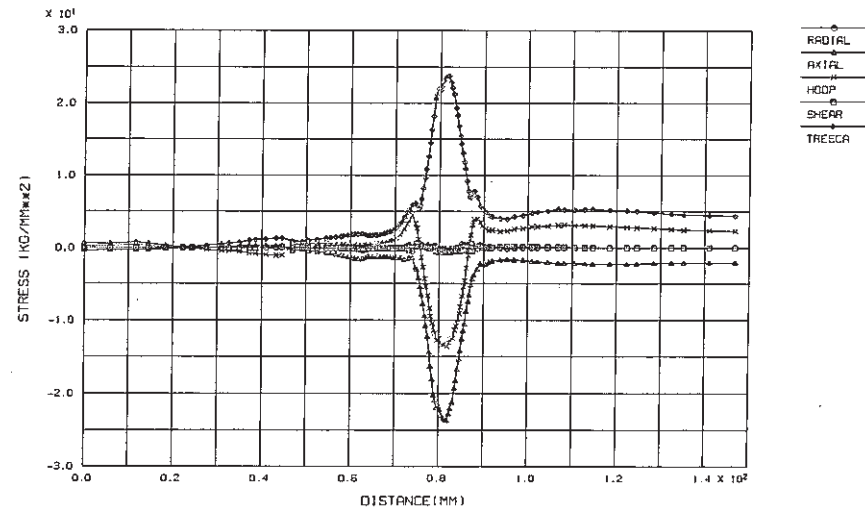
(a) No crack



(c) Crack depth a=15mm

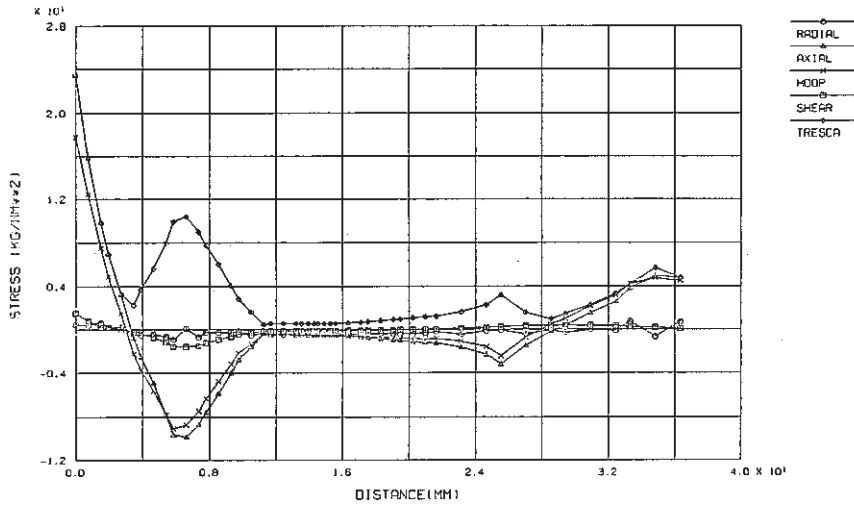


(b) Crack depth a=1mm

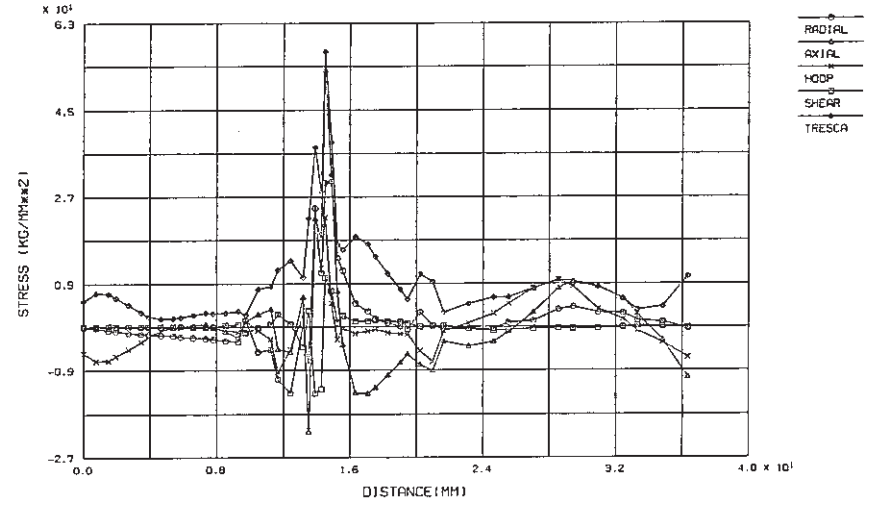


(d) Crack depth a=27mm

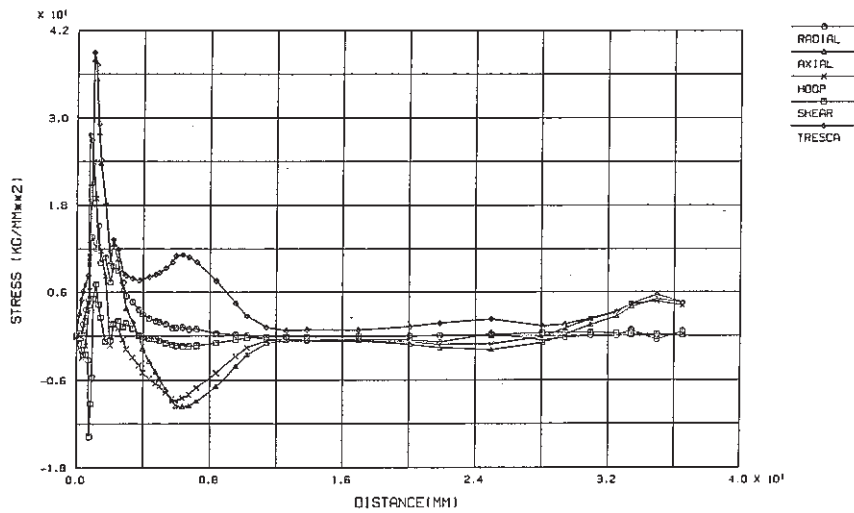
Fig. D-13 Stress Distribution along Outer Surface at Hot Shock (Time=4200 sec) of Finally Welded Joint



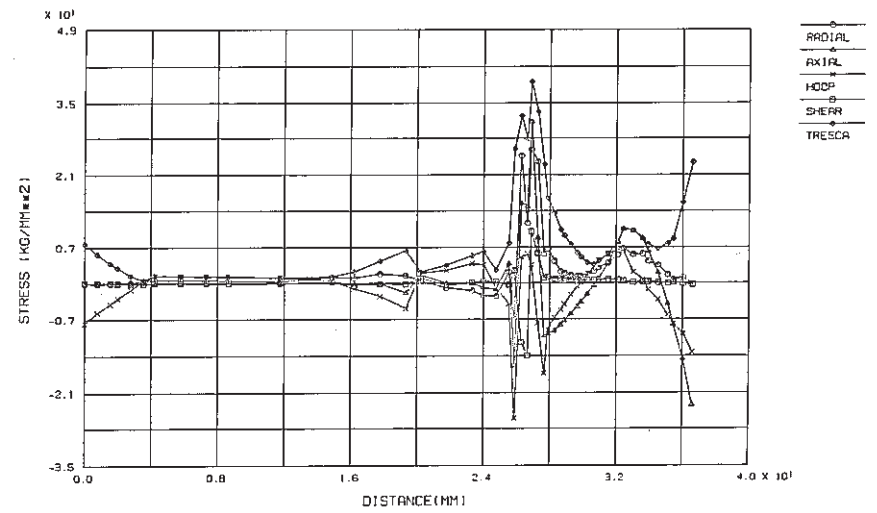
(a) No crack



(c) Crack depth a=15mm



(b) Crack depth a=1mm

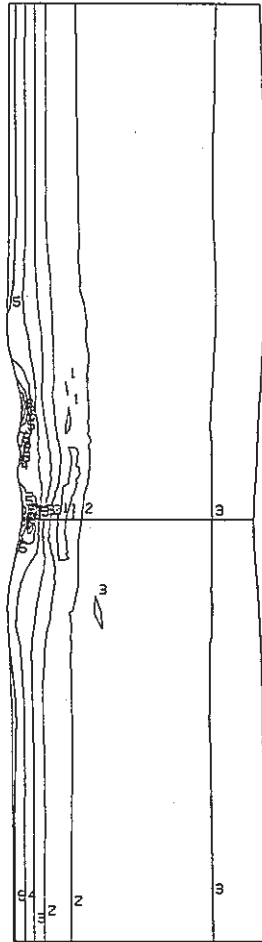


(d) Crack depth a=27mm

Fig. D-14 Stress Distribution along Crack Line at Hot Shock (Time=4200 sec) of Finally Welded Joint

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -9.10000
 2 -4.10000
 3 0.900000
 4 5.899997
 5 10.89999
 6 15.89999
 7 20.89999
 8 25.89999
 9 30.89999
 10 35.89999

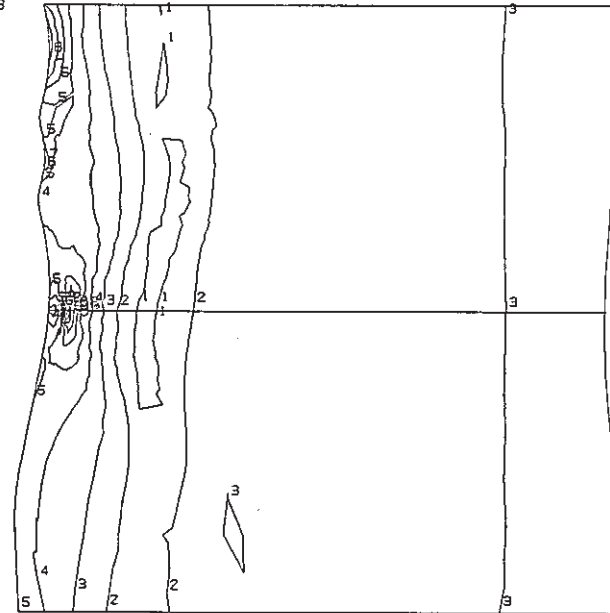


STEP NO. 73

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
 1 -9.10000
 2 -4.10000
 3 0.900000
 4 5.899997
 5 10.89999
 6 15.89999
 7 20.89999
 8 25.89999
 9 30.89999
 10 35.89999



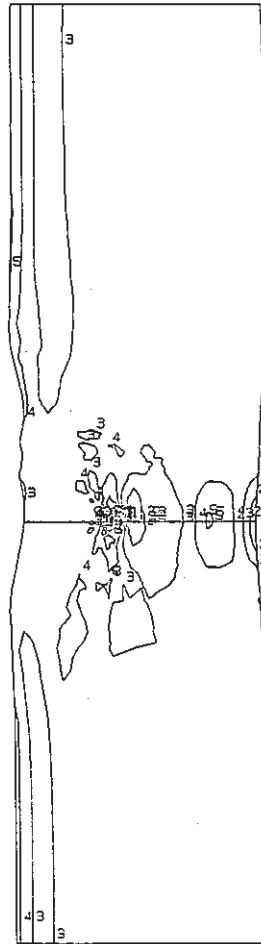
STEP NO. 73

GEOM. SCALE 9.00000

Fig. D-15(a) Contour of Axial Stress at Hot Shock
 (Time=4200 sec) of Finally Welded Joint
 (crack depth a=1 mm)

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -13.4000
2 -7.79999
3 -2.19999
4 3.400005
5 9.000002
6 14.60000
7 20.19999
8 25.79998
9 31.39998
10 36.99996

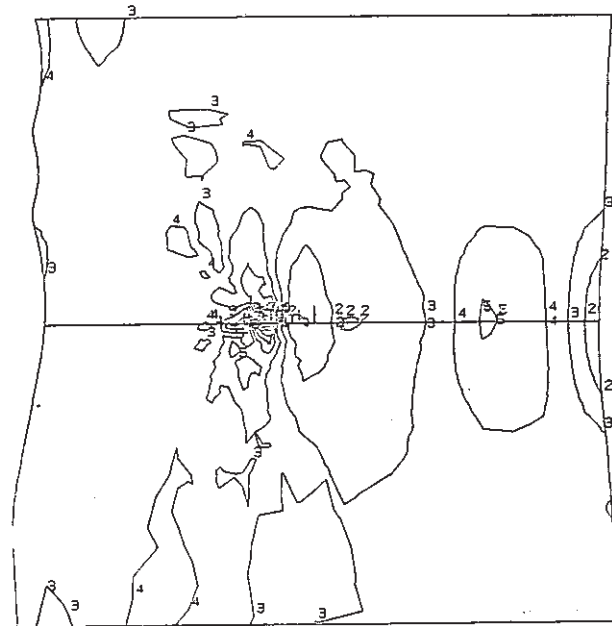


STEP NO. 73

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

CONTOUR VALUES
1 -13.4000
2 -7.79999
3 -2.19999
4 3.400005
5 9.000002
6 14.60000
7 20.19999
8 25.79998
9 31.39998
10 36.99996



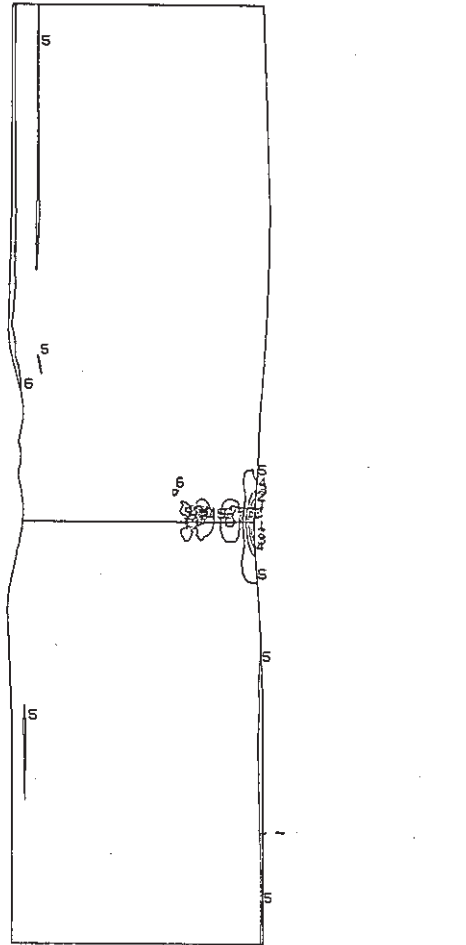
STEP NO. 73

GEOM. SCALE 8.00000

Fig. D-15(b) Contour of Axial Stress at Hot Shock
(Time=4200 sec) of Finally Welded Joint
(crack depth $a=15$ mm)

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -23.7000
 - 2 -18.3000
 - 3 -12.9000
 - 4 -7.49996
 - 5 -2.09996
 - 6 3.300033
 - 7 8.700031
 - 8 14.10002
 - 9 19.50001
 - 10 24.90000

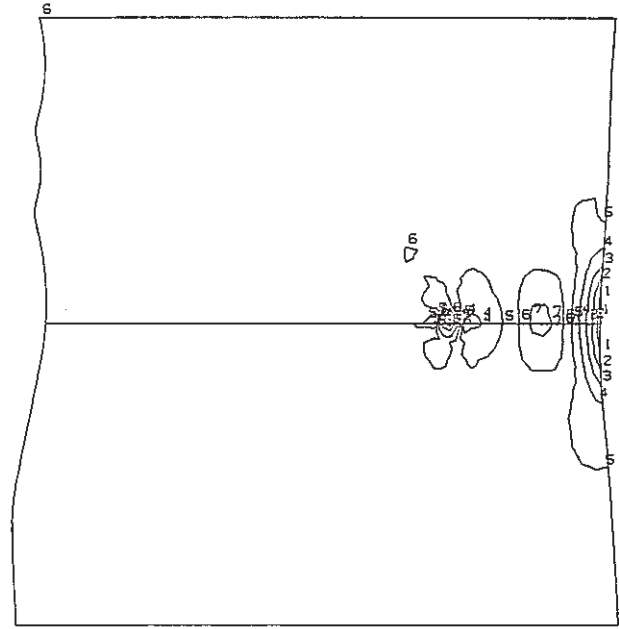


STEP NO. 73

GEOM. SCALE 20.0000

FINAS
STRESS COMPONENT 2

- CONTOUR VALUES
- 1 -23.7000
 - 2 -18.3000
 - 3 -12.9000
 - 4 -7.49996
 - 5 -2.09996
 - 6 3.300033
 - 7 8.700031
 - 8 14.10002
 - 9 19.50001
 - 10 24.90000



STEP NO. 73

GEOM. SCALE 8.0000

Fig. D-15(c) Contour of Axial Stress at Hot Shock
(Time=4200 sec) of Finally Welded Joint
(crack depth a=27 mm)

附録 E 弾性解析に基づく破壊力学パラメータの解析結果

附録E 弾性解析に基づく破壊力学パラメータの解析結果

弾性解析結果に基づいて、各モデル各々について数種類の深さのき裂の破壊力学パラメータを計算した。附録Aで示したように、開口形のモードI変形が主であるため、き裂面に垂直な応力成分より求めた K_I 値を代表値として求めた。J積分については経路に依存することがはっきりしたため、ここでは径路独立性を示す \hat{J} 積分について解析・検討した。

1. 最終溶接部

Table.E.1-1~Table.E.1-6に、き裂深さごとに計算した破壊力学パラメータ値を示す。またFig.E.1.1~Fig.E.1.2にき裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

2. 入口ノズル

Table.E.2.1~Table.E.2.3に想定した3つのき裂の深さごとに計算した破壊力学パラメータ値を示す。また、Fig.E.2.1~Fig.E.2.6に各き裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

3. シンニング部

Table.E.3.1, Table.E.3.2に想定した2つのき裂の深さをもとに計算した破壊力学パラメータ値を示す。また、Fig.E.3.1~Fig.E.3.4に各き裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

4. コニカル・下部鏡部

Table.E.4-1~Table.E.4-3に、き裂深さごとに計算した破壊力学パラメータ値を示す。またFig.E.4.1~Fig.E.4.2に、き裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

5. 出口ノズル部

Table.E.5.1~Table.E.5.3に想定した3つのき裂の深さごとに計算した破壊力学パラメータ値を示す。また、Fig.E.5.1~Fig.E.5.6に、各き裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

6. スタッドボルト

Table.E.6-1~Table.E.6-4に、き裂深さごとに計算した破壊力学パラメータ値を示す。またFig.E.6.1, Fig.E.6.2に、き裂深さごとの K_I 値及び \hat{J} 積分値の時間変化を示す。

7. 計装ノズル

Table.E.7.1~Table.7.3は、き裂半径ごとにコールド及びホットショックにおいて最大を示す時点での破壊力学パラメータ値である。Fig.E.7.1及びFig.E.7.2は、き裂半径ごとの K_I 値及び \hat{J} 積分値の時間変化である。Fig.E.7.3は、き裂半径ごとの K_I 値のき裂縁に沿った分布である。また、Fig.E.7.4は、き裂半径ごとの \hat{J} 積分値のき裂縁に沿った分布をコールド及びホットショック時のピークにおいて示したものである。

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Table E.1-1 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=1 mm

*** CRACK DEPTH = 1.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	60.00	82.2200	16.2700	68.5252	71.8926	0.2909	0.2195	505.8000	0.80910E-02
2	107.00	114.3000	23.0700	95.8542	100.5646	0.5692	0.4530	442.2000	0.12420E-01
3	137.00	118.4000	24.0000	99.1081	103.9783	0.5085	0.5021	414.0000	0.12730E-01
4	152.00	119.5000	24.2400	99.7655	104.6681	0.6165	0.5190	400.8000	0.12760E-01
5	174.00	117.2000	23.8200	97.6560	102.4549	0.5908	0.5089	384.4000	0.12440E-01
6	196.00	110.7000	22.5600	92.6080	97.1589	0.5313	0.4678	371.9000	0.11760E-01
7	240.00	98.8600	20.1500	82.6809	86.7440	0.4235	0.3975	350.5000	0.10470E-01
8	300.00	81.2400	16.5900	68.2085	71.5582	0.2882	0.2926	328.5000	0.86220E-02
9	900.00	8.9650	1.8530	8.7167	9.1450	0.0047	-0.0101	252.9000	0.11350E-02
10	920.00	-6.4540	-0.8505	2.8760	3.0173	0.0005	-0.1428	259.6000	-2.2208E-03
11	933.00	-62.1900	-11.4000	43.0851	45.2024	0.1150	-0.3811	300.6000	-5.2280E-02
12	960.00	-124.9000	-24.6600	96.0561	100.7763	0.5716	-0.0696	373.3000	-1.1800E-01
13	990.00	-135.3000	-27.3700	108.2697	113.5901	0.7262	0.2095	412.8000	-1.1380E-01
14	1020.00	-129.7000	-26.4000	105.4678	110.6506	0.6891	0.2534	435.5000	-1.3100E-01
15	1065.00	-115.3000	-23.5000	94.3777	99.0156	0.5518	0.2342	459.6000	-1.1770E-01
16	1110.00	-98.3200	-20.0000	80.3542	84.3029	0.4000	0.1687	476.1000	-1.0030E-01
17	1200.00	-74.0300	-15.0200	60.3861	63.3535	0.2259	0.0886	505.6000	-7.5560E-02
18	1800.00	-8.0270	-1.9140	5.0294	5.2765	0.0018	-0.0026	568.7000	-5.6470E-03

Table E.1-2 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=5 mm

*** CRACK DEPTH = 5.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	60.00	107.7000	30.5700	110.6513	116.0888	0.7585	0.5288	528.3000	0.29860E-01
2	107.00	158.7000	44.4600	162.0089	169.9702	1.6260	1.1480	468.0000	0.42380E-01
3	137.00	166.4000	46.3800	168.7917	177.0863	1.7650	1.2590	440.8000	0.43690E-01
4	152.00	168.3000	46.8800	170.1253	178.4854	1.7930	1.2860	427.8000	0.43850E-01
5	174.00	166.4000	46.2800	167.4957	175.7265	1.7380	1.2540	410.4000	0.42380E-01
6	196.00	158.9000	44.0900	159.5492	167.3893	1.5770	1.1440	396.2000	0.40690E-01
7	240.00	142.7000	39.3900	142.3313	149.3256	1.2550	0.9283	372.2000	0.36170E-01
8	300.00	118.4000	32.5900	117.7744	123.5620	0.8593	0.6486	346.2000	0.29800E-01
9	900.00	15.4600	4.0300	14.6412	15.3607	0.0133	-0.0084	254.8000	0.36810E-02
10	920.00	0.7515	0.1247	-6.3156	-6.6260	-0.0025	-0.0809	256.3000	-2.2201E-04
11	933.00	-65.4600	-18.8200	60.1853	63.1428	0.2244	-0.2161	279.8000	-1.5560E-01
12	960.00	-164.1000	-46.3900	156.2927	164.0119	1.5140	0.5790	341.6000	-1.3900E-01
13	990.00	-189.6000	-52.8500	184.7273	193.8050	2.1140	1.1730	383.8000	-1.45910E-01
14	1020.00	-184.9000	-51.2700	182.1313	191.0814	2.0550	1.2340	409.0000	-1.45320E-01
15	1065.00	-164.6000	-45.3600	164.0388	172.0998	1.6670	1.0390	437.0000	-1.4100E-01
16	1110.00	-139.9000	-38.5100	140.0447	146.9267	1.2150	0.7610	457.3000	-1.35120E-01
17	1200.00	-104.3000	-28.8000	105.0460	110.2081	0.8336	0.4210	491.4000	-1.26560E-01
18	1800.00	-8.1020	-2.5010	8.9208	9.3591	0.0049	-0.0002	568.5000	-2.2440E-02

Table E.1-3 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=10 mm

*** CRACK DEPTH = 10.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	60.00	113.9000	27.6600	117.8703	123.6826	0.8607	0.6482	548.3000	0.41800E-01
2	107.00	178.1000	42.4200	182.1756	191.1279	2.0560	1.5340	498.0000	0.62520E-01
3	137.00	188.8000	44.6400	191.7168	201.1379	2.2770	1.6990	468.4000	0.65040E-01
4	152.00	191.3000	45.1500	193.5603	203.0720	2.3210	1.7320	455.6000	0.65380E-01
5	174.00	190.2000	44.8200	191.5062	200.9170	2.2720	1.6940	437.7000	0.64280E-01
6	196.00	182.9000	42.9900	183.4119	192.4249	2.0840	1.5510	422.0000	0.61210E-01
7	240.00	164.9000	38.5900	164.2354	172.3061	1.6710	1.2430	398.3000	0.54400E-01
8	300.00	138.3000	31.9500	136.3656	143.0668	1.1520	0.8535	365.4000	0.44890E-01
9	900.00	19.8600	4.2260	17.3414	18.1936	0.0186	-0.0058	257.3000	0.52460E-02
10	920.00	7.0080	2.4350	-5.3978	-5.6631	-0.0018	-0.0309	256.8000	0.97790E-03
11	933.00	-54.5800	-13.2800	53.0125	55.6176	0.1741	-0.0273	266.9000	-1.1900E-01
12	960.00	-172.6000	-42.2300	156.2381	174.4072	1.7120	1.0570	312.1000	-1.55040E-01
13	990.00	-213.9000	-51.0500	208.3019	218.5381	2.6880	1.8910	352.6000	-1.7990E-01
14	1020.00	-212.7000	-50.0700	208.8823	219.1470	2.7030	1.9680	380.0000	-1.68110E-01
15	1065.00	-192.0000	-44.9700	190.1528	199.4971	2.2400	1.6540	411.8000	-1.62200E-01
16	1110.00	-162.4000	-37.7100	162.8056	170.5962	1.6380	1.2160	436.1000	-1.53500E-01
17	1200.00	-119.4000	-27.8200	121.5050	127.4753	0.9146	0.6750	475.5000	-1.4050E-01
18	1800.00	-5.8620	-1.7130	9.4403	9.9042	0.0055	0.0016	567.1000	-1.43470E-02

Table E.1-4 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=15 mm

*** CRACK DEPTH = 15.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	37.00	41.9300	5.3420	45.8497	48.2077	0.1308	0.1112	579.3000	0.15680E-01
2	60.00	107.9000	15.7600	113.8651	119.4605	0.8022	0.6631	561.0000	0.40420E-01
3	107.00	177.7000	26.4700	182.4412	191.4056	2.0620	1.7720	515.8000	0.63230E-01
4	137.00	190.3000	28.2800	193.3934	202.8969	2.3170	2.0690	489.1000	0.66340E-01
5	152.00	193.2000	28.6800	195.5515	205.1611	2.3690	2.1600	476.4000	0.66790E-01
6	174.00	192.9000	28.7000	194.0184	203.5527	2.3320	2.1940	458.5000	0.65880E-01
7	196.00	186.5000	27.7500	186.5101	195.6754	2.1550	2.1030	441.9000	0.62390E-01
8	218.00	177.7000	26.3500	176.8249	185.5143	1.9370	1.9670	427.0000	0.59450E-01
9	240.00	168.9000	25.0200	167.3993	175.6254	1.7360	1.8370	413.1000	0.56070E-01
10	300.00	142.6000	21.0700	139.6407	146.5028	1.2080	1.4470	380.4000	0.46320E-01
11	900.00	21.7100	3.1460	18.8747	19.8022	0.0221	0.1615	259.2000	0.53360E-02
12	916.00	18.4400	3.2610	15.1718	15.9174	0.0143	0.1362	258.4000	0.42040E-02
13	920.00	11.4100	3.1010	5.6762	5.3552	0.0020	0.0715	258.3000	0.16170E-02
14	925.00	-4.5130	1.1970	4.9729	5.2173	0.0015	-0.0593	258.6000	-4.0100E-02
15	933.00	-39.8200	-4.1300	43.6990	45.8464	0.1183	-0.2199	262.0000	-1.16010E-01
16	960.00	-160.0000	-23.7300	158.0243	165.7897	1.5470	0.1986	292.8000	-5.2940E-01
17	990.00	-213.1000	-32.0300	207.2142	217.3959	2.6800	0.8815	329.0000	-1.68500E-01
18	1020.00	-216.4000	-32.2000	210.7871	221.1244	2.7520	1.0500	357.1000	-1.69670E-01
19	1110.00	-167.0000	-24.6400	165.2642	173.3855	1.6920	0.7088	418.9000	-1.55380E-01
20	1200.00	-121.2000	-17.7700	122.7409	128.7725	0.9333	0.4008	462.8000	-1.41950E-01
21	1800.00	-2.9550	-0.4855	6.1130	6.4134	0.0023	0.0007	566.0000	-4.7260E-02

Table E.1-5 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=20 mm

*** CRACK DEPTH = 20.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	60.00	93.5200	-6.4830	102.4871	107.5234	0.6507	0.5823	570.7000	0.29200E-01
2	107.00	159.1000	-6.8390	169.1261	177.4371	1.7720	1.6260	533.4000	0.47560E-01
3	137.00	171.6000	-6.7850	180.3948	189.2595	2.0160	1.9150	508.1000	0.50300E-01
4	152.00	174.4000	-6.8240	182.6181	191.5921	2.0660	2.0020	495.6000	0.50730E-01
5	174.00	174.5000	-6.5320	181.5543	190.4760	2.0420	2.0390	477.7000	0.50170E-01
6	196.00	169.3000	-6.0970	175.0358	183.6372	1.8900	1.9600	460.8000	0.48110E-01
7	240.00	153.9000	-5.6050	157.4615	165.1953	1.5360	1.7150	430.0000	0.42900E-01
8	300.00	130.4000	-4.7250	131.7295	138.2028	1.0750	1.3510	394.6000	0.35510E-01
9	900.00	24.4600	-1.4530	17.9857	18.8695	0.0200	0.1460	261.1000	0.39530E-02
10	920.00	15.5900	1.4280	5.4528	5.7208	0.0018	0.0621	259.9000	0.14430E-01
11	933.00	-27.6500	6.7510	35.9085	37.6731	0.0799	-0.2114	260.6000	-1.10610E-01
12	960.00	-134.7000	8.8700	142.4447	149.4446	1.2570	0.1531	268.1000	-1.38340E-01
13	990.00	-189.1000	7.5080	193.2264	202.7217	2.3130	0.8432	307.6000	-1.51640E-01
14	1020.00	-195.4000	6.8680	198.9883	208.7667	2.4530	1.0430	335.2000	-1.53310E-01
15	1065.00	-178.6000	5.8300	183.4999	192.5172	2.0860	0.9543	371.3000	-1.49930E-01
16	1110.00	-151.3000	4.9000	157.5127	165.2530	1.5370	0.7097	401.9000	-1.42860E-01
17	1200.00	-108.8000	3.7010	116.5275	122.2537	0.8412	0.3980	450.4000	-1.32450E-01
18	1800.00	2.3090	-0.7558	4.1423	4.3459	0.0011	-0.0003	565.0000	-1.39000E-02

Table E.1-6 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=27 mm

*** CRACK DEPTH = 27.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	60.00	84.9200	-9.4880	83.2646	87.3563	0.4295	0.4091	577.7000	0.32090E-01
2	107.00	142.4000	-12.3900	138.3050	145.1014	1.1850	1.1900	548.4000	0.52990E-01
3	137.00	153.3000	-12.8200	147.8932	155.1608	1.3550	1.4310	524.7000	0.56240E-01
4	152.00	155.9000	-12.9800	149.8450	157.2085	1.3910	1.5090	512.6000	0.56770E-01
5	174.00	156.0000	-12.8000	149.1431	156.4722	1.3780	1.5590	494.8000	0.56210E-01
6	196.00	151.3000	-12.2400	144.0225	151.0599	1.2850	1.5230	477.4000	0.53990E-01
7	240.00	137.8000	-11.2400	130.0026	136.3910	1.0470	1.3740	445.3000	0.48230E-01
8	300.00	117.0000	-9.6440	109.2197	114.5868	0.7390	1.1280	407.6000	0.39990E-01
9	900.00	21.7100	-1.9030	16.3842	17.1893	0.0166	0.1712	262.9000	0.43560E-02
10	920.00	13.1700	0.5457	8.4639	8.8799	0.0044	0.0953	261.5000	0.15810E-02
11	933.00	-27.4800	6.9960	28.1326	29.5150	0.0490	-0.1394	261.0000	-1.1520E-01
12	960.00	-122.5000	14.1600	113.5883	119.1701	0.7993	-0.0864	268.1000	-1.42080E-01
13	990.00	-170.2000	14.9800	156.5361	164.2284	1.5180	0.2876	289.4000	-1.57560E-01
14	1020.00	-175.8000	14.3600	162.3076	170.2835	1.6320	0.4353	315.3000	-1.59880E-01
15	1065.00	-160.7000	12.7900	150.0055	157.3779	1.3940	0.4318	352.7000	-1.55830E-01
16	1110.00	-136.1000	10.9800	128.6322	135.0163	1.0260	0.3220	386.0000	-1.48440E-01
17	1200.00	-97.6900	8.3620	94.9320	99.5970	0.5583	0.1842	438.9000	-1.36610E-01
18	1800.00	3.0590	-0.2287	5.7777	6.0516	-0.0021	-0.0003	564.0000	-1.43930E-02

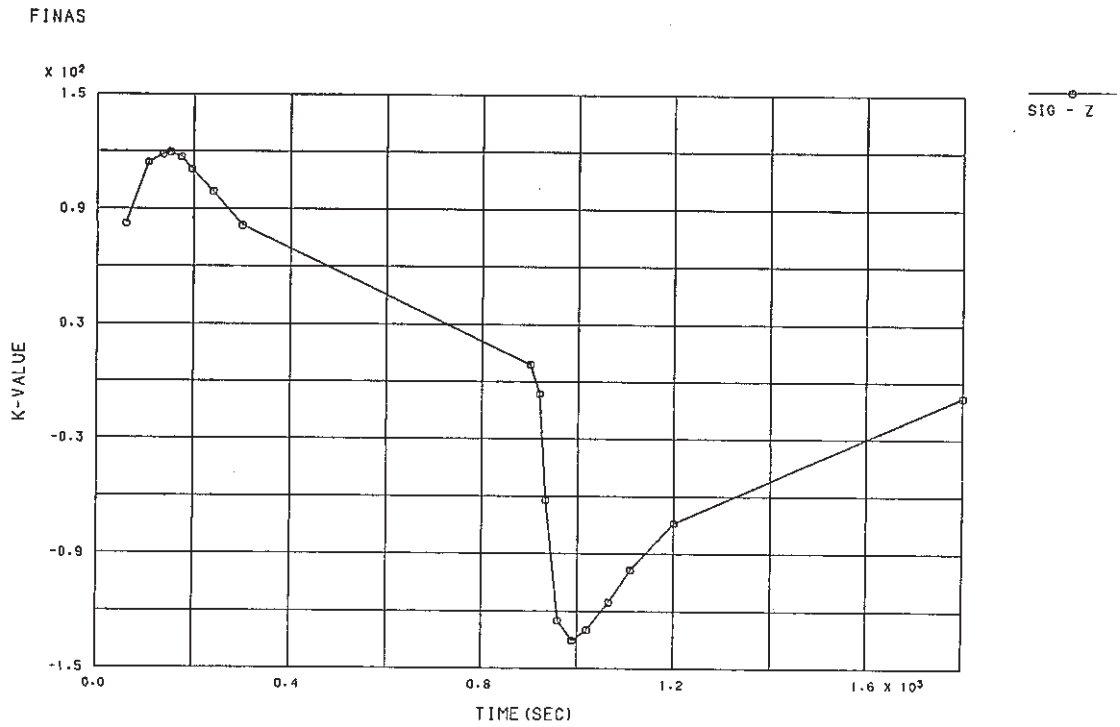


Fig. E.1.1-1 History of Stress Intensity Factor for Finally Welded Joint, crack depth $a=1$ mm

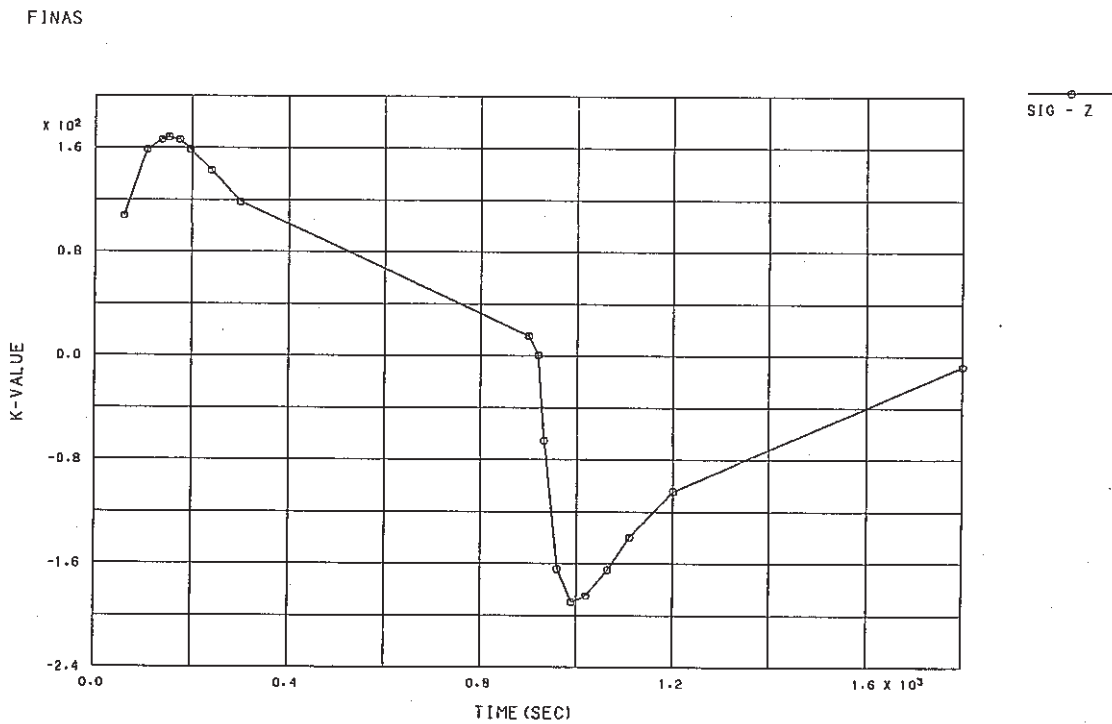


Fig. E.1.1-2 History of Stress Intensity Factor for Finally Welded Joint, crack depth $a=5$ mm

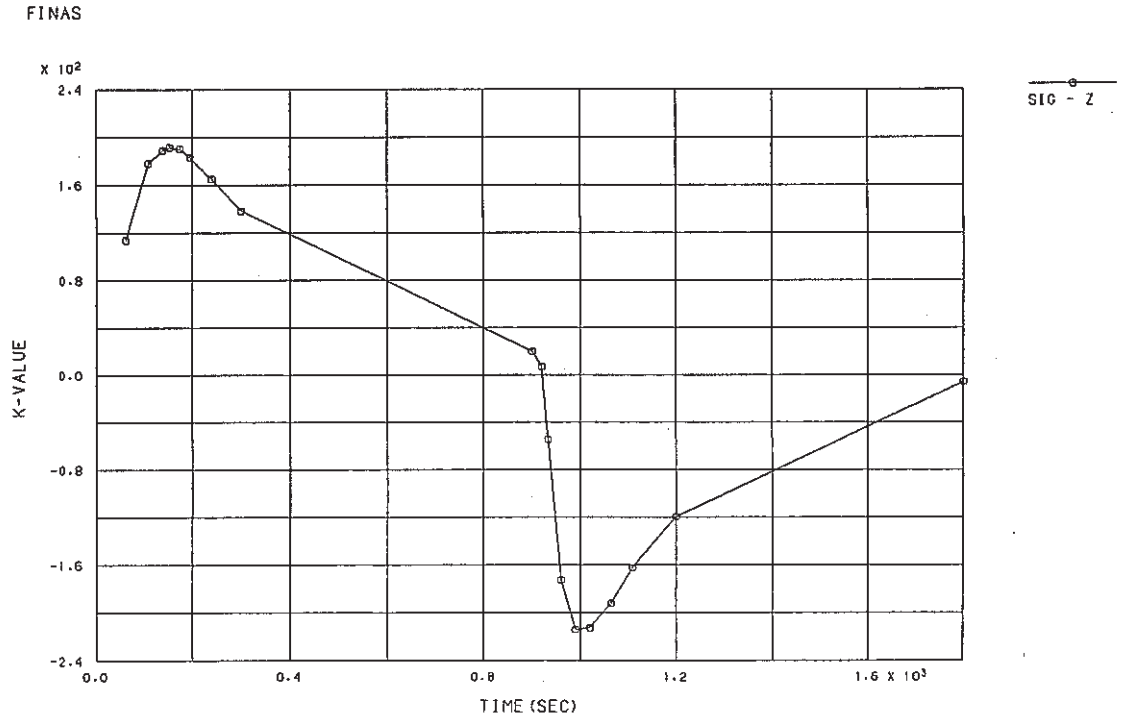


Fig. E.1.1-3 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=10 mm

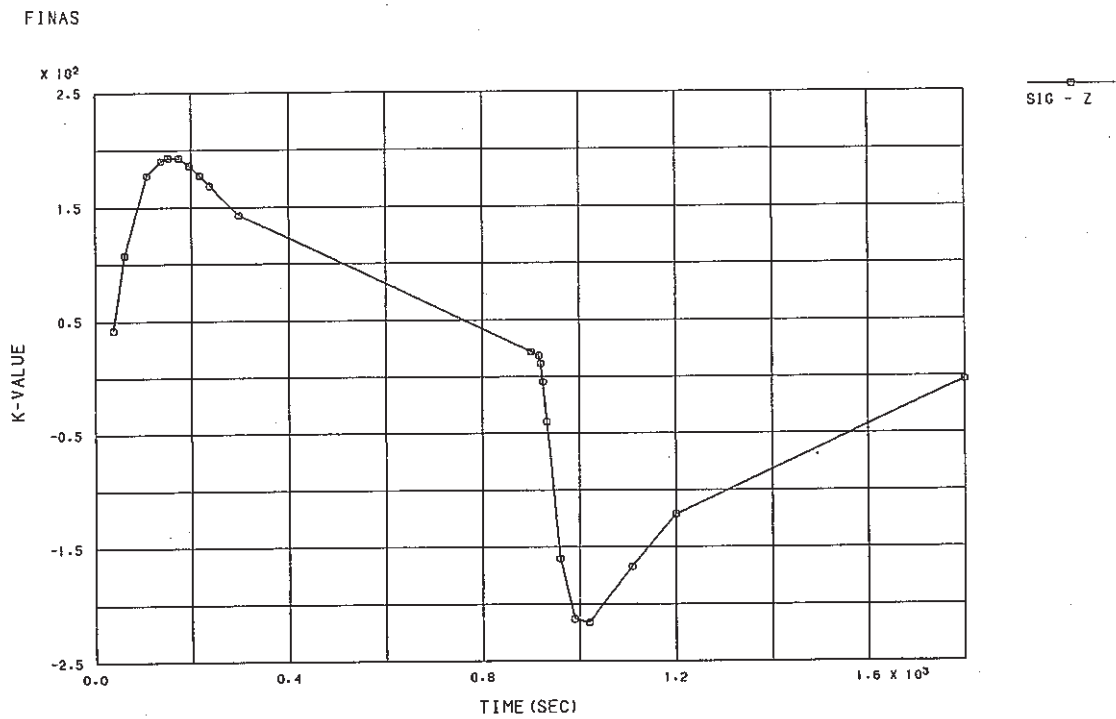


Fig. E.1.1-4 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=15 mm

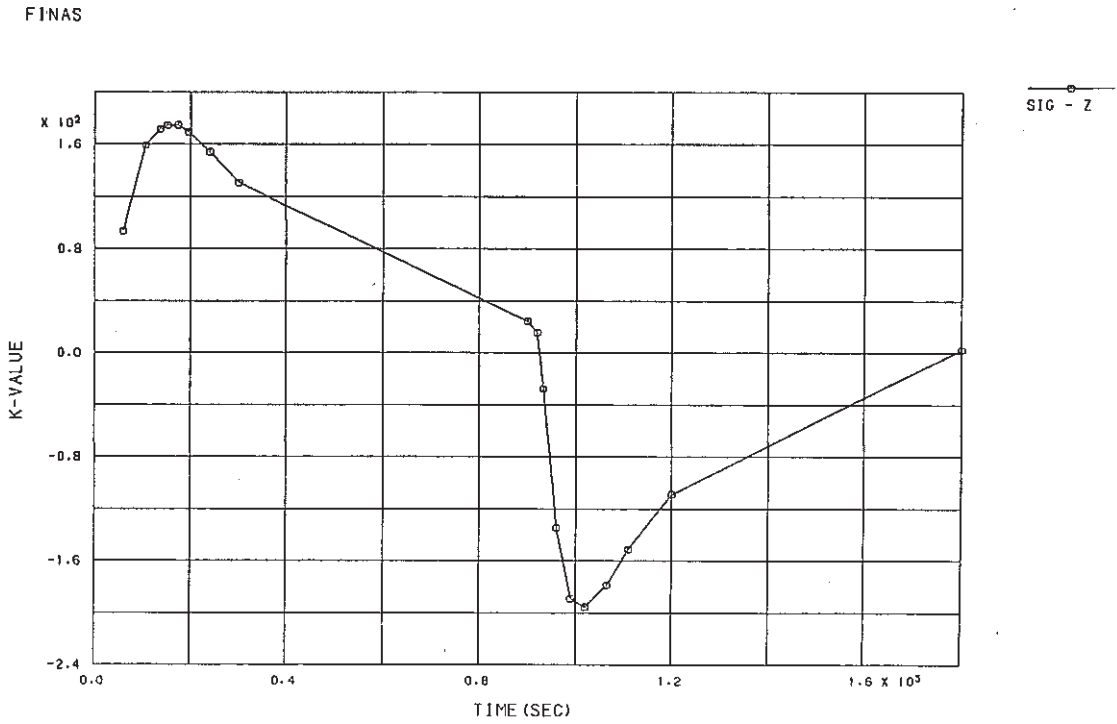


Fig. E.1.1-5 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=20 mm

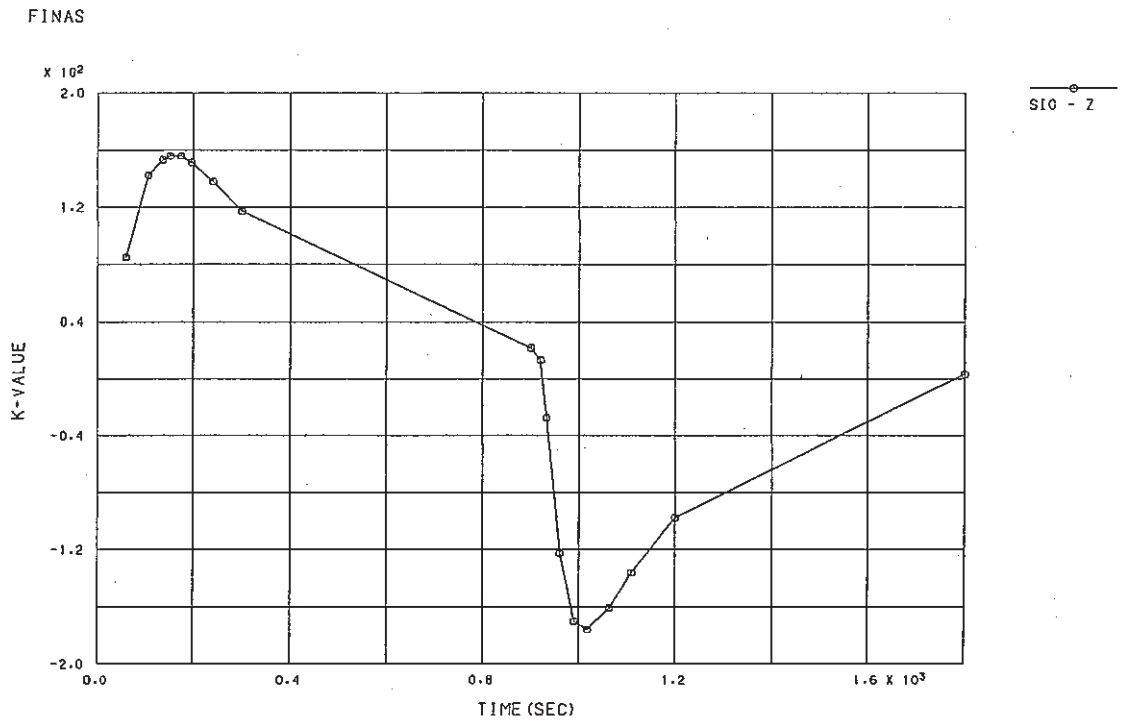


Fig. E.1.1-6 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=27 mm

FINAS

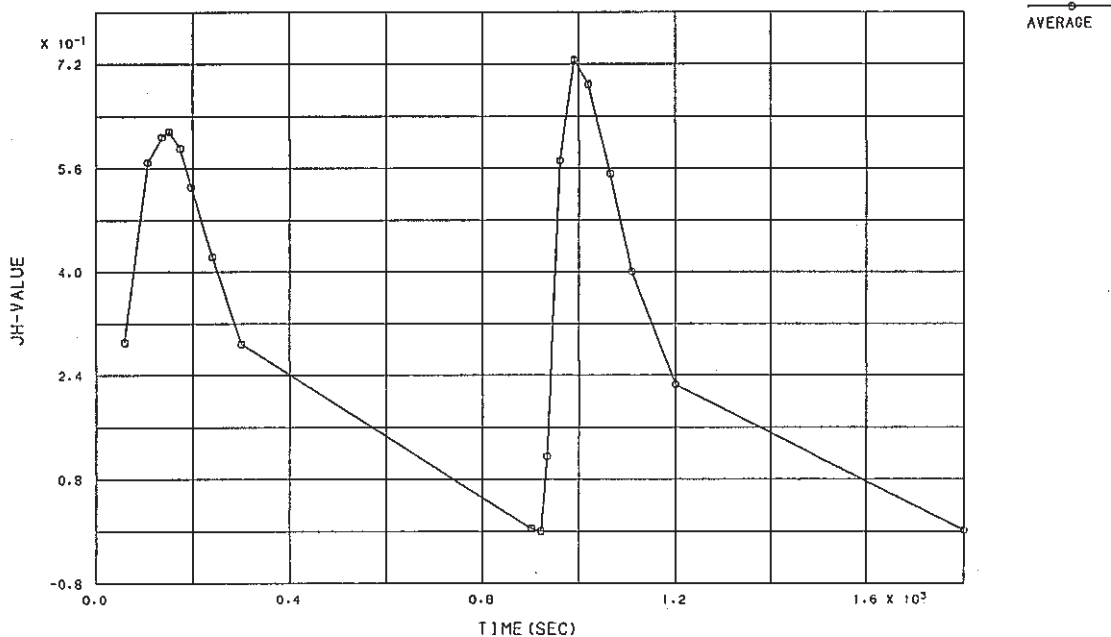


Fig. E.1.2-1 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=1$ mm

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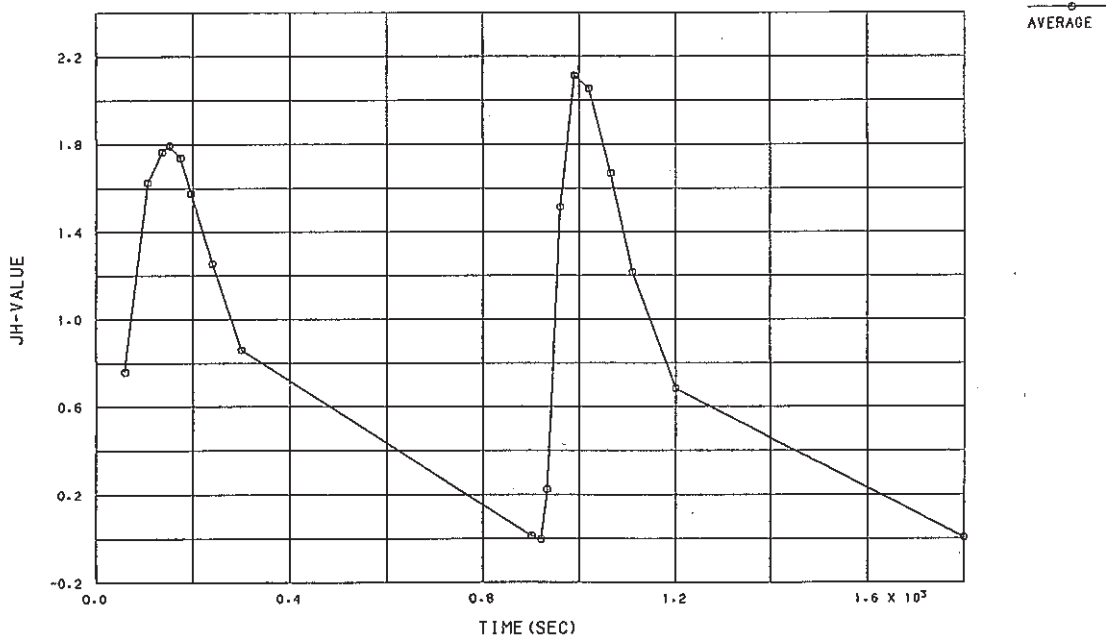


Fig. E.1.2-2 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=5$ mm

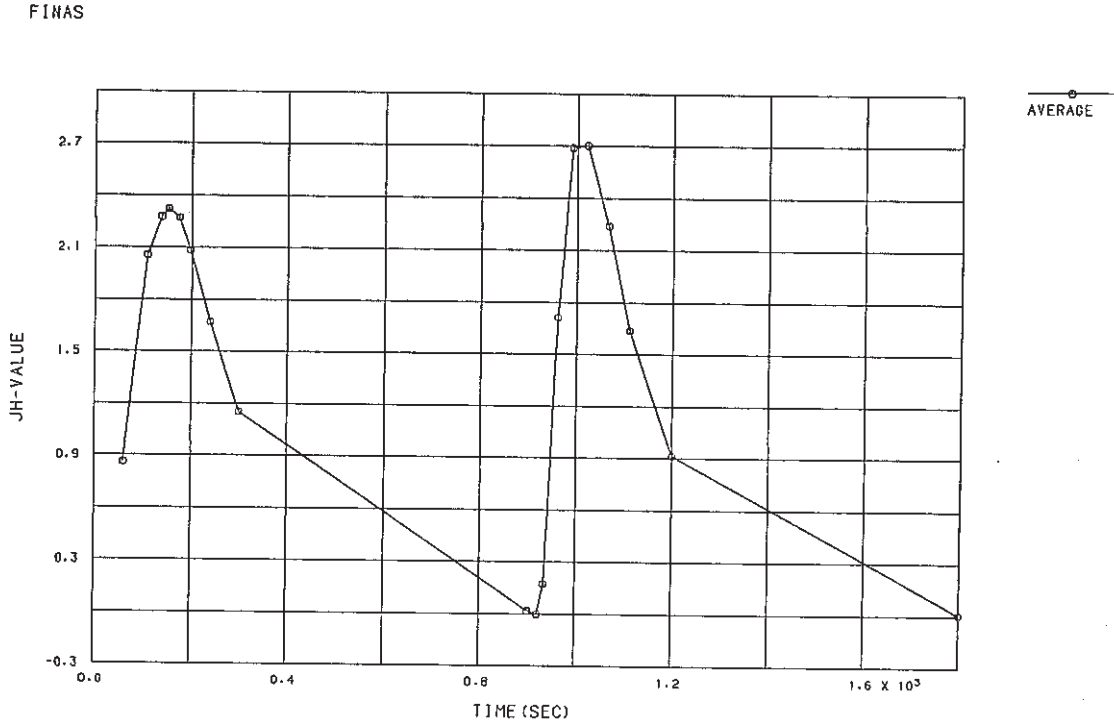


Fig. E.1.2-3 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=10$ mm

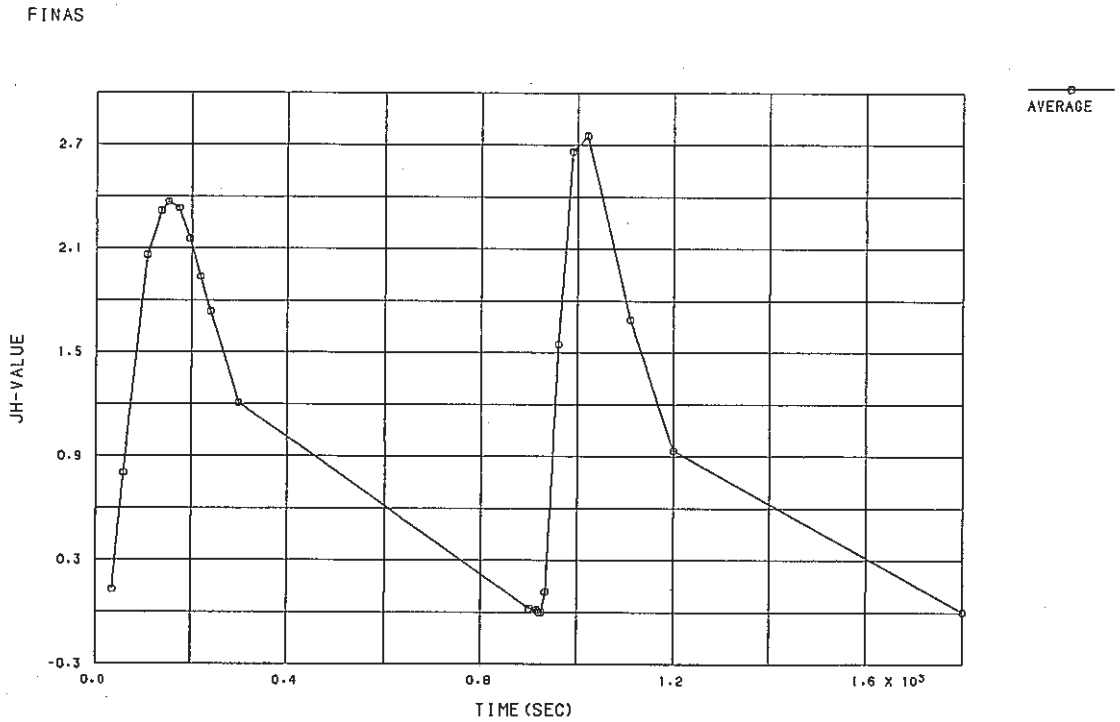


Fig. E.1.2-4 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=15$ mm

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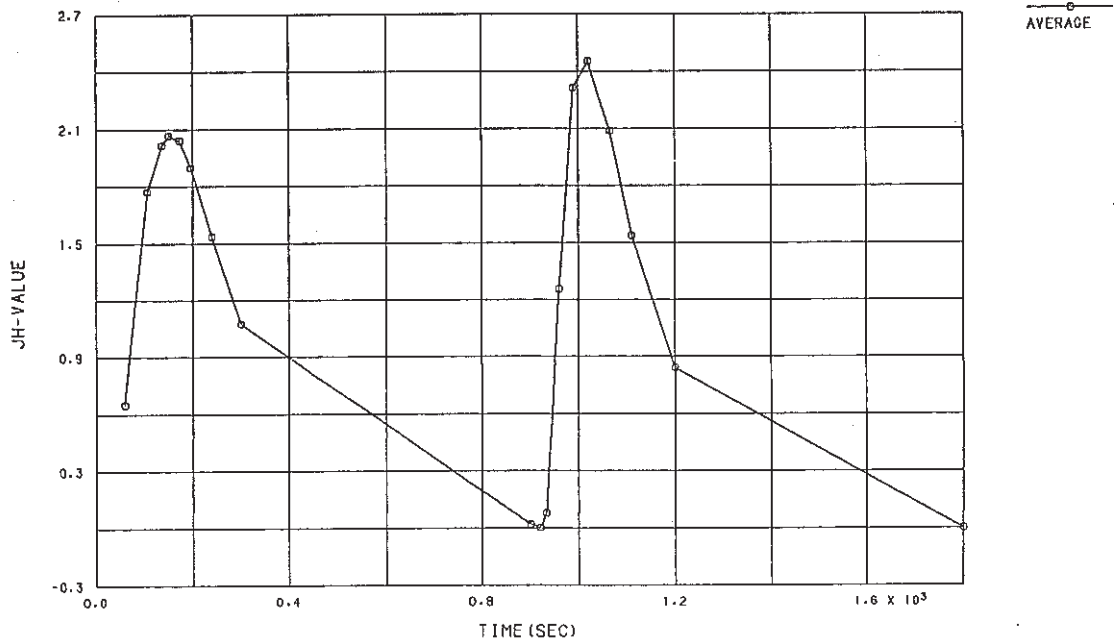


Fig. E.1.2-5 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=20$ mm

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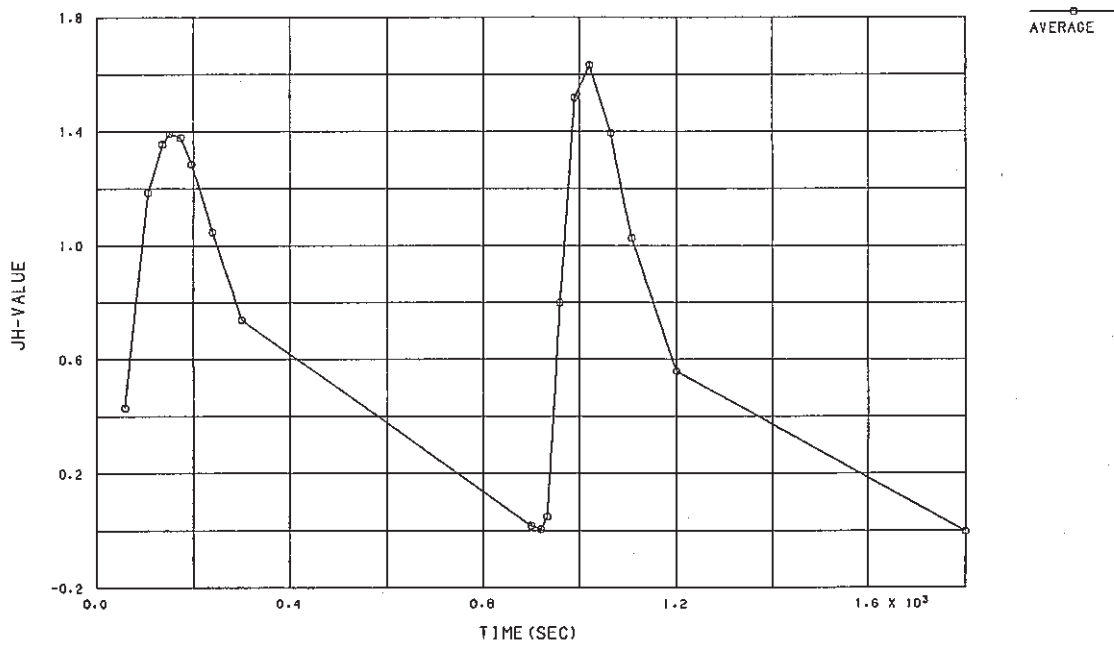


Fig. E.1.2-6 History of \hat{J} -Integral for Finally Welded Joint, crack depth $a=27$ mm

Table E.2.1-1 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_1=1$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	71.8697	11.1649	64.8303	67.9880	0.2579	0.1108	490.2590	0.84507E-02
2	9.50	76.6167	11.9677	70.9485	74.3525	0.3039	0.1185	463.9026	0.89892E-02
3	12.00	76.3669	11.8318	72.2332	75.6258	0.3068	0.0854	419.2419	0.88321E-02
4	14.00	67.9453	10.4234	64.8827	67.9020	0.2446	0.0409	398.4836	0.78390E-02
5	17.50	52.6995	7.8894	50.5661	52.8852	0.1469	-0.0068	373.5410	0.60806E-02
6	20.00	27.3609	3.7913	26.4943	27.6863	0.0397	-0.0098	340.8618	0.32740E-02
7	46.00	-14.5966	-3.1098	14.2491	14.8776	0.0113	0.1429	307.4316	-1.3523E-02
8	90.00	-41.7784	-7.4807	41.2687	43.0619	0.0939	0.3311	282.1260	-4.2906E-02
9	120.00	-47.1822	-8.3100	46.5788	48.5939	0.1192	0.3740	274.8713	-4.8590E-02
10	180.00	-50.5242	-8.8062	49.8360	51.9825	0.1360	0.3975	267.4412	-5.2004E-02
11	240.00	-50.2717	-8.7320	49.5211	51.6488	0.1341	0.3897	263.3098	-5.1594E-02
12	300.00	-48.9798	-8.4901	48.1687	50.2363	0.1267	0.3705	261.7241	-5.0135E-02
13	360.00	-46.7290	-8.0928	45.8587	47.8262	0.1148	0.3453	260.8525	-4.7665E-02
14	907.00	-93.3773	-15.2450	83.2007	86.9178	0.3896	0.2427	328.8872	-9.4481E-02
15	908.00	-107.3653	-17.1411	96.3727	100.7710	0.5314	0.3704	365.1785	-1.0953E-01
16	909.00	-108.9114	-17.4932	99.6322	104.2386	0.5738	0.4181	387.3503	-1.1372E-01
17	910.00	-108.5081	-17.4650	100.2616	104.9420	0.5862	0.4284	405.2397	-1.1504E-01
18	916.60	-80.5475	-12.7685	75.2890	78.8952	0.3417	0.2245	461.0039	-8.8819E-02
19	921.00	-66.0588	-10.3705	61.3709	64.3473	0.2300	0.1146	482.7222	-7.2536E-02
20	930.50	-39.7556	-5.9649	35.8395	37.6049	0.0798	-0.0101	509.9822	-4.2356E-02
21	960.00	-2.5302	0.1996	0.2410	0.2531	0.0000	-0.0525	547.0671	0.18109E-03
22	1020.00	21.6081	3.9768	24.1757	25.4063	0.0377	0.0100	568.1870	0.31271E-02
23	1080.00	22.8553	4.1748	25.4628	26.7643	0.0420	0.0213	575.6792	0.33180E-02

Table E.2.1-2 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_1=2$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	68.2939	21.3124	63.6964	66.8517	0.2536	0.1435	519.9629	0.11118E-01
2	9.50	76.8087	23.5291	72.6719	76.2186	0.3247	0.1682	493.7480	0.12248E-01
3	12.00	79.7877	23.6681	76.4420	80.0787	0.3497	0.1364	448.9219	0.12368E-01
4	14.00	71.7806	20.8387	69.2505	72.5131	0.2832	0.0745	426.4409	0.11028E-01
5	17.50	55.6345	15.5072	53.8119	56.3170	0.1683	0.0029	399.1892	0.86498E-02
6	20.00	26.8442	6.4286	25.5105	26.6737	0.0372	-0.0029	363.5869	0.41456E-02
7	46.00	-22.7761	-9.0399	22.7401	23.7525	0.0290	0.2562	323.0093	-2.9936E-02
8	90.00	-55.3540	-18.7283	54.8813	57.2793	0.1667	0.5841	291.4219	-7.5312E-02
9	120.00	-61.7016	-20.4788	61.1126	63.7686	0.2059	0.6594	282.4324	-8.3876E-02
10	180.00	-65.4414	-21.4613	64.7472	67.5456	0.2302	0.7014	273.1821	-8.8768E-02
11	240.00	-64.8279	-21.1873	64.0950	66.8568	0.2250	0.6876	268.1521	-8.7757E-02
12	300.00	-62.9185	-20.5262	62.1432	64.8172	0.2113	0.6540	265.8276	-8.5068E-02
13	360.00	-59.8770	-19.5251	59.1204	61.6625	0.1912	0.6096	264.6365	-8.0862E-02
14	907.00	-94.1236	-30.2749	87.4970	91.3480	0.6260	0.4793	303.6492	-1.3045E-01
15	908.00	-112.5004	-35.3779	105.4173	110.1502	0.6278	0.6576	337.2593	-1.5705E-01
16	909.00	-117.3844	-36.5771	110.9264	115.9735	0.7023	0.7361	359.9468	-1.6556E-01
17	910.00	-118.7434	-36.7258	112.7315	117.9158	0.7314	0.7568	378.2048	-1.6883E-01
18	916.60	-90.6521	-27.0241	86.9748	91.0966	0.4503	0.4241	439.9697	-1.3251E-01
19	921.00	-73.4917	-21.5797	70.4345	73.8127	0.2994	0.2356	463.2866	-1.0870E-01
20	930.50	-42.5103	-11.7522	40.3830	42.3547	0.1003	0.0139	494.4714	-6.3412E-02
21	960.00	3.3394	2.4900	3.9827	4.1820	0.0010	-0.0679	537.4165	0.34089E-03
22	1020.00	32.5833	11.0038	32.3864	34.0311	0.0674	0.0399	563.9727	0.51415E-02
23	1080.00	33.9542	11.3058	33.7131	35.4332	0.0734	0.0568	572.3052	0.53887E-02

Table E.2.1-3 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_1=4$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	54.7986	14.9886	48.3899	50.8396	0.1499	0.0895	558.3486	0.11435E-01
2	9.50	68.0237	17.6773	60.0770	63.0828	0.2281	0.1273	537.5452	0.13629E-01
3	12.00	75.6991	18.3587	67.3930	70.6884	0.2799	0.1277	497.1177	0.14576E-01
4	14.00	69.0645	15.9704	61.6431	64.6174	0.2308	0.0820	473.7329	0.13082E-01
5	17.50	51.4464	10.9128	45.7698	47.9429	0.1250	0.0236	444.3013	0.96515E-02
6	20.00	15.7745	1.5859	13.1936	13.8094	0.0101	0.0544	404.5977	0.31887E-02
7	46.00	-47.0662	-14.6426	45.1908	47.2378	0.1162	0.4729	352.3572	-7.6599E-02
8	90.00	-88.5933	-24.5118	85.6684	87.3635	0.3906	0.9728	309.4434	-1.4502E-01
9	120.00	-96.4166	-26.1423	90.9026	94.8878	0.4585	1.0825	297.0725	-1.5735E-01
10	180.00	-100.4272	-26.9061	94.5809	98.6960	0.4935	1.1364	284.3591	-1.6335E-01
11	240.00	-98.7689	-26.3839	93.0269	97.0582	0.4760	1.1062	277.5977	-1.6042E-01
12	300.00	-95.2837	-25.4172	89.7258	93.6056	0.4422	1.0458	273.9944	-1.5469E-01
13	360.00	-90.4814	-24.1344	85.2757	88.9587	0.3990	0.9701	272.0349	-1.4698E-01
14	907.00	-94.5662	-26.2408	86.6192	90.3725	0.4127	0.6335	277.4966	-1.4640E-01
15	908.00	-117.0336	-31.5259	106.1810	110.8402	0.6260	0.7646	298.5796	-2.0241E-01
16	909.00	-127.0855	-33.4038	115.2029	120.3178	0.7434	0.8445	318.3850	-2.1916E-01
17	910.00	-131.3444	-33.9151	119.1743	124.5185	0.8016	0.8731	335.2688	-2.2692E-01
18	916.60	-105.1619	-25.1675	96.5166	101.0159	0.5422	0.5081	402.0151	-1.8636E-01
19	921.00	-83.5865	-19.3675	76.6818	80.2964	0.3674	0.2675	427.6304	-1.5111E-01
20	930.50	-43.7702	-8.9748	40.6836	42.6363	0.1000	-0.0144	464.6438	-8.4486E-02
21	960.00	17.6062	4.7134	15.2029	15.9554	0.0144	-0.0763	518.5100	0.22412E-02
22	1020.00	55.7454	15.3796	49.5678	52.0734	0.1571	0.1217	555.7339	0.92386E-02
23	1080.00	57.3405	15.5612	51.1474	53.7472	0.1683	0.1467	565.5725	0.96038E-02

Table E.2.2-1 Fracture Mechanics Parameters of Inlet Nozzle, crack depth $a_2=1$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	98.8067	11.3465	90.6882	95.1188	0.5063	0.3901	495.5454	0.12101E-01
2	9.50	112.9508	13.0586	104.5350	109.5643	0.6618	0.5302	468.8018	0.13626E-01
3	12.00	124.7742	14.3552	116.8512	122.3338	0.8017	0.6742	416.9116	0.14703E-01
4	14.00	120.7751	13.8721	113.9801	119.2520	0.7511	0.6462	388.0369	0.14099E-01
5	17.50	110.2639	12.5665	104.8059	109.5476	0.6242	0.5480	350.2827	0.12740E-01
6	20.00	90.6938	10.5209	87.9479	91.8127	0.4299	0.3786	301.0461	0.10470E-01
7	46.00	56.4611	6.8730	56.7681	59.2258	0.1762	0.1345	261.8083	0.66872E-02
8	90.00	38.1033	4.9141	39.2787	40.9543	0.0839	0.0478	251.4867	0.44673E-02
9	120.00	33.3689	4.3924	34.6094	36.0851	0.0651	0.0327	250.6421	0.41380E-02
10	180.00	27.5335	3.7306	28.9008	30.1319	0.0454	0.0166	249.0912	0.36904E-02
11	240.00	24.1758	3.3014	25.5753	26.6640	0.0355	0.0088	247.8853	0.31147E-02
12	300.00	21.3599	2.9157	22.7859	23.7560	0.0282	0.0027	248.1781	0.28009E-02
13	360.00	19.5060	2.6189	20.8813	21.7707	0.0237	-0.0003	248.7552	0.25892E-02
14	907.00	-75.3189	-9.2041	64.1571	67.0053	0.2305	-0.0329	318.2056	-7.4034E-02
15	908.00	-102.7655	-11.9887	88.3888	92.3942	0.4445	0.1608	353.0332	-1.0244E-01
16	909.00	-111.9289	-13.1868	97.9346	102.4319	0.5514	0.2805	375.7551	-1.1449E-01
17	910.00	-116.3771	-13.7428	102.7493	107.5227	0.6125	0.3573	395.5857	-1.2111E-01
18	916.60	-96.5026	-11.5179	86.7584	90.9636	0.4571	0.3462	473.3704	-1.0560E-01
19	921.00	-84.5792	-10.3019	76.6890	80.2479	0.3625	0.2898	505.8894	-9.4365E-02
20	930.50	-62.3416	-7.9806	56.9874	59.8514	0.2063	0.1800	545.4614	-7.0837E-02
21	960.00	-58.9047	-5.5757	35.5719	37.3943	0.0821	0.0763	579.6899	-4.3767E-02
22	1020.00	-24.4949	-4.1245	21.8663	22.9899	0.0311	0.0290	584.9124	-2.5730E-02
23	1080.00	-22.2928	-3.8958	19.5766	20.5837	0.0250	0.0228	587.1519	-2.2597E-02

Table E.2.2-2 Fracture Mechanics Parameters of Inlet Nozzle, crack depth $a_2=2.65$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	93.7980	24.0248	94.0534	98.7616	0.5593	0.5696	538.4456	0.17276E-01
2	9.50	111.8521	27.8751	111.6517	117.1572	0.7752	0.8055	511.8154	0.20039E-01
3	12.00	127.4660	30.9643	127.8604	133.9686	0.9827	1.0610	456.3960	0.22104E-01
4	14.00	125.5999	30.2635	126.4201	132.3647	0.9412	1.0414	421.9792	0.21383E-01
5	17.50	117.3040	28.3221	118.3070	123.7419	0.8049	0.9191	376.3762	0.19475E-01
6	20.00	99.5549	24.9043	101.0406	105.5232	0.5715	0.6804	317.0798	0.16156E-01
7	46.00	66.0003	18.2804	67.4286	70.3296	0.2488	0.3107	265.5823	0.10491E-01
8	90.00	46.4052	14.5731	47.6808	49.7157	0.1237	0.1601	252.1567	0.73748E-02
9	120.00	41.0338	13.5834	42.2556	44.0580	0.0971	0.1290	251.3299	0.65374E-02
10	180.00	34.4937	12.2842	35.6597	37.1792	0.0691	0.0953	249.5676	0.55151E-02
11	240.00	30.6475	11.3751	31.7805	33.1337	0.0549	0.0779	248.2803	0.49152E-02
12	300.00	27.4528	10.4999	28.5491	29.7667	0.0443	0.0642	248.3439	0.44193E-02
13	360.00	25.1728	9.7942	26.2568	27.3753	0.0375	0.0557	249.0240	0.40712E-02
14	907.00	-62.4370	-14.7340	61.8463	64.5291	0.2106	0.0552	279.3062	-9.7761E-02
15	908.00	-95.6894	-22.1335	93.2795	97.3965	0.4852	0.2915	308.3665	-1.4748E-01
16	909.00	-108.5350	-24.8316	105.8034	110.5400	0.6310	0.4539	332.3745	-1.6829E-01
17	910.00	-114.8421	-26.0951	112.1542	117.2395	0.7160	0.5616	354.0592	-1.7970E-01
18	916.60	-99.5021	-21.9402	97.6139	102.2595	0.5705	0.5322	449.7427	-1.6234E-01
19	921.00	-88.0465	-19.7551	86.5516	90.7626	0.4591	0.4462	488.3120	-1.4671E-01
20	930.50	-66.6048	-15.5616	65.5660	68.8461	0.2716	0.2795	537.3240	-1.1367E-01
21	960.00	-42.4322	-11.2568	41.7707	43.9086	0.1132	0.1219	577.9863	-7.3482E-02
22	1020.00	-26.5762	-8.4855	26.0631	27.4022	0.0443	0.0483	584.9158	-4.5186E-02
23	1080.00	-24.2343	-8.2400	23.5904	24.8036	0.0363	0.0389	586.5615	-4.0675E-02

Table E.2.2-3 Fracture Mechanics Parameters of Inlet Nozzle, crack depth $a_2=5.3$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	8.50	62.3730	41.0458	52.3026	54.9622	0.1761	0.2292	566.3704	0.98446E-02
2	9.50	75.3241	47.0448	62.8225	65.9761	0.2503	0.3513	543.3911	0.11672E-01
3	12.00	88.5688	50.3109	73.3326	76.8970	0.3292	0.5415	486.6216	0.11319E-01
4	14.00	89.0285	48.6197	73.5418	77.0395	0.3235	0.5939	448.2993	0.12939E-01
5	17.50	84.8787	46.1262	70.2433	73.5091	0.2845	0.6143	396.9238	0.11996E-01
6	20.00	73.2641	43.1197	61.4455	64.1921	0.2126	0.5738	329.8018	0.10171E-01
7	46.00	49.4123	36.8089	43.1445	45.0043	0.1020	0.3984	268.7397	0.69056E-02
8	90.00	34.6476	33.2277	32.0007	33.3669	0.0557	0.2836	252.7817	0.50354E-02
9	120.00	30.3173	32.4592	28.8357	30.0661	0.0452	0.2513	251.8846	0.45061E-02
10	180.00	25.0497	32.0413	24.9768	26.0413	0.0339	0.2134	249.9407	0.38538E-02
11	240.00	22.0284	29.9187	22.6192	23.5825	0.0278	0.1909	248.5828	0.34618E-02
12	300.00	19.6308	28.2853	20.6049	21.4823	0.0231	0.1715	248.5358	0.31347E-02
13	360.00	17.9483	26.7150	19.0783	19.8911	0.0198	0.1568	249.2199	0.28934E-02
14	907.00	-40.0175	-31.7108	31.7108	33.0688	0.0548	-0.1682	257.8259	-5.0564E-02
15	908.00	-62.5953	-32.5009	50.4339	52.6169	0.1398	-0.1865	275.6851	-8.1053E-02
16	909.00	-72.7888	-36.4762	58.5437	61.1125	0.1903	-0.1538	298.5293	-9.9467E-02
17	910.00	-78.3617	-37.5703	62.8041	65.5971	0.2212	-0.1134	321.1965	-1.0283E-01
18	916.60	-71.3223	-36.4633	56.3006	58.9581	0.1876	0.0208	430.7275	-9.6867E-02
19	921.00	-63.2976	-26.3052	50.2099	52.6332	0.1532	0.0480	474.2329	-8.8673E-02
20	930.50	-47.8544	-22.3242	38.5524	40.4736	0.0935	0.0551	530.4634	-7.0629E-02
21	960.00	-29.8440	-19.2683	25.2623	26.5542	0.0413	0.0377	576.3923	-4.7762E-02
22	1020.00	-17.7042	-17.3256	16.3957	17.2382	0.0175	0.0171	585.0579	-3.0835E-02
23	1080.00	-15.3219	-18.2654	14.9938	15.7647	0.0147	0.0145	585.9375	-2.7875E-02

Table E.2.3-1 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_3=1$ mm

STEP	TIME	K-1	K-2	JH --> K		JH	J	TEMP.	DISP.
		SIG-Z	TAU-RZ	P.STRS	P.STRN				
1	8.50	10.9743	-3.1949	10.9277	11.4914	0.0078	0.0078	591.9978	0.14034E-02
2	9.50	16.1948	-4.6974	16.1184	16.9499	0.0170	0.0169	591.9956	0.20703E-02
3	12.00	28.1057	-8.0169	27.9300	29.3707	0.0510	0.0507	591.9065	0.35884E-02
4	14.00	36.2337	-10.1515	35.9472	37.8011	0.0845	0.0838	591.5164	0.46194E-02
5	17.50	48.1632	-13.0495	47.6917	50.1483	0.1486	0.1464	589.3655	0.61233E-02
6	20.00	66.5555	-17.1358	66.0031	69.3816	0.2825	0.2706	578.0847	0.84139E-02
7	46.00	88.9172	-21.2996	89.3215	93.7740	0.5021	0.4303	530.9871	0.11048E-01
8	90.00	96.6825	-21.8610	98.5886	103.3023	0.5848	0.3987	457.8672	0.11625E-01
9	120.00	96.0704	-21.3397	98.4538	103.0971	0.5732	0.3428	428.8035	0.11396E-01
10	180.00	93.3711	-20.4348	96.0870	100.5482	0.5354	0.2592	394.5903	0.10889E-01
11	240.00	89.7127	-19.4796	92.4313	96.6737	0.4910	0.1973	374.8508	0.10374E-01
12	300.00	85.2918	-18.4490	87.9936	92.0012	0.4423	0.1453	361.6162	0.98153E-02
13	360.00	80.6063	-17.3958	83.2373	87.0072	0.3940	0.1016	352.1235	0.92438E-02
14	907.00	42.2678	-8.6231	43.7264	45.6528	0.1065	-0.0823	305.2976	0.47109E-02
15	908.00	34.7656	-7.0298	38.1979	39.8807	0.0812	-0.0907	305.2324	0.41016E-02
16	909.00	31.7242	-5.5782	33.1388	34.5986	0.0612	-0.0954	305.1685	0.35446E-02
17	910.00	26.8532	-4.1935	28.2684	29.5136	0.0445	-0.0974	305.1084	0.30068E-02
18	916.60	1.1094	2.5862	2.9358	3.0652	0.0005	-0.0639	306.1565	0.18060E-03
19	921.00	-11.9225	5.6229	10.3891	10.8481	0.0060	-0.0165	309.9771	-1.2446E-02
20	930.50	-31.8027	9.8340	30.1782	31.5238	0.0512	0.0974	325.5298	-3.3439E-02
21	960.00	-54.5256	13.4671	53.5526	56.0302	0.1658	0.2872	388.4685	-6.1046E-02
22	1020.00	-57.1670	12.6345	57.2645	60.0195	0.1986	0.3018	468.6709	-6.7044E-02
23	1080.00	-54.7495	11.9526	55.2723	57.9795	0.1886	0.2677	500.0122	-6.6563E-02

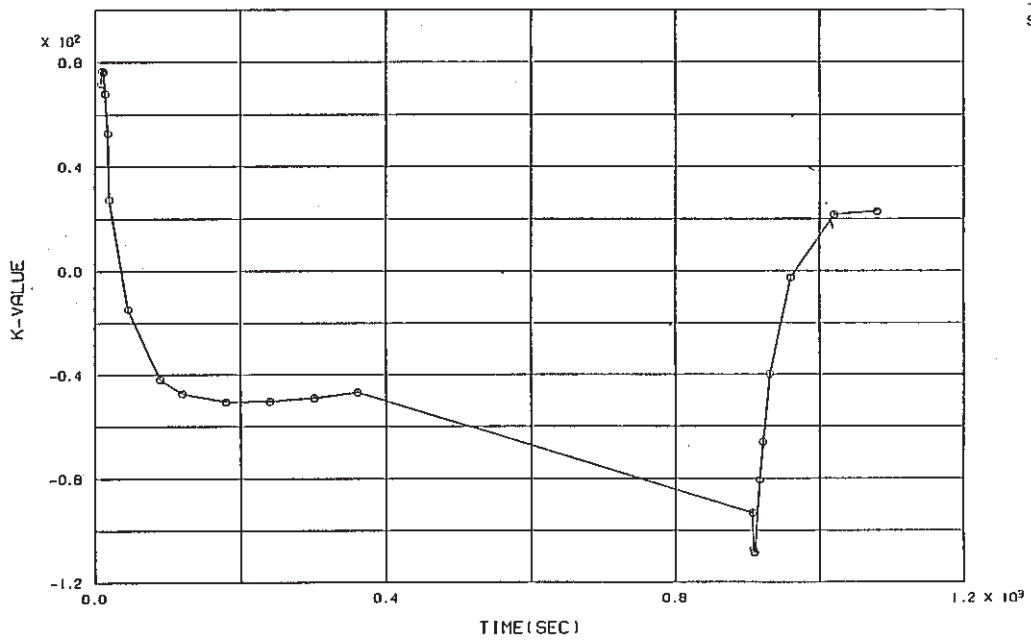
Table E.2.3-2 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_3=2$ mm

STEP	TIME	K-1	K-2	JH --> K		JH	J	TEMP.	DISP.
		SIG-Z	TAU-RZ	P.STRS	P.STRN				
1	8.50	11.0884	-6.5318	12.0214	12.6415	0.0095	0.0116	591.9978	0.20475E-02
2	9.50	16.4884	-9.7329	17.8564	18.7775	0.0209	0.0255	591.9949	0.30429E-02
3	12.00	28.8391	-16.7387	31.1736	32.7816	0.0636	0.0776	591.8997	0.53166E-02
4	14.00	37.2792	-21.1555	40.2368	42.3119	0.1059	0.1290	591.4927	0.68643E-02
5	17.50	49.6873	-27.0590	53.5509	56.3092	0.1873	0.2261	589.2964	0.91285E-02
6	20.00	69.1488	-35.1551	74.6288	78.4484	0.3612	0.4202	577.9343	0.12627E-01
7	46.00	94.3176	-43.2225	102.8089	107.9331	0.6651	0.6810	530.7664	0.16858E-01
8	90.00	105.1852	-43.8111	115.7032	121.2342	0.8053	0.6495	457.5518	0.18065E-01
9	120.00	105.4227	-42.5575	116.2553	121.7373	0.7990	0.5652	428.4543	0.17810E-01
10	180.00	103.2852	-40.5956	114.1114	119.4084	0.7550	0.4326	394.2336	0.17111E-01
11	240.00	99.4974	-38.6176	110.0118	115.0601	0.6954	0.3299	374.5081	0.16335E-01
12	300.00	94.7782	-36.5388	104.8526	109.6271	0.6279	0.2421	361.2927	0.15472E-01
13	360.00	89.6733	-34.4327	99.2409	103.7348	0.5601	0.1674	351.8184	0.14580E-01
14	907.00	47.8679	-17.0668	52.8146	55.1412	0.1553	-0.1412	305.1223	0.75367E-02
15	908.00	42.0834	-13.7040	46.6353	48.6896	0.1211	-0.1496	305.0579	0.66330E-02
16	909.00	36.7710	-10.5924	40.9351	42.7382	0.0933	-0.1530	304.9944	0.57976E-02
17	910.00	31.6223	-7.6345	35.4352	36.9960	0.0699	-0.1522	304.9346	0.49912E-02
18	916.60	4.3792	6.4698	6.7283	7.0248	0.0025	-0.0789	306.0337	0.73493E-03
19	921.00	-9.4594	12.5555	8.7400	9.1261	0.0043	0.0044	309.9155	-1.4223E-02
20	930.50	-30.9808	20.8952	31.5838	32.9920	0.0561	0.1935	325.5488	-4.8032E-02
21	960.00	-57.3100	27.5642	60.5005	63.2997	0.2117	0.4993	388.5552	-9.1388E-02
22	1020.00	-62.6615	25.2541	67.4072	70.6505	0.2752	0.5236	468.8706	-1.0421E-01
23	1080.00	-60.6332	23.8057	65.7092	68.9280	0.2666	0.4671	500.2271	-1.0301E-01

Table E.2.3-3 Fracture Mechanics Parameters of Inlet
Nozzle, crack depth $a_3=4$ mm

STEP	TIME	K-1	K-2	JH --> K		JH	J	TEMP.	DISP.
		SIG-Z	TAU-RZ	P.STRS	P.STRN				
1	8.50	15.0748	-4.6347	13.1125	13.7889	0.0113	0.0139	591.9968	0.22803E-02
2	9.50	22.7118	-7.2417	19.6823	20.6976	0.0254	0.0314	591.9929	0.34280E-02
3	12.00	40.5314	-13.1903	34.9527	36.7556	0.0799	0.0991	591.8691	0.61004E-02
4	14.00	52.8323	-17.0117	45.4918	47.8377	0.1354	0.1676	591.3884	0.79464E-02
5	17.50	71.0604	-22.1073	61.1580	64.3076	0.2443	0.3001	588.9873	0.10679E-01
6	20.00	100.4713	-29.1790	86.7323	91.1697	0.4876	0.5801	577.2561	0.15040E-01
7	46.00	141.8941	-36.6987	123.9439	130.1181	0.9640	1.0291	529.7900	0.20860E-01
8	90.00	163.7418	-37.6901	144.7542	151.6690	1.2595	1.1088	456.2986	0.23235E-01
9	120.00	165.8114	-36.6859	147.0904	154.0224	1.2780	1.0198	427.1138	0.23175E-01
10	180.00	164.0145	-35.0988	145.8393	152.6039	1.2325	0.8466	392.9043	0.22506E-01
11	240.00	158.5696	-33.3897	141.1544	147.6270	1.1442	0.6921	373.2407	0.21575E-01
12	300.00	151.2798	-31.6176	134.7989	140.9327	1.0372	0.5500	360.0994	0.20480E-01
13	360.00	143.2153	-29.8058	127.7153	133.4949	0.9271	0.4238	350.6973	0.19323E-01
14	907.00	77.9229	-15.6426	69.4322	72.4896	0.2684	-0.1404	304.4841	0.10239E-01
15	908.00	70.0540	-13.0434	62.5875	65.3434	0.2181	-0.1635	304.4199	0.92146E-02
16	909.00	62.5786	-10.4284	56.1350	58.6067	0.1754	-0.1805	304.3569	0.82449E-02
17	910.00	55.2686	-7.8798	49.8458	52.0405	0.1383	-0.1918	304.3005	0.72979E-02
18	916.60	15.9463	4.5718	16.3197	17.0388	0.0148	-0.1549	305.6313	0.21982E-02
19	921.00	-4.3022	9.8905	4.5701	4.7720	0.0012	-0.0658	309.7861	-4.3905E-03
20	930.50	-36.9905	17.3179	30.5845	31.9484	0.0526	0.1724	325.7900	-4.7247E-02
21	960.00	-82.0876	25.5355	70.2202	73.4699	0.2852	0.6539	389.0542	-1.0834E-01
22	1020.00	-98.0380	21.9370	84.7001	88.7773	0.4347	0.7996	469.6675	-1.3405E-01
23	1080.00	-96.9610	20.6889	84.0327	88.1510	0.4362	0.7422	501.0359	-1.3497E-01

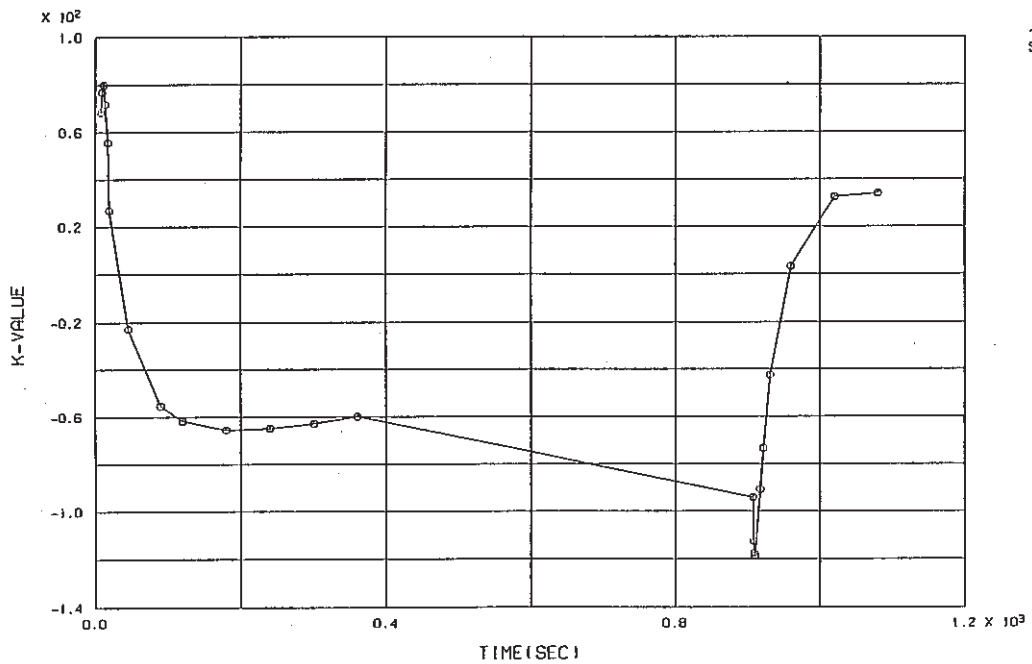
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SIG - 2

Fig. E.2.1-1 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_1=1$ mm

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SIG - 2

Fig. E.2.1-2 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_1=2$ mm

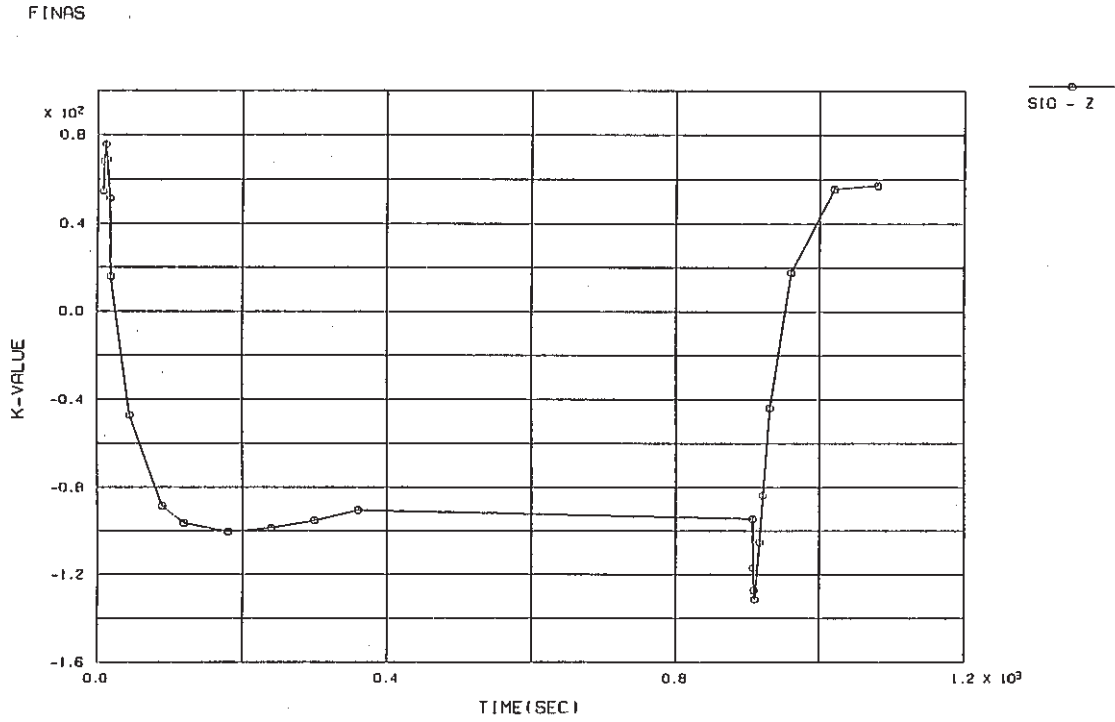


Fig. E.2.1-3 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_1=4$ mm

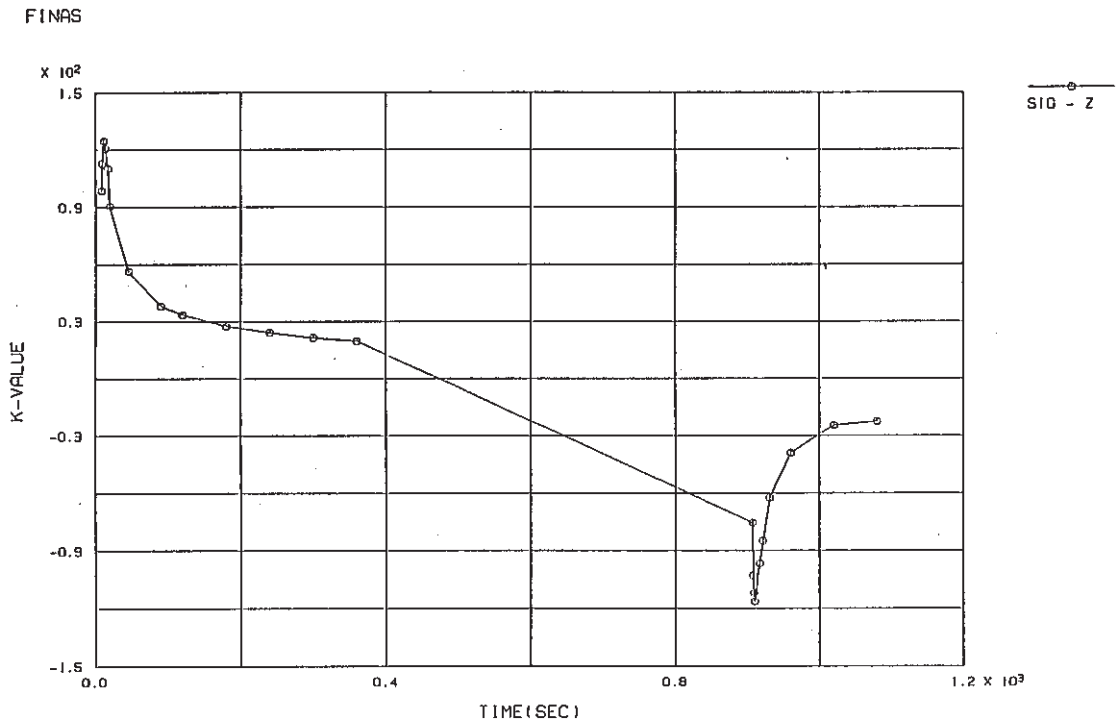


Fig. E.2.2-1 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_2=1$ mm

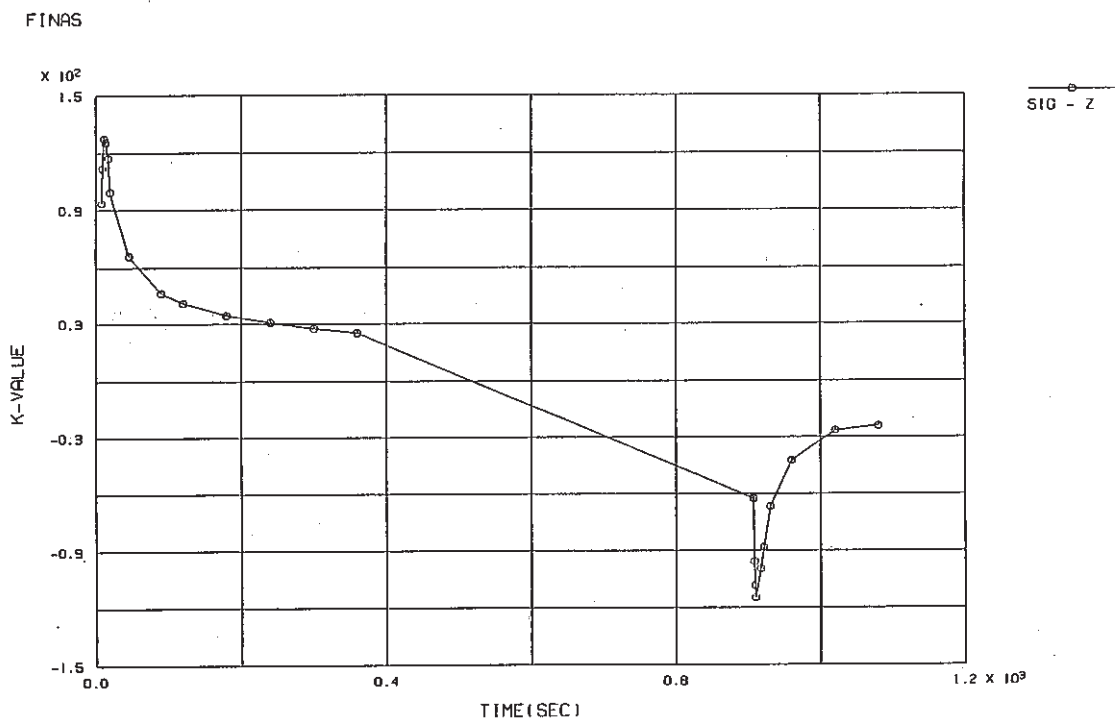


Fig. E.2.2-2 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_2=2.65$ mm

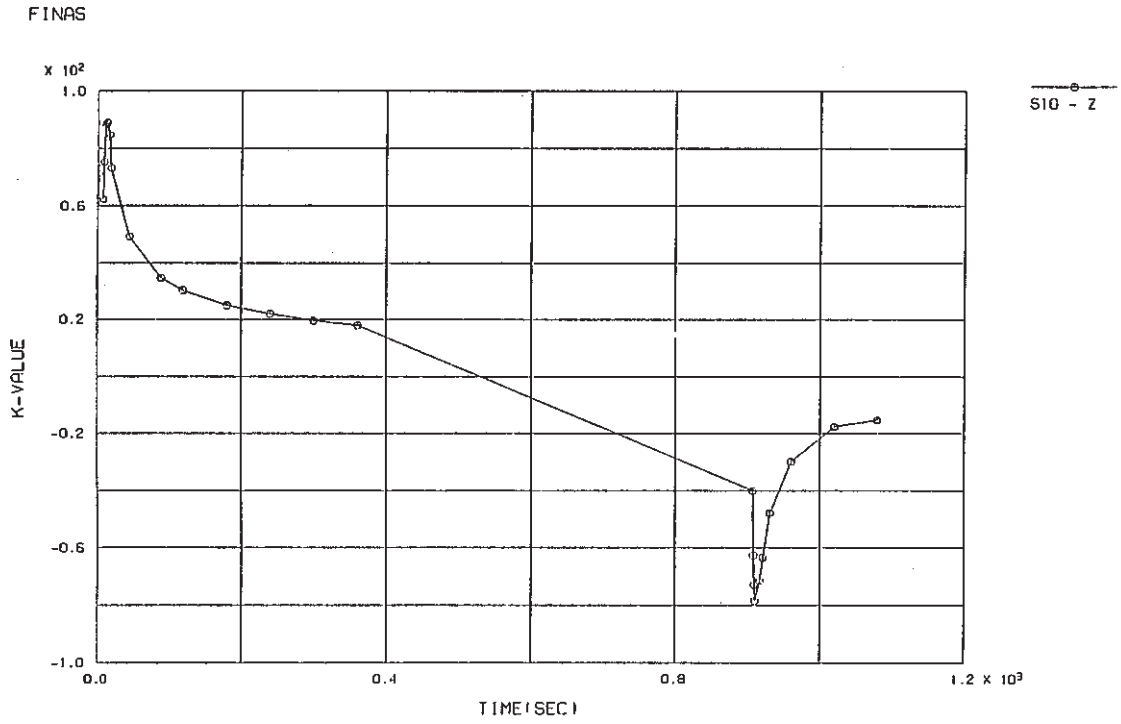


Fig. E.2.2-3 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_2=5.3$ mm

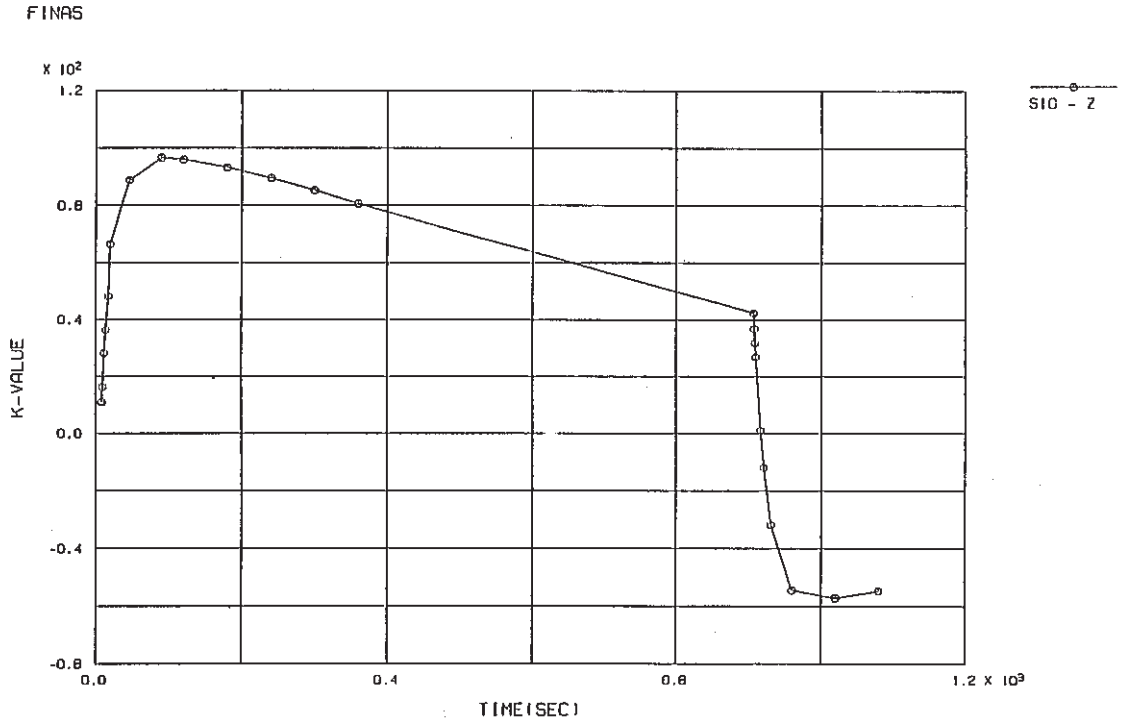


Fig. E.2.3-1 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_3=1$ mm

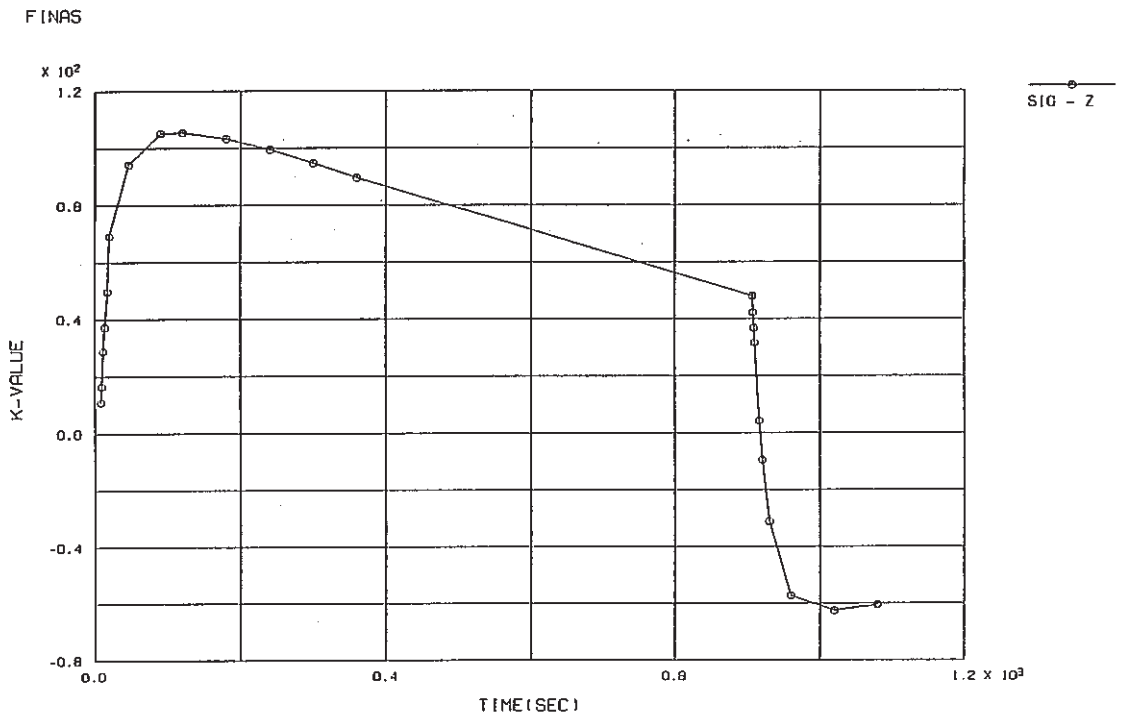


Fig. E.2.3-2 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_3=2$ mm

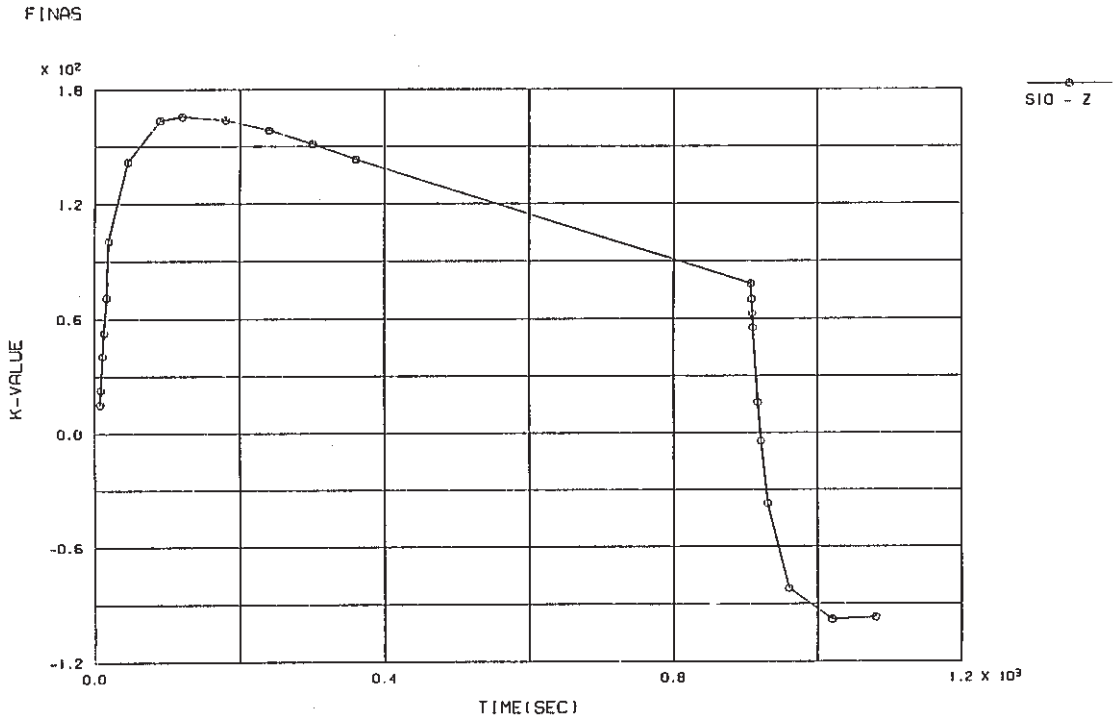


Fig. E.2.3-3 History of Stress Intensity Factor for Inlet Nozzle, crack depth $a_3=4$ mm

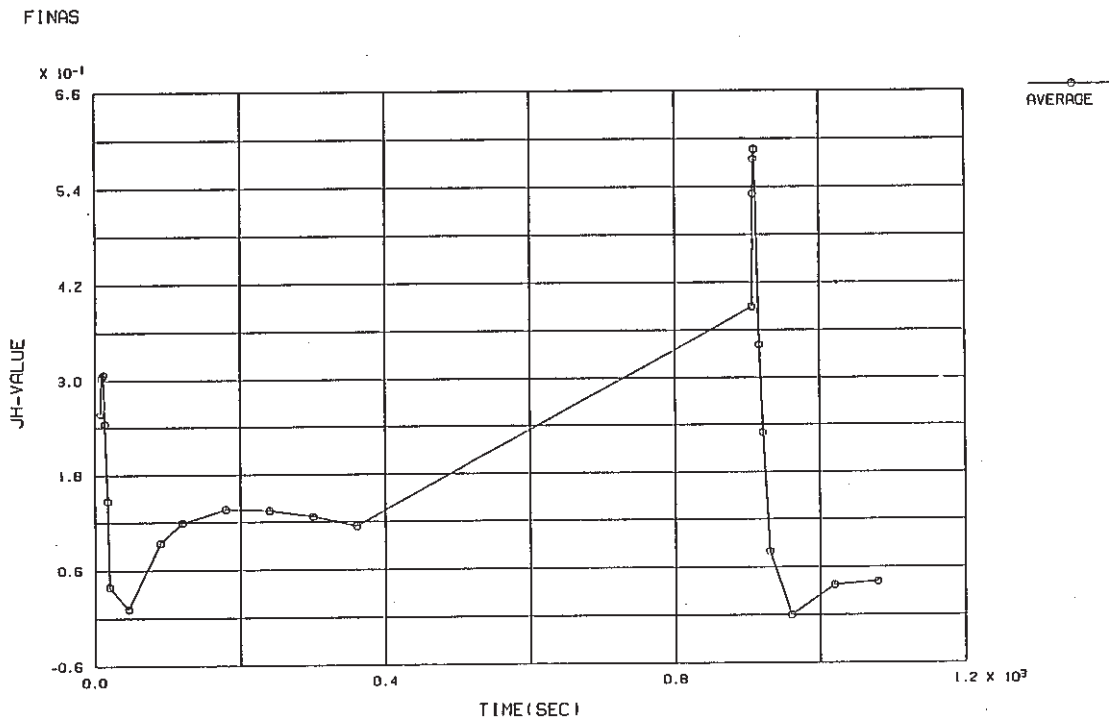


Fig. E.2.4-1 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_1=1$ mm

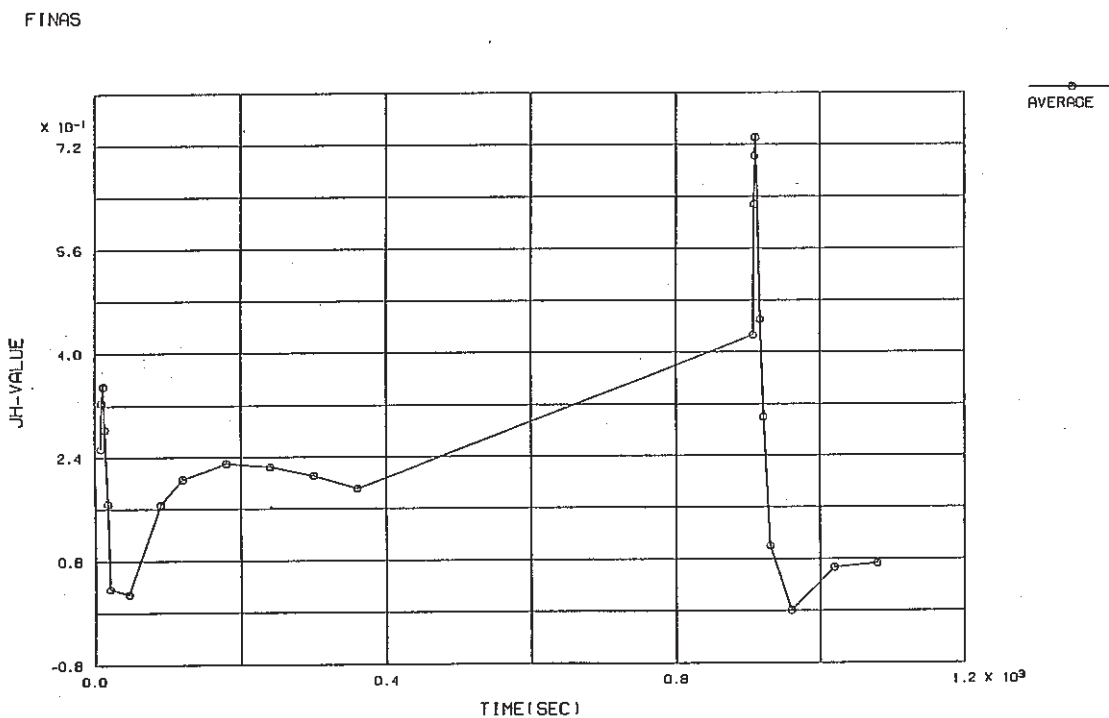


Fig. E.2.4-2 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_1=2$ mm

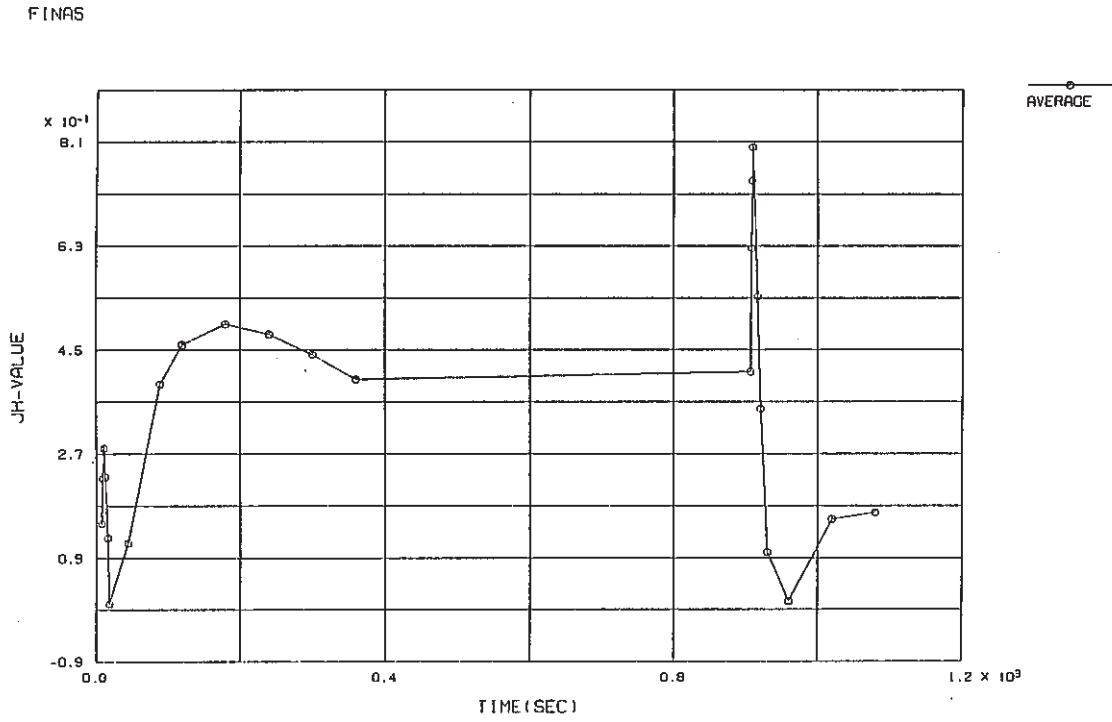


Fig. E.2.4-3 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_1=4$ mm

FINAS

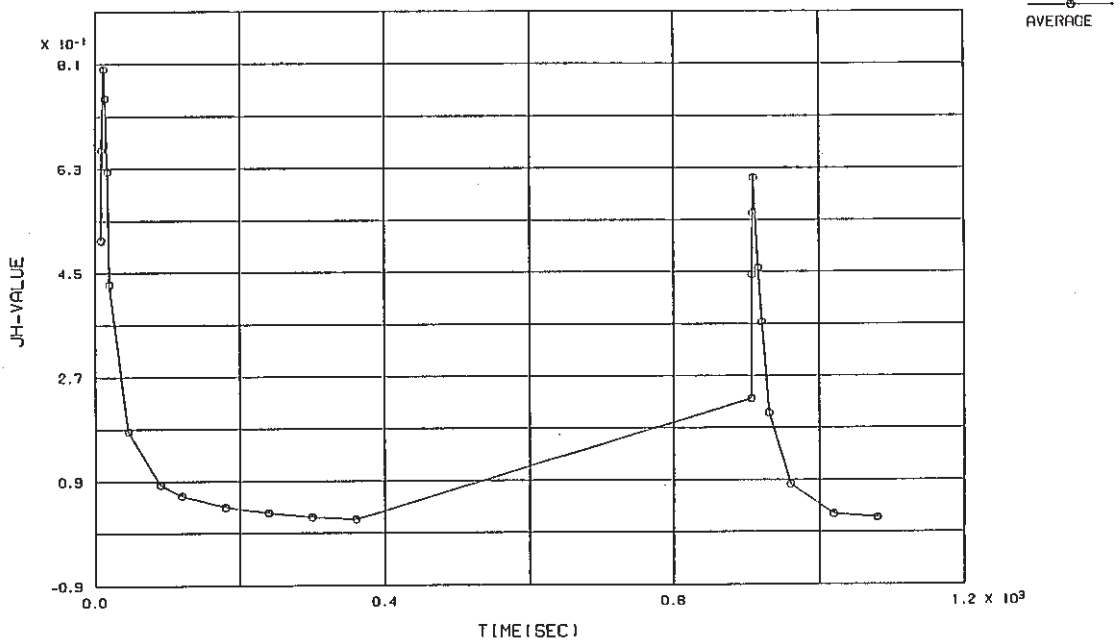


Fig. E.2.5-1 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_2=1$ mm

FINAS

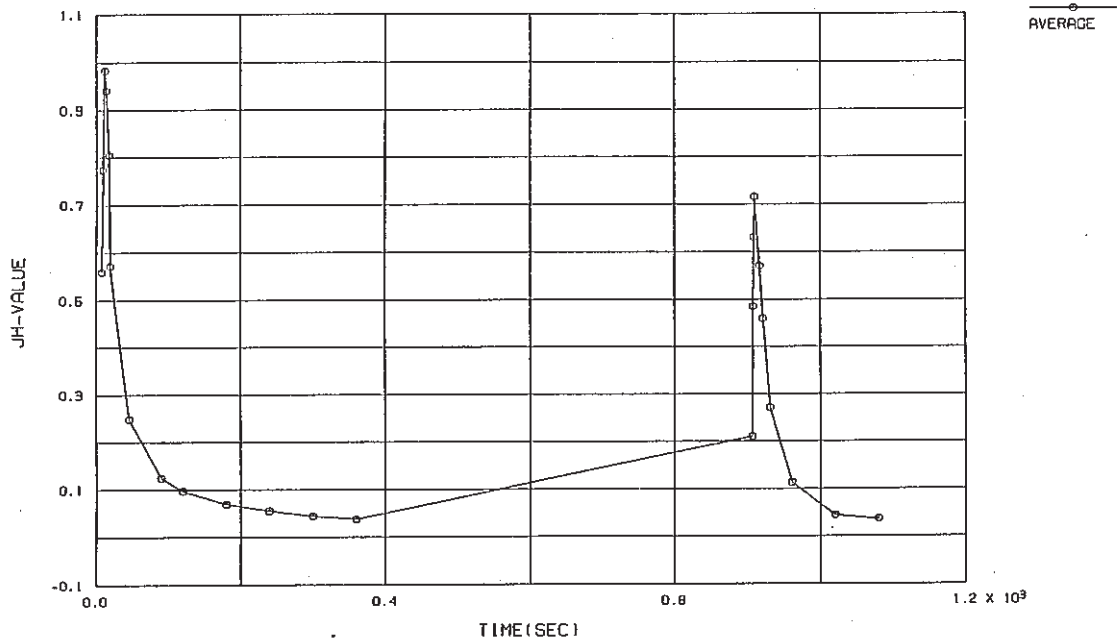


Fig. E.2.5-2 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_2=2.65$ mm

FINAS

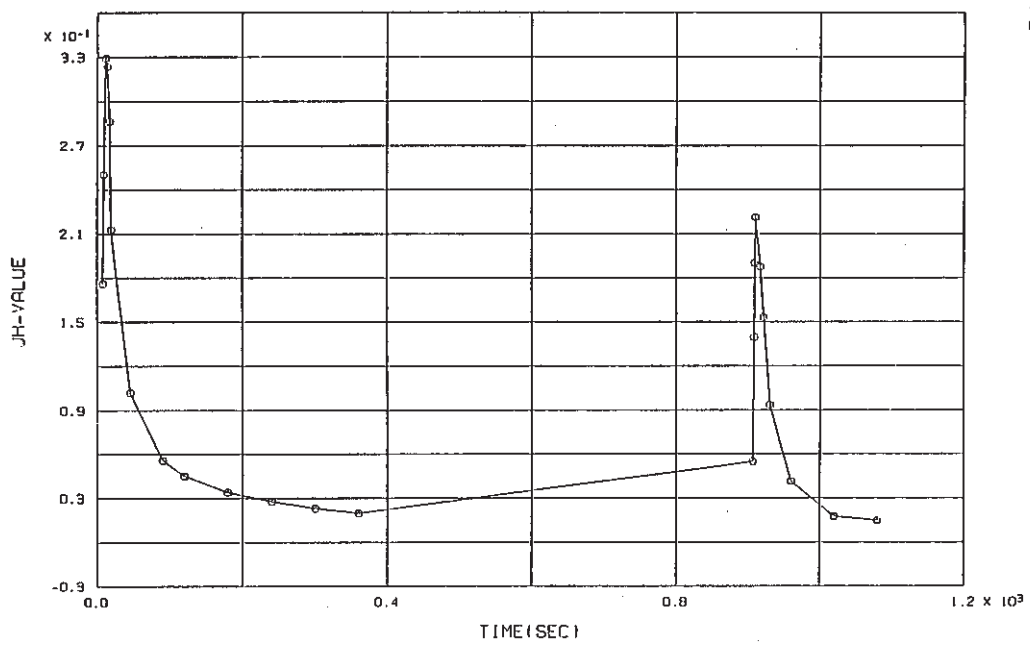


Fig. E.2.5-3 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_2=5.3$ mm

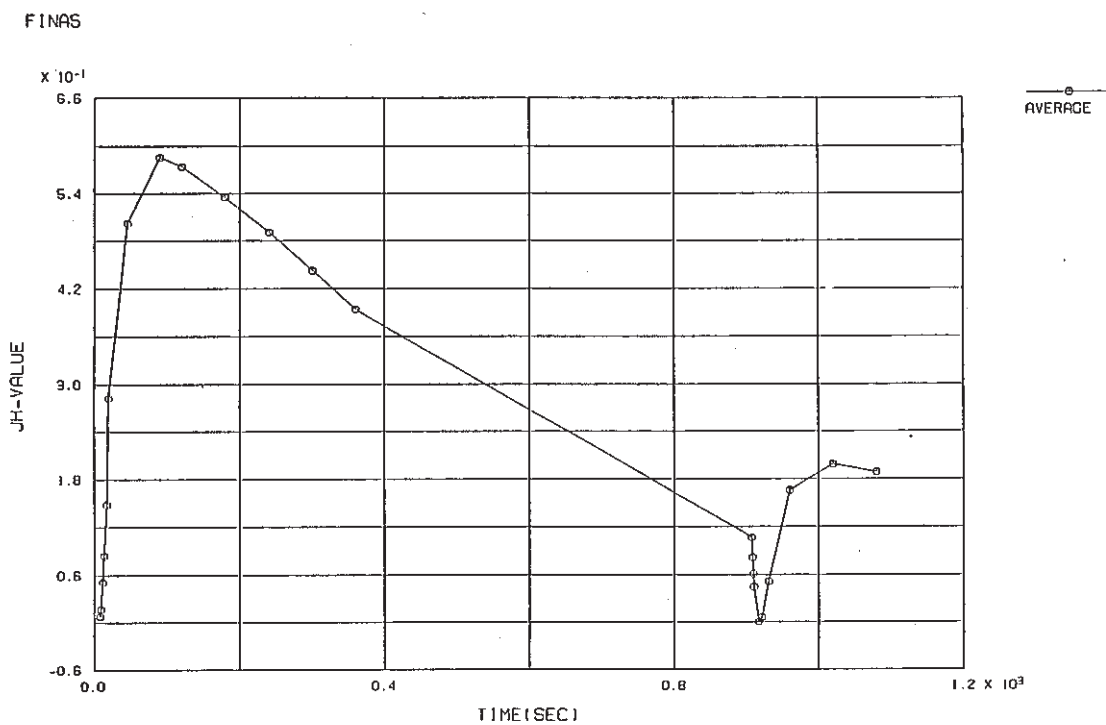


Fig. E.2.6-1 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_3=1$ mm

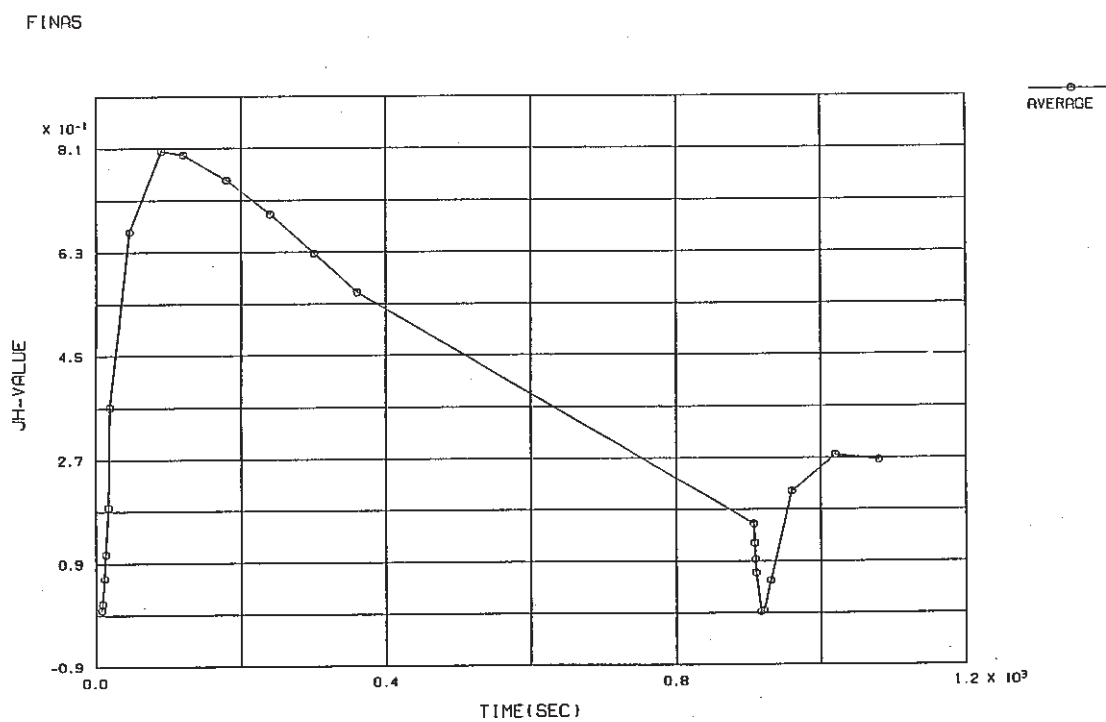


Fig. E.2.6-2 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_3=2$ mm

FINAS

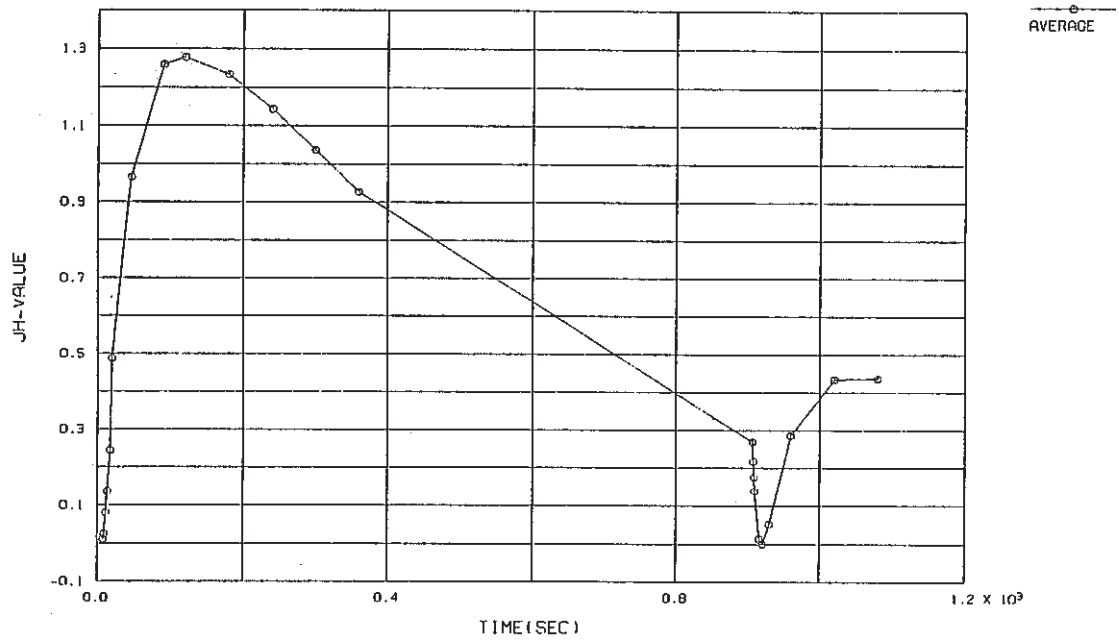


Fig. E.2.6-3 History of \hat{J} -Integral for Inlet Nozzle, crack depth $a_3=4$ mm

Table E.3.1-1 Fracture Mechanics Parameters of Thinning
Portion, crack depth $a_1=1$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	--> K P.STRN	JH	J	TEMP.	DISP.
1	75.00	43.7872	-4.5248	40.7511	42.7366	0.1019	0.0502	490.8013	0.54636E-02
2	93.00	50.6589	-5.2886	47.4005	49.6782	0.1359	0.0684	466.5742	0.62315E-02
3	98.00	52.1283	-5.4509	48.8029	51.1400	0.1435	0.0731	460.6511	0.63879E-02
4	109.00	54.9521	-5.7587	51.4951	53.9438	0.1586	0.0824	447.7563	0.66800E-02
5	120.00	56.9508	-5.9725	53.4330	55.9598	0.1694	0.0891	434.9531	0.68725E-02
6	138.00	57.4923	-6.0479	54.0890	56.6271	0.1718	0.0893	417.2038	0.68774E-02
7	152.00	57.1876	-6.0209	53.9267	56.4434	0.1695	0.0874	404.6091	0.68046E-02
8	180.00	55.9317	-5.9062	52.8143	55.2464	0.1607	0.0804	380.5352	0.65776E-02
9	240.00	45.4974	-4.8086	43.7086	45.6824	0.1084	0.0402	347.1960	0.53654E-02
10	390.00	25.8348	-2.7365	25.6376	26.7630	0.0365	-0.0135	299.1082	0.30870E-02
11	945.00	-78.6649	8.1858	67.6051	70.7531	0.2657	0.0326	399.5986	-0.80805E-02
12	960.00	-85.6433	8.9699	74.1254	77.6246	0.3253	0.1044	430.9976	-0.90160E-02
13	975.00	-82.7575	8.7274	72.3992	75.8472	0.3141	0.1414	451.0527	-0.88730E-02
14	1005.00	-72.6221	7.4592	63.1548	66.2072	0.2426	0.1276	475.5339	-0.78058E-02
15	1050.00	-58.5721	6.1764	50.2785	52.7431	0.1562	0.0913	501.4348	-0.62468E-02
16	1200.00	-29.7898	3.1410	24.0248	25.2334	0.0367	0.0232	547.1147	-0.29319E-02

Table E.3.1-2 Fracture Mechanics Parameters of Thinning
Portion, crack depth $a_1=4$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	--> K P.STRN	JH	J	TEMP.	DISP.
1	75.00	67.7301	-5.6335	66.6907	69.9802	0.2767	0.1948	512.3437	0.11262E-01
2	93.00	80.4944	-7.1185	79.1916	83.0456	0.3845	0.2736	488.7781	0.13117E-01
3	98.00	83.1112	-7.4593	81.7611	85.7267	0.4083	0.2914	482.8638	0.13484E-01
4	109.00	88.0615	-8.0695	86.6422	90.8137	0.4550	0.3259	469.9744	0.14161E-01
5	120.00	91.5884	-8.4289	90.1491	94.4576	0.4887	0.3501	457.1763	0.14610E-01
6	138.00	93.2863	-8.6675	91.9372	96.2911	0.5026	0.3573	438.3303	0.14719E-01
7	152.00	93.2194	-8.6989	91.9216	96.2495	0.4985	0.3515	424.9062	0.14595E-01
8	180.00	91.5478	-8.5176	90.4283	94.6391	0.4753	0.3278	399.5911	0.14145E-01
9	240.00	76.2912	-7.1154	75.3389	78.7692	0.3241	0.1997	361.1279	0.11585E-01
10	390.00	44.7050	-4.1341	44.5209	46.4828	0.1104	0.0276	305.6851	0.66881E-02
11	945.00	-121.6816	11.7528	113.9879	119.1982	0.7443	0.5188	367.7944	-0.16992E-01
12	960.00	-135.1906	13.1179	127.2923	133.2173	0.9416	0.7080	398.9568	-0.19212E-01
13	975.00	-134.6745	13.0579	126.6875	132.6444	0.9456	0.7454	422.6450	-0.19294E-01
14	1005.00	-117.4684	11.2199	110.9744	116.2658	0.7388	0.6099	453.0715	-0.17125E-01
15	1050.00	-93.9174	8.8536	88.6467	92.9527	0.4808	0.4119	485.4482	-0.13849E-01
16	1200.00	-45.9053	4.2420	42.9520	45.1057	0.1169	0.1051	541.3928	-0.67816E-02

Table E.3.1-3 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_1=7$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	75.00	69.9667	-2.2515	68.8353	72.2625	0.2978	0.2395	528.9124	0.12598E-01
2	93.00	85.1288	-3.6516	83.4409	87.5428	0.4315	0.3541	506.4578	0.15001E-01
3	98.00	88.2544	-4.0181	86.4843	90.7218	0.4619	0.3811	500.6177	0.15482E-01
4	109.00	94.1696	-4.6616	92.2686	96.7567	0.5216	0.4349	487.8459	0.16372E-01
5	120.00	98.3767	-4.9779	96.4251	101.0813	0.5653	0.4753	475.1215	0.16965E-01
6	138.00	101.0495	-5.3050	99.0663	103.7968	0.5897	0.5017	455.6201	0.17211E-01
7	152.00	101.2883	-5.4022	99.3943	104.1079	0.5886	0.5049	441.5791	0.17121E-01
8	180.00	99.8649	-5.2962	98.1693	102.7720	0.5653	0.4915	415.2339	0.16644E-01
9	240.00	84.3141	-4.5389	83.0068	86.8117	0.3956	0.3494	372.6733	0.13730E-01
10	390.00	50.1827	-2.6993	49.7330	51.9317	0.1381	0.1183	311.2170	0.79718E-02
11	945.00	-128.3025	7.3279	121.7413	127.2216	0.8390	0.4806	341.7607	-0.19629E-01
12	960.00	-145.1648	8.5415	137.8148	144.1303	1.0901	0.7084	372.1602	-0.22456E-01
13	975.00	-147.0084	8.7254	139.2601	145.7376	1.1263	0.7746	397.7183	-0.22874E-01
14	1005.00	-128.7026	7.4779	122.1781	127.9518	0.8851	0.6492	433.4385	-0.20381E-01
15	1050.00	-101.7589	5.6931	97.4413	102.1373	0.5760	0.4469	471.6824	-0.16567E-01
16	1200.00	-48.1301	2.5004	47.0044	49.3549	0.1395	0.1176	536.6257	-0.82821E-02

Table E.3.1-4 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_1=9.4$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	75.00	57.2114	-1.5371	57.9675	60.8708	0.2126	0.1666	539.3523	0.13797E-01
2	93.00	71.3260	-2.9726	71.9310	75.4902	0.3230	0.2577	517.9067	0.16807E-01
3	98.00	74.3810	-3.3766	74.9667	78.6640	0.3495	0.2802	512.1584	0.17438E-01
4	109.00	80.2049	-4.1192	80.7935	84.7496	0.4028	0.3257	499.5320	0.18621E-01
5	120.00	84.3324	-4.5095	84.9499	89.0797	0.4419	0.3595	486.8982	0.19408E-01
6	138.00	87.2962	-4.8996	87.9223	92.1484	0.4677	0.3831	467.0850	0.19819E-01
7	152.00	87.8651	-5.0395	88.5593	92.7810	0.4704	0.3870	452.6689	0.19779E-01
8	180.00	86.9432	-4.9507	87.8018	91.9371	0.4550	0.3762	425.6362	0.19288E-01
9	240.00	74.1128	-4.2228	74.8862	78.3345	0.3231	0.2641	380.4226	0.15989E-01
10	390.00	44.5616	-2.4951	45.2486	47.2535	0.1145	0.0808	314.9653	0.93136E-02
11	945.00	-110.9293	7.4385	109.7139	114.6034	0.6762	0.4175	324.7241	-0.22956E-01
12	960.00	-126.7687	8.8047	125.0090	130.6775	0.8896	0.6067	354.1567	-0.26911E-01
13	975.00	-128.9553	8.9840	126.7581	132.5950	0.9257	0.6597	380.4180	-0.23894E-01
14	1005.00	-112.5763	7.5644	110.8990	116.1088	0.7234	0.5460	419.7844	-0.23894E-01
15	1050.00	-88.2331	5.5275	87.8485	92.0592	0.4655	0.3722	462.1843	-0.19350E-01
16	1200.00	-40.6860	2.2818	41.7069	43.7888	0.1096	0.0958	533.4009	-0.96506E-02

Table E.3.2-1 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_2=1$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
1	75.00	73.0954	-2.7049	69.7068	73.0858	0.2966	0.1911	481.8770	0.94260E-02
2	93.00	82.2635	-3.0471	78.6250	82.3790	0.3714	0.2385	455.4275	0.10422E-01
3	98.00	83.7271	-3.1015	80.0477	83.8562	0.3835	0.2460	449.1262	0.10566E-01
4	109.00	86.3478	-3.1987	82.6181	86.5261	0.4053	0.2589	435.6785	0.10808E-01
5	120.00	88.5302	-3.2773	84.6952	88.6787	0.4226	0.2682	422.5173	0.10986E-01
6	138.00	88.5903	-3.2811	84.9612	88.9259	0.4208	0.2608	404.4050	0.10897E-01
7	152.00	87.6029	-3.2443	84.1115	88.0103	0.4098	0.2482	391.7678	0.10712E-01
8	180.00	84.9246	-3.1601	82.0003	85.7486	0.3852	0.2216	367.8838	0.10334E-01
9	240.00	69.6944	-2.6084	68.0847	71.1391	0.2617	0.1170	335.9763	0.84783E-02
10	390.00	40.0076	-1.5109	40.3178	42.0806	0.0900	-0.0135	292.5513	0.49732E-02
11	945.00	-109.8391	3.9767	94.8286	99.2520	0.5239	0.2503	403.5247	-1.1360E-01
12	960.00	-122.2109	4.4381	106.2584	111.2854	0.6705	0.4114	436.0063	-1.2992E-01
13	975.00	-121.9330	4.4485	106.8059	111.9097	0.6859	0.4851	456.8848	-1.3184E-01
14	1005.00	-110.5201	4.0387	96.5474	101.2278	0.5691	0.4392	481.9771	-1.2028E-01
15	1050.00	-91.5069	3.3408	79.0255	82.9130	0.3873	0.3167	507.6711	-9.9934E-02
16	1200.00	-48.9867	1.7645	39.7359	41.7385	0.1006	0.0852	550.4250	-4.48633E-02

Table E.3.2-2 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_2=5$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
1	75.00	129.9419	-16.4346	130.6475	137.0734	1.0585	0.8081	507.3826	0.25898E-01
2	93.00	149.0412	-18.9283	149.7847	157.0424	1.3690	1.0318	481.1255	0.29095E-01
3	98.00	152.0625	-19.3426	152.8367	160.2150	1.4197	1.0655	474.6663	0.29553E-01
4	109.00	157.3363	-20.0805	158.1888	165.7655	1.5083	1.1204	460.9265	0.30309E-01
5	120.00	161.5450	-20.6714	162.4660	170.1907	1.5782	1.1592	447.5530	0.30863E-01
6	138.00	162.9467	-20.9124	164.1253	171.8624	1.5919	1.1422	427.8137	0.30786E-01
7	152.00	161.7151	-20.7982	163.0132	170.6521	1.5577	1.0950	414.0166	0.30326E-01
8	180.00	158.1935	-20.4291	159.5780	166.9607	1.4726	0.9898	388.4573	0.29270E-01
9	240.00	131.3550	-17.2102	133.9246	139.9833	1.0192	0.5844	350.1887	0.24157E-01
10	390.00	77.3287	-10.3023	80.1934	83.7126	0.3571	0.0682	298.7231	0.14208E-01
11	945.00	-189.1151	24.4150	178.7531	186.9060	1.8272	1.7529	364.0820	-3.1114E-01
12	960.00	-215.3964	27.6163	204.7881	214.3082	2.4346	2.3277	396.7510	-3.6171E-01
13	975.00	-220.9390	28.1281	210.0383	219.9169	2.5988	2.4976	422.4526	-3.7470E-01
14	1005.00	-200.6747	25.5915	191.3710	200.5097	2.2005	2.1443	455.7187	-3.4646E-01
15	1050.00	-165.7315	21.2579	157.5817	165.2555	1.5233	1.4992	489.8777	-2.8905E-01
16	1200.00	-86.3465	11.1466	80.4130	84.4523	0.4104	0.4080	544.5852	-1.4877E-01

Table E.3.2-3 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_2=10$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
1	75.00	154.4114	-16.0825	156.2534	144.0429	1.5366	1.3190	531.1138	0.36980E-01
2	93.00	179.6836	-18.9518	181.5454	190.4686	2.0423	1.7477	506.1902	0.42178E-01
3	98.00	183.7963	-19.4538	185.6843	194.7772	2.1279	1.8194	499.6702	0.42942E-01
4	109.00	190.8644	-20.3517	192.8615	202.2310	2.2760	1.9416	485.7219	0.44189E-01
5	120.00	196.4077	-21.0678	198.5394	208.1102	2.3921	2.0350	472.1504	0.45096E-01
6	138.00	199.5756	-21.5386	201.8302	211.4433	2.4410	2.0640	451.2168	0.45241E-01
7	152.00	198.7195	-21.5646	201.1326	210.6494	2.4027	2.0202	436.3315	0.44683E-01
8	180.00	195.3574	-21.3991	197.8641	207.1160	2.2882	1.8998	409.0320	0.43251E-01
9	240.00	166.4519	-18.5351	168.5152	176.2042	1.6244	1.2911	364.7544	0.35941E-01
10	390.00	100.8903	-11.5246	102.4454	106.9585	0.5844	0.3788	305.2461	0.21243E-01
11	945.00	-214.6447	23.6487	211.4288	220.8574	2.5123	2.2637	325.8176	-0.43816E-01
12	960.00	-251.6194	27.2278	247.7735	259.0298	3.4998	3.1847	357.3440	-0.51894E-01
13	975.00	-263.6768	28.2122	259.3894	271.3689	3.8856	3.5577	385.4854	-0.54847E-01
14	1005.00	-243.6995	26.0449	239.6490	250.9450	3.3933	3.1583	427.5120	-0.51528E-01
15	1050.00	-201.0767	21.8348	198.8349	208.4161	2.3977	2.2637	471.0933	-0.43709E-01
16	1200.00	-102.6129	11.4251	102.6929	107.8341	0.6669	0.6388	538.6438	-0.23476E-01

Table E.3.2-4 Fracture Mechanics Parameters of Thinning Portion, crack depth $a_2=15$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
1	75.00	146.0834	-20.6473	162.5762	170.7542	1.6804	1.5835	547.0894	0.37431E-01
2	93.00	171.0700	-24.5788	190.0364	199.4705	2.2624	2.1448	523.7351	0.43056E-01
3	98.00	175.2774	-25.2846	194.6575	204.2857	2.3642	2.2458	517.2649	0.43911E-01
4	109.00	182.5186	-26.5493	202.6775	212.6228	2.5408	2.4241	503.2568	0.45305E-01
5	120.00	188.2145	-27.5644	209.0411	219.2190	2.6801	2.5677	489.5583	0.46323E-01
6	138.00	192.1205	-28.3603	213.4094	223.6727	2.7569	2.6584	468.0095	0.46665E-01
7	152.00	191.8786	-28.5110	213.2281	223.3910	2.7264	2.6427	452.3835	0.46187E-01
8	180.00	189.3040	-28.4784	210.5859	220.4960	2.6145	2.5586	423.8064	0.44851E-01
9	240.00	163.5916	-25.1263	181.7272	190.0711	1.8984	1.9004	375.4790	0.37628E-01
10	390.00	100.9601	-16.0001	112.1526	117.1078	0.7019	0.7469	310.1279	0.22429E-01
11	945.00	-194.8082	29.3833	215.4684	224.9301	2.5791	2.0846	299.8232	-0.43304E-01
12	960.00	-233.3090	34.4110	256.8323	268.3083	3.7127	3.1285	329.1353	-0.52087E-01
13	975.00	-247.6925	36.1222	271.8823	284.2371	4.2149	3.6280	357.7842	-0.55717E-01
14	1005.00	-232.2532	33.8013	254.5233	266.4089	3.7796	3.3340	406.0215	-0.53194E-01
15	1050.00	-193.6407	28.5831	212.3994	222.5490	2.7126	2.4445	456.8718	-0.45704E-01
16	1200.00	-98.5791	14.9463	110.0805	115.5778	0.7641	0.7058	534.2156	-0.25195E-01

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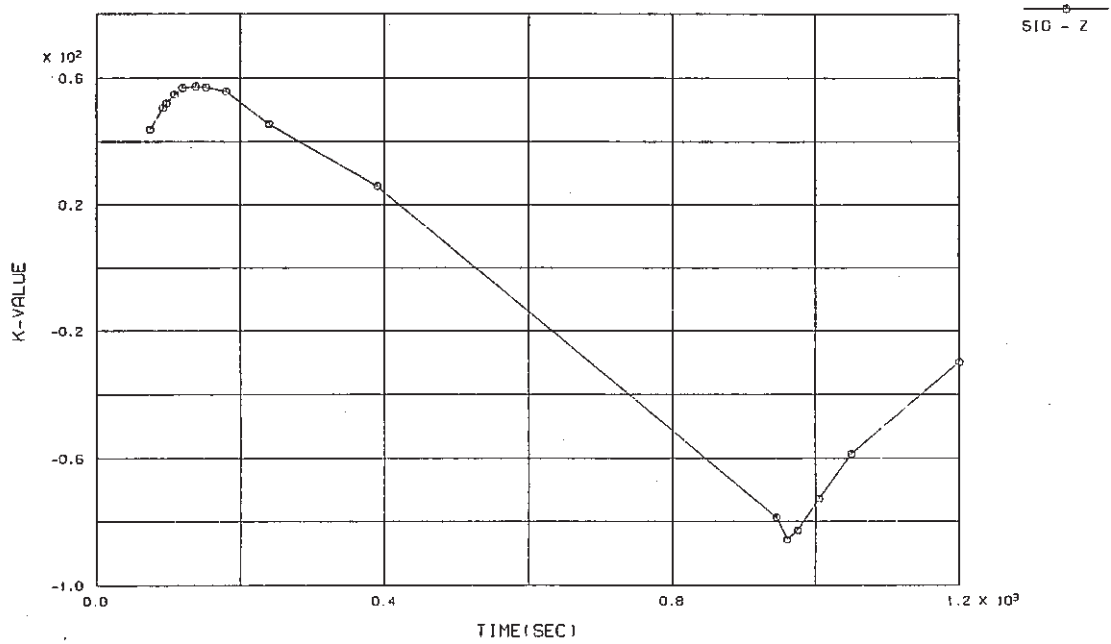


Fig. E.3.1-1 History of Stress Intensity Factor for Thinning Portion, crack depth $a_1=1$ mm

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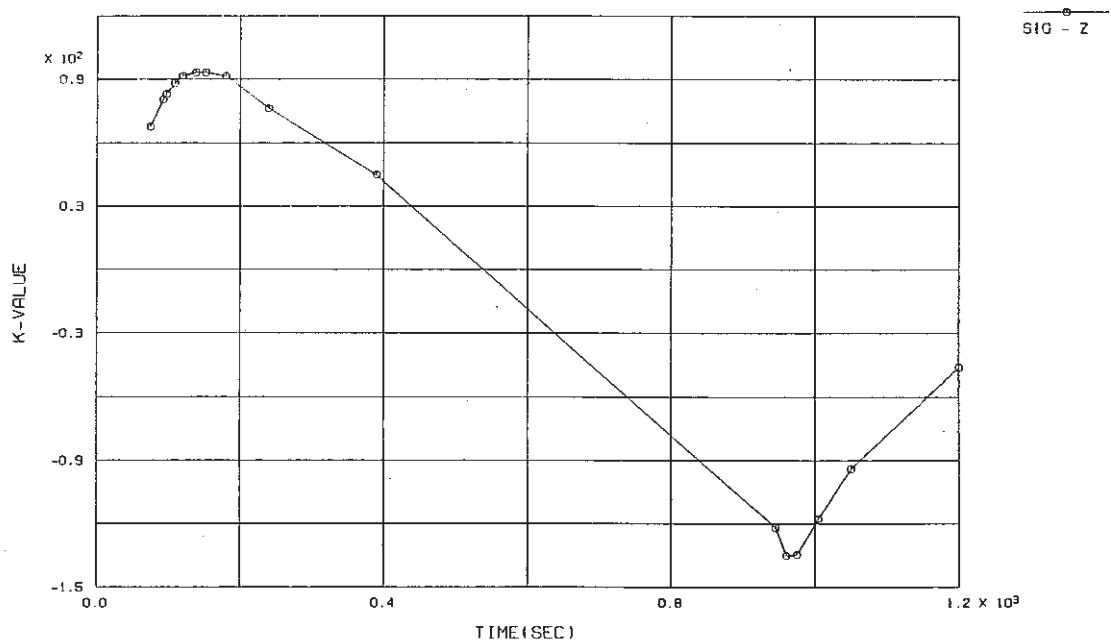


Fig. E.3.1-2 History of Stress Intensity Factor for Thinning Portion, crack depth $a_1=4$ mm

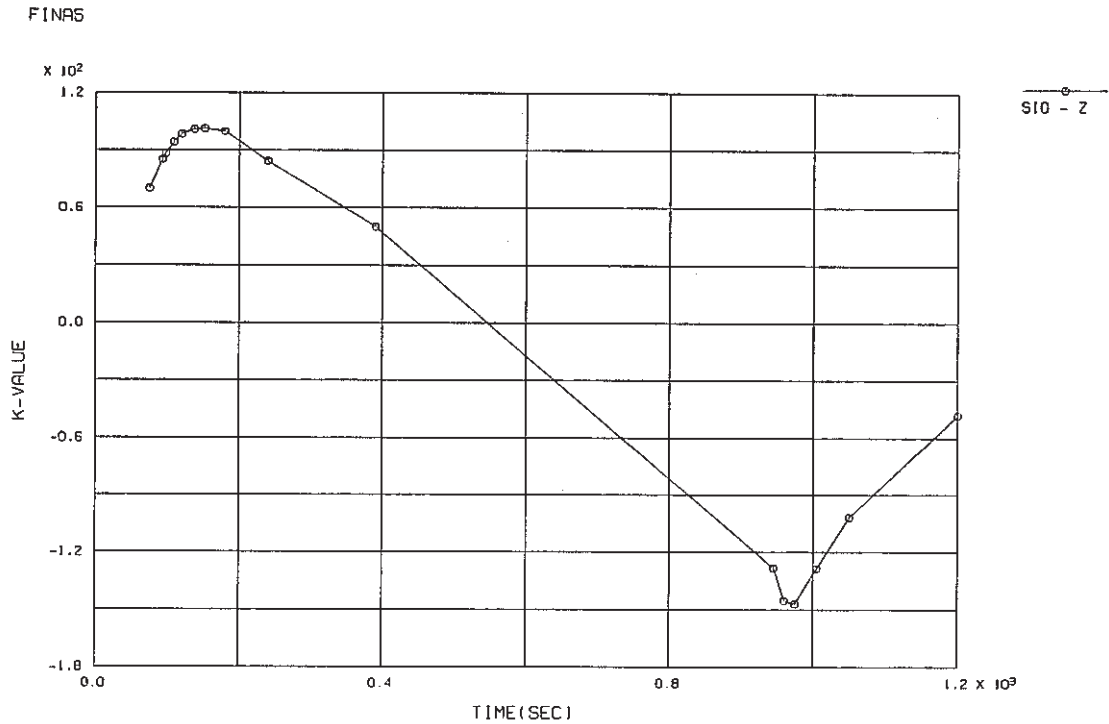


Fig. E.3.1-3 History of Stress Intensity Factor for Thinning Portion, crack depth $a_1=7$ mm

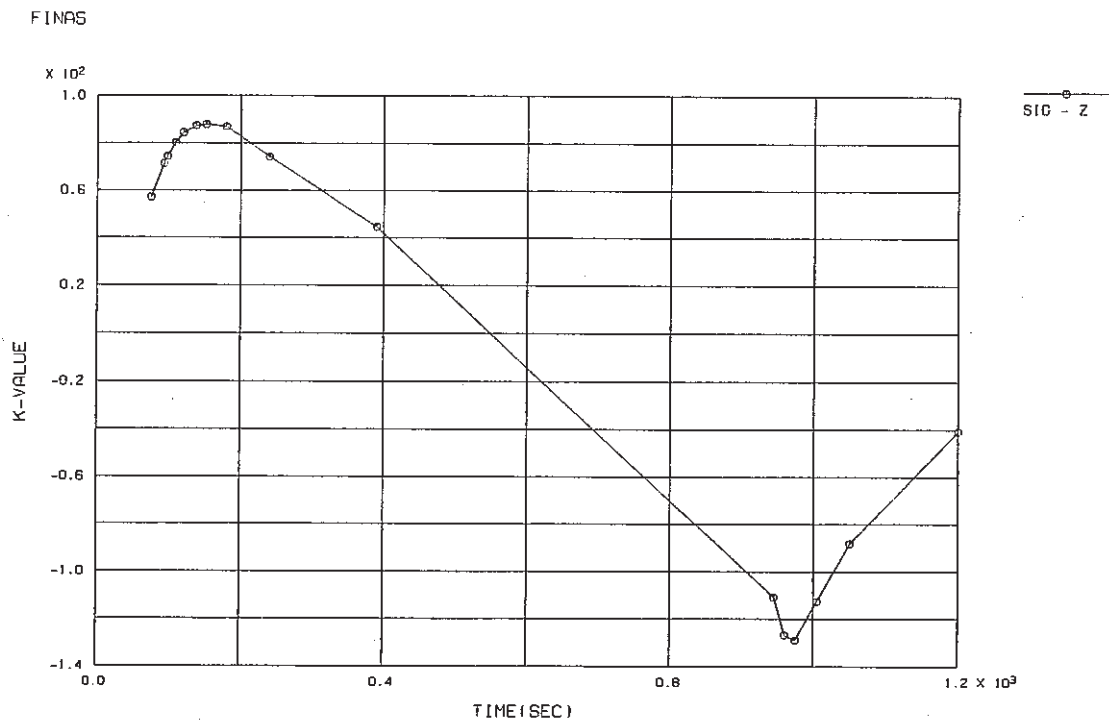


Fig. E.3.1-4 History of Stress Intensity Factor for Thinning Portion, crack depth $a_1=9.4$ mm

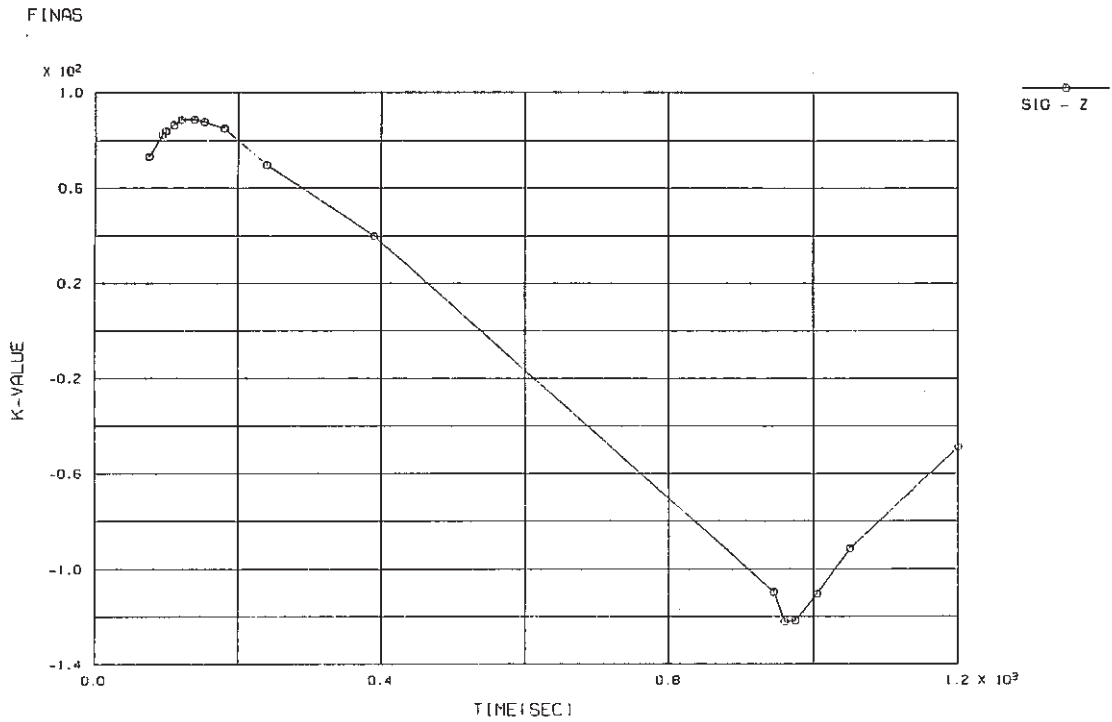


Fig. E.3.2-1 History of Stress Intensity Factor for Thinning Portion, crack depth $a_2=1$ mm

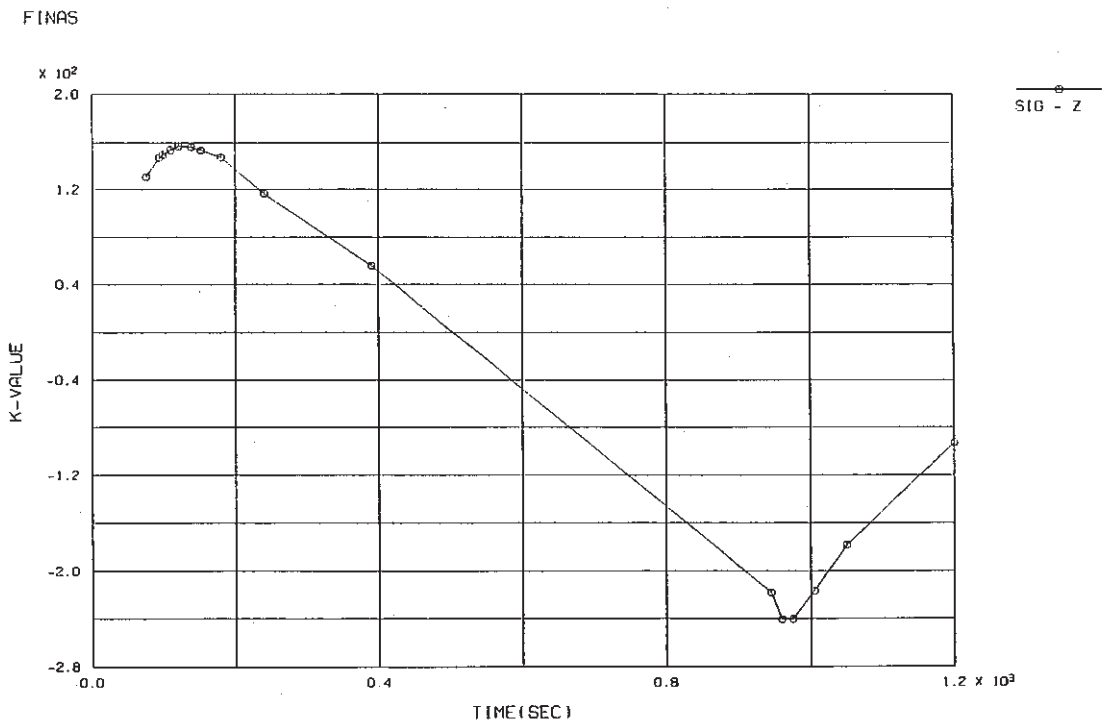


Fig. E.3.2-2 History of Stress Intensity Factor for Thinning Portion, crack depth $a_2=5$ mm

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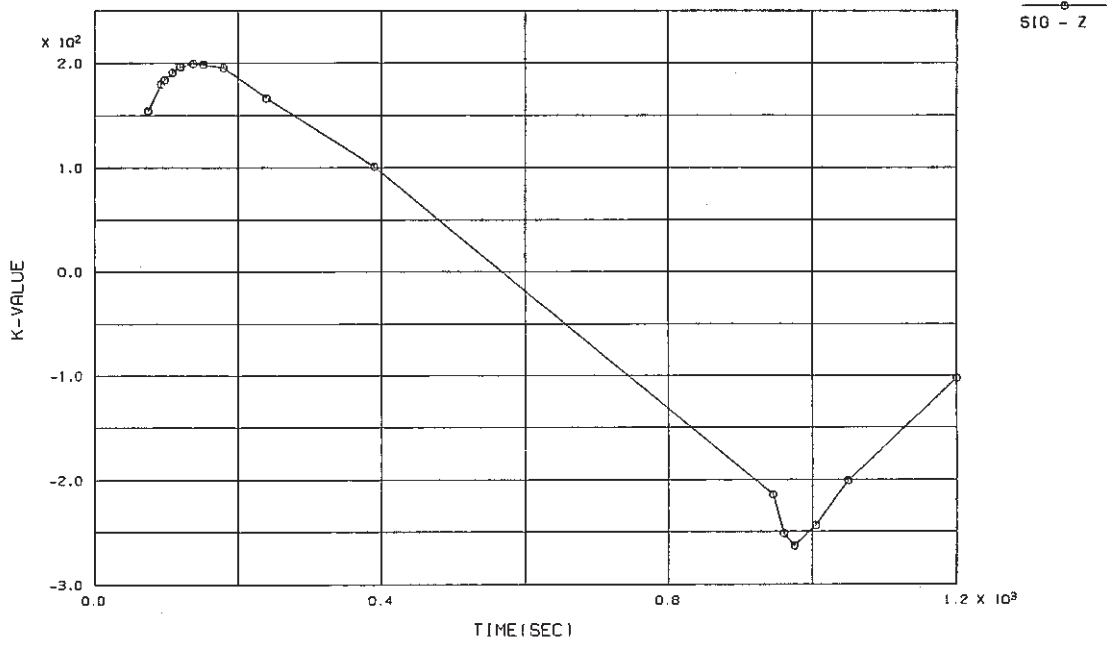


Fig. E.3.2-3 History of Stress Intensity Factor for Thinning Portion, crack depth $a_2=10$ mm

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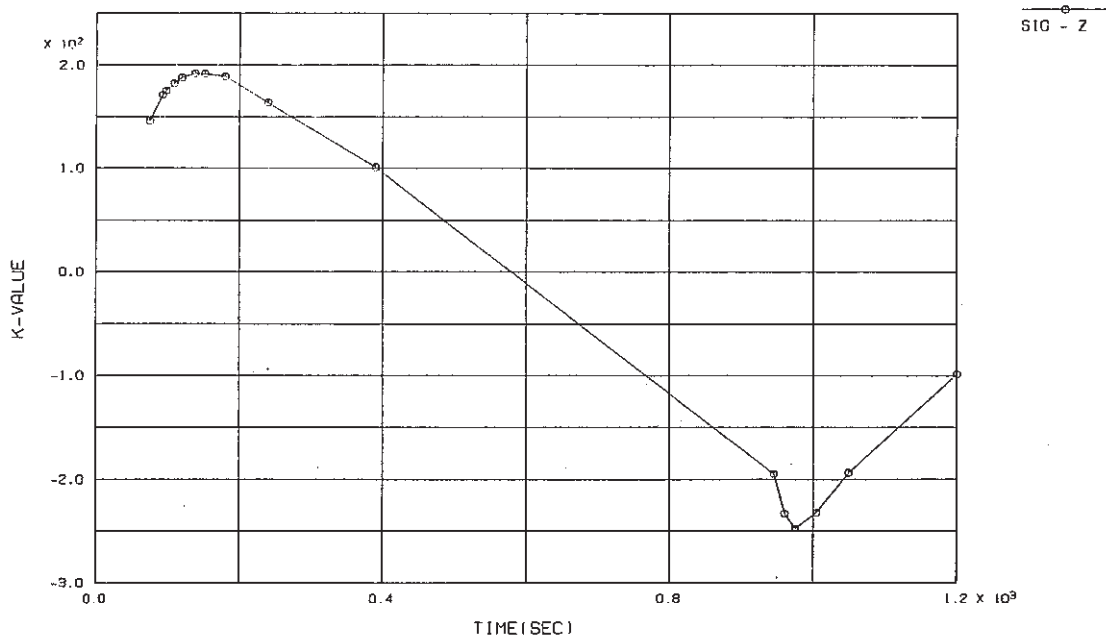


Fig. E.3.2-4 History of Stress Intensity Factor for Thinning Portion, crack depth $a_2=15$ mm

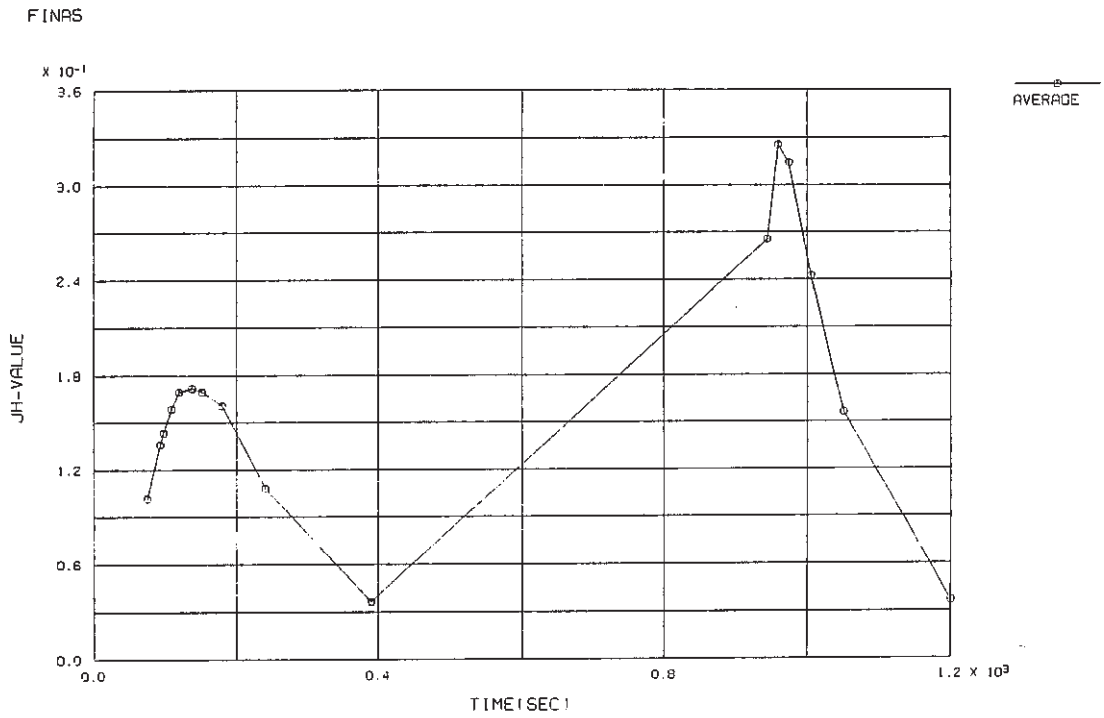


Fig. E.3.3-1 History of \hat{J} -Integral for Thinning Portion, crack depth $a_1=1$ mm

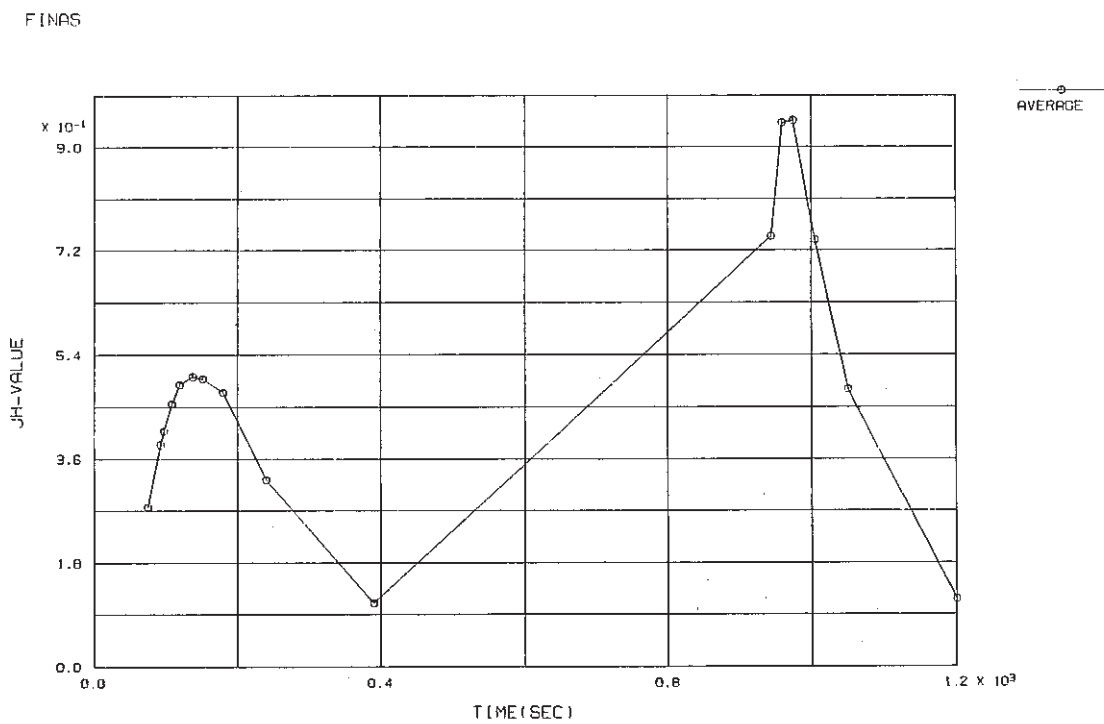


Fig. E.3.3-2 History of \hat{J} -Integral for Thinning Portion, crack depth $a_1=4$ mm

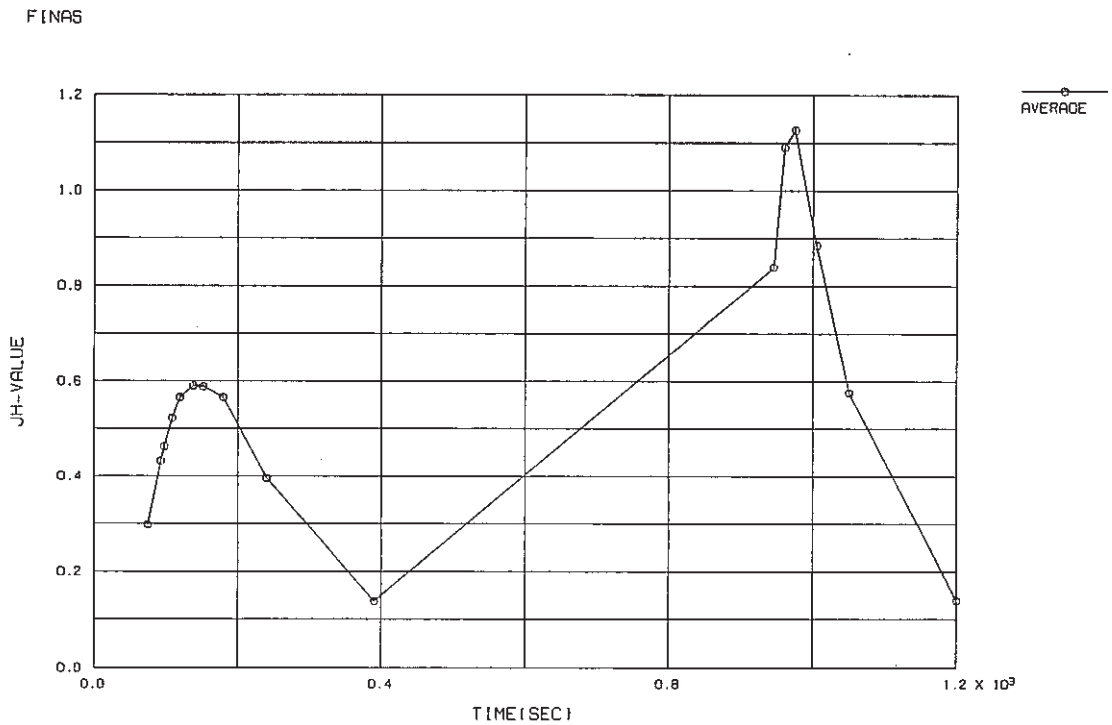


Fig. E.3.3-3 History of \hat{J} -Integral for Thinning Portion, crack depth $a_1=7$ mm

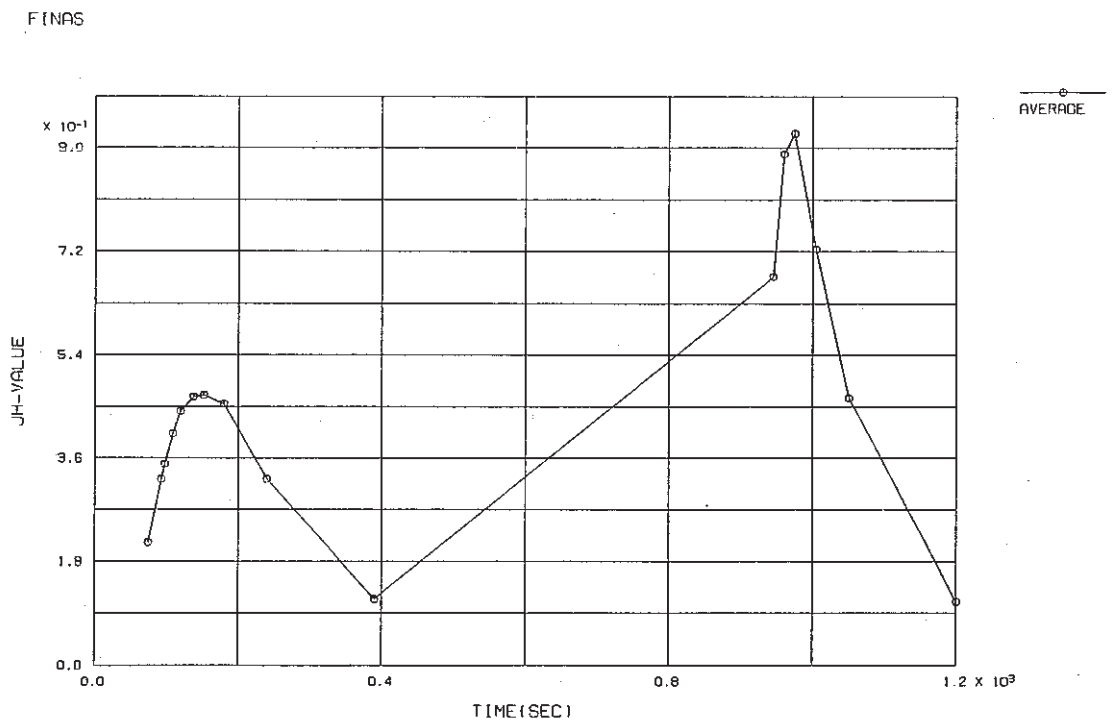


Fig. E.3.3-4 History of \hat{J} -Integral for Thinning Portion, crack depth $a_1=9.4$ mm

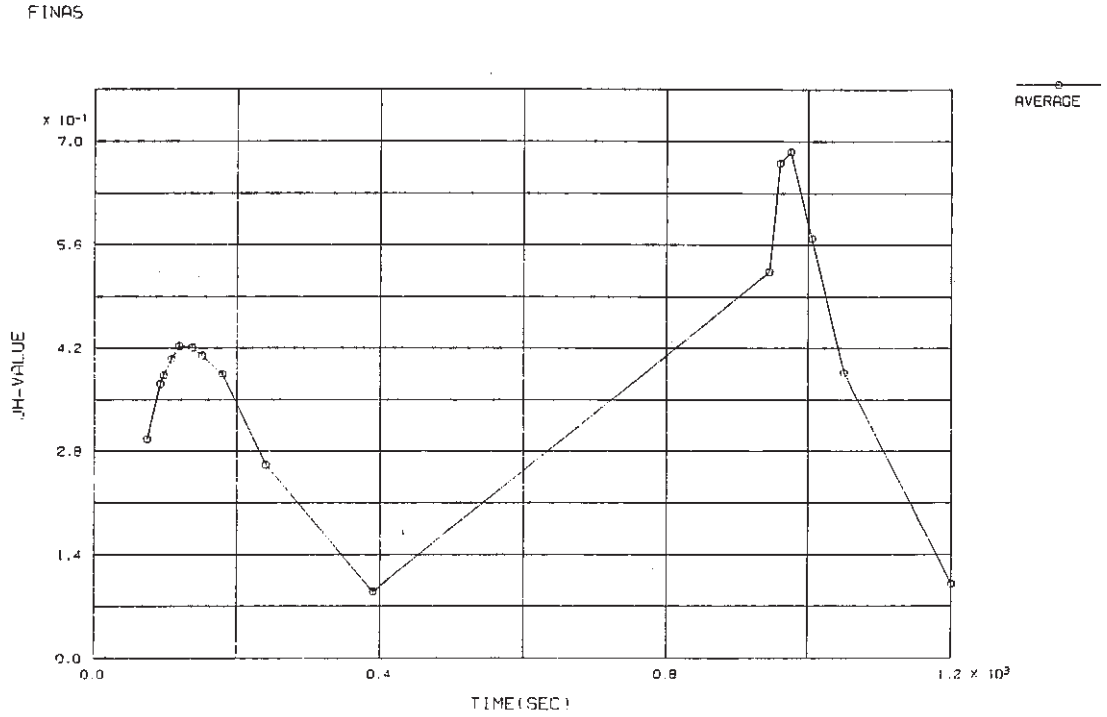


Fig. E.3.4-1 History of \hat{J} -Integral for Thinning Portion, crack depth $a_2=1$ mm

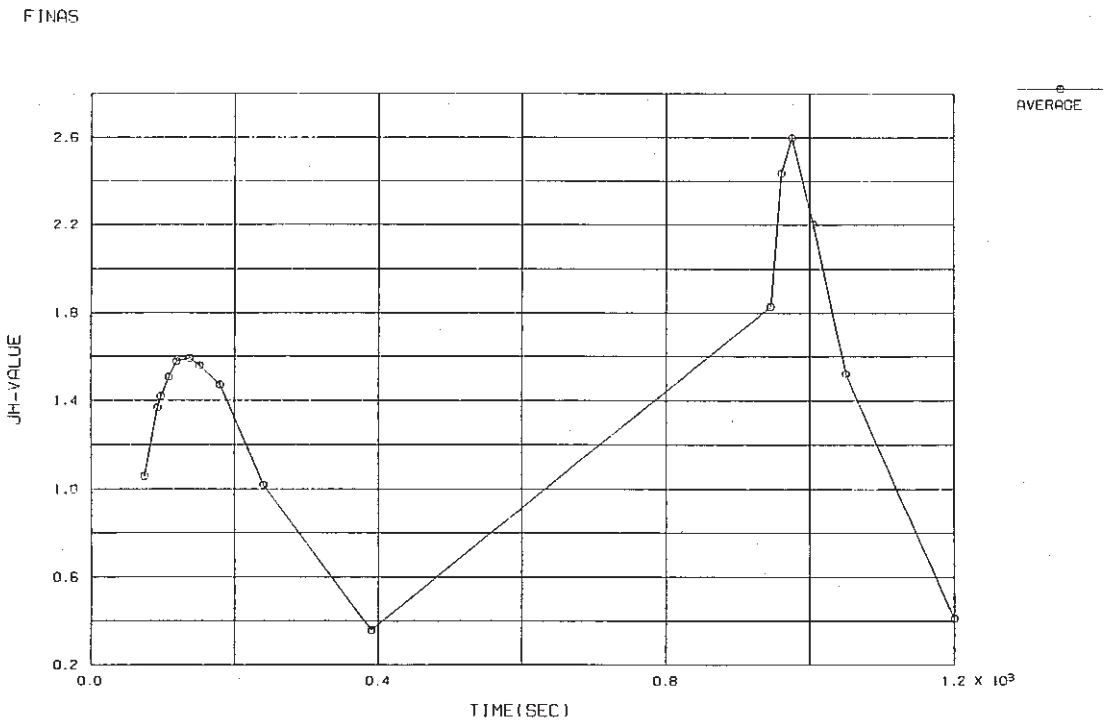


Fig. E.3.4-2 History of \hat{J} -Integral for Thinning Portion, crack depth $a_2=5$ mm

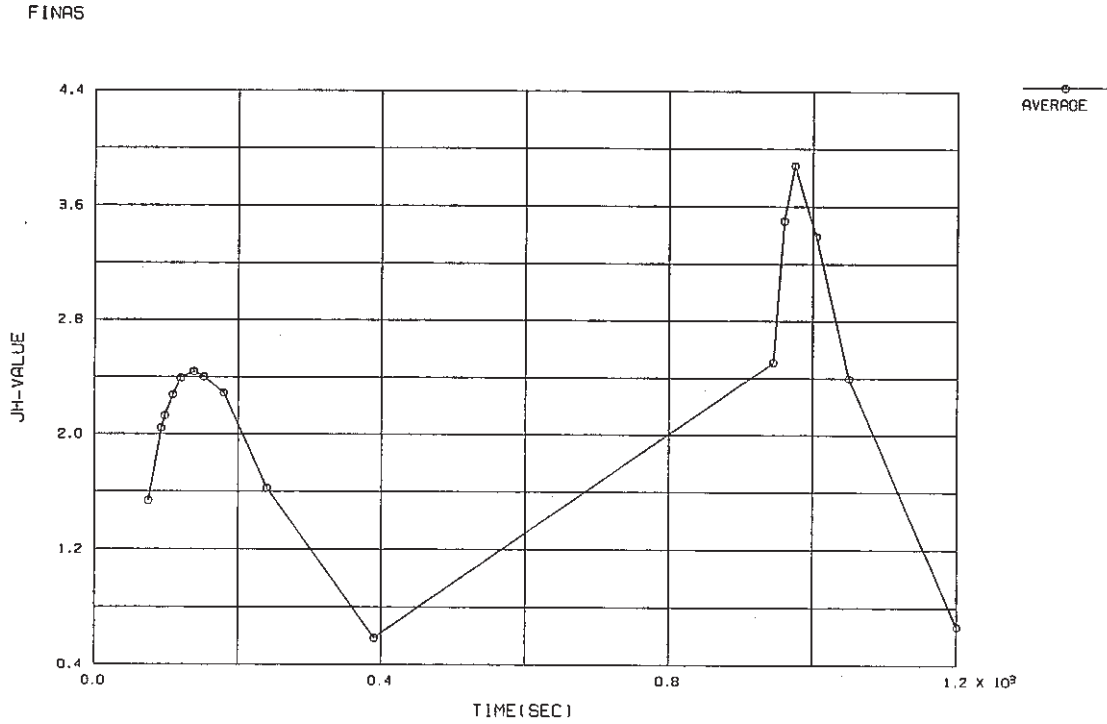


Fig. E.3.4-3 History of \hat{J} -Integral for Thinning Portion, crack depth $a_2=10$ mm

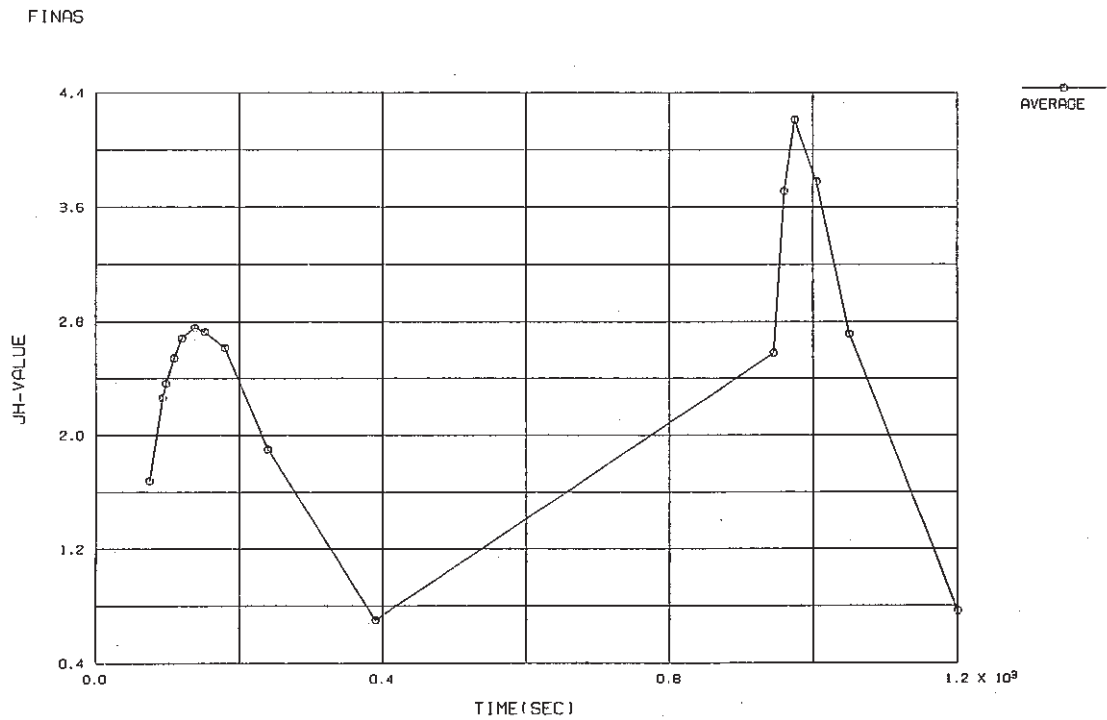


Fig. E.3.4-4 History of \hat{J} -Integral for Thinning Portion, crack depth $a_2=15$ mm

Table E.4-1 Fracture Mechanics Parameters of Conical-Bottom Head, crack depth a=1 mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P. STRS	P. STRN	JH	J	TEMP.	DISP.
1	40.20	29.2490	-5.8817	17.0961	17.9548	0.0186	0.0288	544.4437	0.18130E-02
2	60.00	35.5478	-7.6510	22.7369	23.8585	0.0322	0.0520	513.3711	0.23556E-02
3	90.00	35.2548	-7.7091	24.2590	25.4270	0.0358	0.0739	476.2880	0.24508E-02
4	105.00	33.4547	-7.1296	23.3362	24.4542	0.0328	0.0817	461.4342	0.23373E-02
5	120.00	31.5665	-6.4359	22.0778	23.1275	0.0291	0.0907	447.4490	0.21946E-02
6	150.00	25.0198	-4.4600	17.7616	18.5975	0.0186	0.1006	423.9039	0.17439E-02
7	165.00	21.3212	-3.3058	15.0181	15.7220	0.0132	0.1048	414.2325	0.14733E-02
8	180.00	17.9277	-2.2018	12.3826	12.9806	0.0089	0.1122	405.0116	0.12177E-02
9	240.00	1.8124	2.5126	0.7213	0.7544	0.0030	0.1233	377.8559	0.72550E-04
10	300.00	-11.4533	6.5792	10.0882	10.5471	0.0058	0.1458	359.7516	-9.0039E-03
11	540.00	-39.6851	15.0016	35.0101	34.4726	0.0609	0.2080	314.8912	-2.9922E-02
12	720.00	-46.0840	16.8000	38.4051	40.0905	0.0819	0.2086	298.8040	-3.4638E-02
13	900.00	-46.7438	16.8119	38.8441	40.5366	0.0833	0.1879	286.7282	-3.4891E-02
14	940.00	-71.7770	20.8685	50.9804	53.2344	0.1451	-0.1223	311.3595	-4.4613E-02
15	960.00	-88.8381	25.3765	63.6217	66.5131	0.2308	-0.2069	358.0137	-5.8829E-02
16	990.00	-86.3010	25.7936	65.9527	69.0276	0.2532	-0.1299	402.3379	-6.2354E-02
17	1008.00	-82.3206	24.7132	63.9477	66.9531	0.2407	-0.1093	420.7612	-6.1161E-02
18	1020.00	-79.3908	23.8949	62.3292	65.2728	0.2301	-0.1078	431.9620	-6.0033E-02
19	1040.00	-73.5590	22.0847	58.4956	61.2769	0.2046	-0.1025	447.6062	-5.6909E-02
20	1060.00	-65.8427	19.8268	53.2156	55.7612	0.1705	-0.0956	458.6455	-5.2153E-02
21	1080.00	-59.5212	17.6643	48.1364	50.4514	0.1403	-0.1045	467.9952	-4.7482E-02
22	1200.00	-27.4743	6.9088	21.7843	22.8569	0.0295	-0.1155	509.2446	-2.2475E-02

Table E.4-2 Fracture Mechanics Parameters of Conical-Bottom Head, crack depth a=15 mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P. STRS	P. STRN	JH	J	TEMP.	DISP.
1	40.20	33.0588	20.9957	30.3486	31.9063	0.0599	0.0409	583.0960	0.23907E-01
2	60.00	53.7500	32.8970	49.2566	51.7642	0.1564	0.0995	568.4210	0.36445E-01
3	90.00	65.0620	41.5819	59.6208	62.6148	0.2256	0.1328	544.0859	0.42121E-01
4	105.00	63.9032	42.7721	58.4774	61.3949	0.2154	0.1256	532.4827	0.40801E-01
5	120.00	60.5962	43.0137	55.2966	58.0379	0.1913	0.1153	521.2445	0.38307E-01
6	150.00	48.7131	40.5215	43.9125	46.0629	0.1190	0.1002	489.7153	0.30100E-01
7	165.00	40.4695	38.0224	36.2203	37.9840	0.0805	0.1024	489.7432	0.24762E-01
8	180.00	31.7916	35.3220	28.3442	29.7169	0.0490	0.1158	480.2858	0.19334E-01
9	240.00	-5.7852	21.7538	14.9076	15.6163	0.0133	0.2815	447.2122	-3.9222E-02
10	300.00	-41.8068	7.6396	46.4946	48.6806	0.1273	0.5846	421.6912	-2.5160E-01
11	540.00	-122.3592	-26.4030	124.7094	130.3742	0.8865	1.7794	357.1316	-7.0976E-01
12	720.00	-142.1963	-36.7684	143.8556	150.2933	1.1662	2.1319	331.7754	-8.1329E-01
13	900.00	-143.8187	-39.3075	145.1804	151.6102	1.1784	2.1215	314.1899	-8.1619E-01
14	940.00	-158.1064	-50.7686	158.3357	165.3428	1.4008	2.2990	312.9045	-9.1714E-01
15	960.00	-194.8607	-72.4778	190.8113	199.3155	2.0453	2.6189	324.8351	-1.1346
16	990.00	-218.1155	-85.5212	211.6038	221.1907	2.5452	2.7117	350.9598	-1.2611
17	1008.00	-216.9408	-85.4820	210.6217	220.2362	2.5385	2.5607	365.5235	-1.2572
18	1020.00	-213.3539	-88.6533	207.2534	216.7650	2.4683	2.4126	374.6822	-1.2401
19	1040.00	-203.4567	-86.8807	197.8164	206.9718	2.2636	2.1055	389.1381	-1.1885
20	1060.00	-188.5718	-82.3040	183.5890	192.1482	1.9622	1.7464	402.2695	-1.1063
21	1080.00	-171.4247	-76.5675	167.0088	174.8342	1.6348	1.3958	413.8173	-1.0120
22	1200.00	-74.3656	-41.0871	75.2886	78.9065	0.3428	0.0903	466.6559	-0.48424E-01

Table E.4-3 Fracture Mechanics Parameters of Conical-Bottom Head, crack depth a=32 mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P. STRS	P. STRN	JH	J	TEMP.	DISP.
1	40.20	19.0146	23.6325	31.1885	32.7968	0.0636	0.0772	591.3170	0.23068E-01
2	60.00	33.9432	42.0009	54.2741	57.0672	0.1922	0.2331	587.7041	0.35682E-01
3	90.00	46.5571	59.1855	72.5980	76.3102	0.3414	0.4187	576.2572	0.50928E-01
4	105.00	48.7335	63.3773	75.2673	79.0998	0.3652	0.4506	568.7364	0.51230E-01
5	120.00	49.3244	65.9851	75.6223	79.4553	0.3667	0.4539	560.5050	0.49610E-01
6	150.00	46.6572	67.1036	70.8369	74.3923	0.3182	0.3866	543.1805	0.41895E-01
7	165.00	43.7001	65.8467	66.2671	69.5765	0.2769	0.3250	534.3056	0.36281E-01
8	180.00	40.2387	64.0434	61.2802	64.3254	0.2355	0.2580	525.4939	0.30240E-01
9	240.00	22.8416	52.1483	41.5387	43.5643	0.1060	-0.0169	492.2933	0.32536E-02
10	300.00	3.8722	37.2636	38.0635	40.9277	0.0921	-0.2084	468.9032	-2.2828E-01
11	540.00	-4.0983	-3.4094	200.8798	102.9545	0.5602	-0.3220	389.3387	-8.2610E-01
12	720.00	-59.4463	-19.1313	119.3902	124.8164	0.8129	-0.3124	358.0763	-9.7605E-01
13	900.00	-63.1291	-24.7855	122.9691	128.4884	0.8540	-0.3941	336.7514	-9.9020E-01
14	940.00	-72.3680	-36.6714	136.3404	142.4461	1.0481	-0.2304	332.9418	-1.0796
15	960.00	-95.1156	-64.8947	169.9888	177.5983	1.6287	0.3322	332.2774	-1.3066
16	990.00	-117.4486	-93.1127	200.5018	209.5095	2.2721	1.0181	338.3560	-1.5051
17	1008.00	-122.3579	-100.9630	205.5192	214.7913	2.3950	1.2153	345.5349	-1.5324
18	1020.00	-123.3806	-104.0163	205.5519	214.8564	2.4019	1.2874	351.1800	-1.5277
19	1040.00	-121.8999	-105.8721	200.8778	210.0256	2.3047	1.3083	361.4396	-1.4874
20	1060.00	-116.5714	-103.6078	190.1701	199.1993	2.0824	1.2070	372.3142	-1.4078
21	1080.00	-109.0283	-98.9505	176.9075	185.0671	1.8055	1.0486	383.2636	-1.3060
22	1200.00	-57.9493	-62.6298	91.9006	96.2547	0.5025	0.2929	439.3621	-0.66814E-01

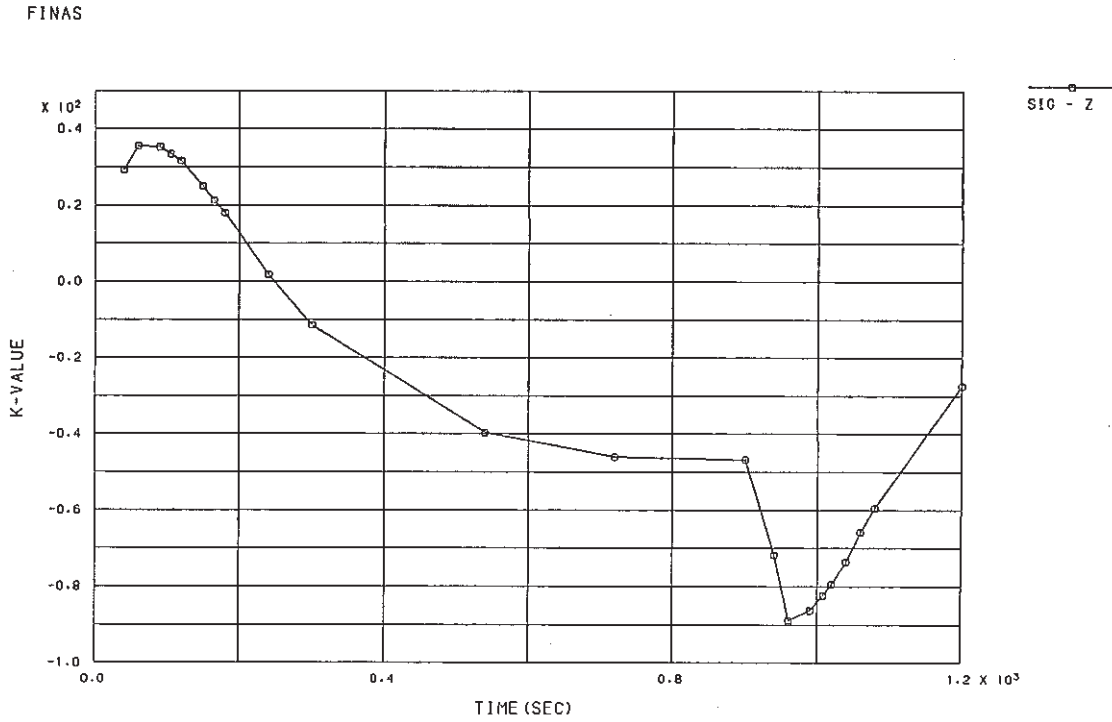


Fig. E.4.1-1 History of Stress Intensity Factor for Conical-Bottom Head, crack depth a=1 mm

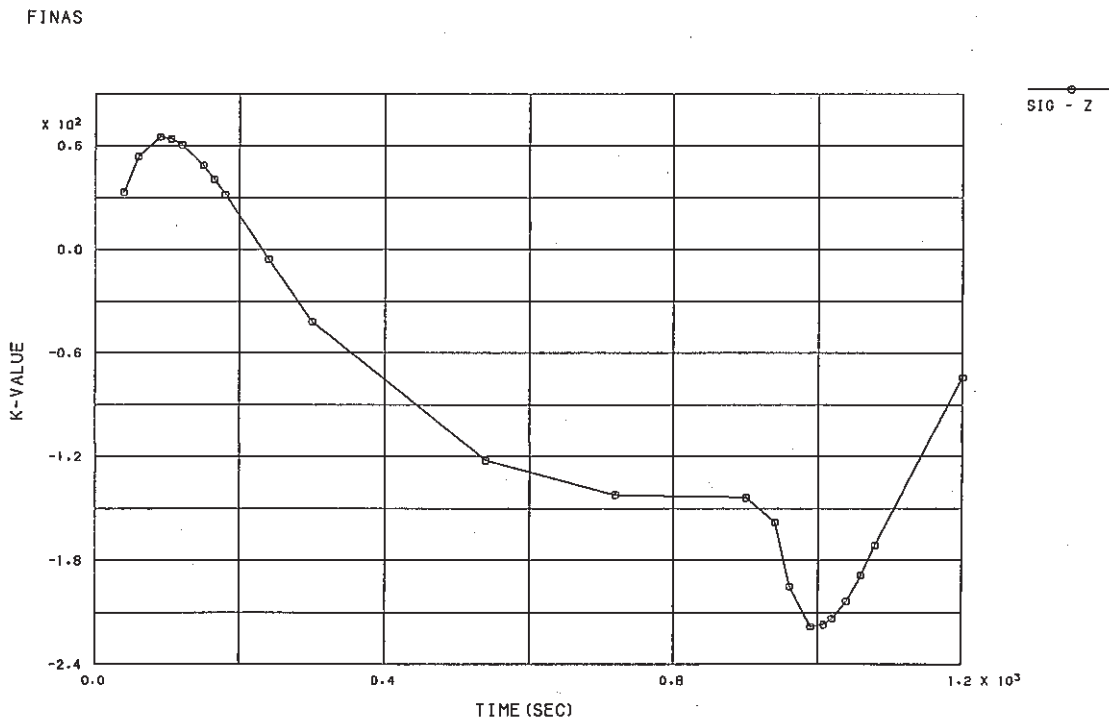


Fig. E.4.1-2 History of Stress Intensity Factor for Conical-Bottom Head, crack depth a=15 mm

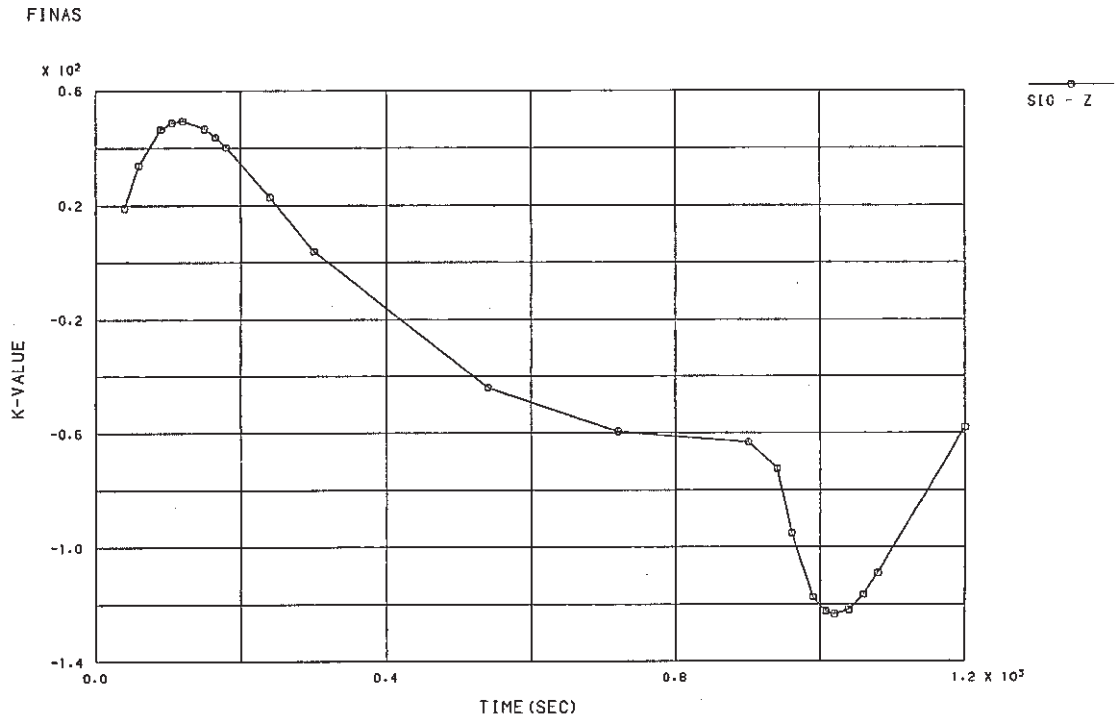


Fig. E.4.1-3 History of Stress Intensity Factor for Conical-Bottom Head, crack depth $a=32$ mm

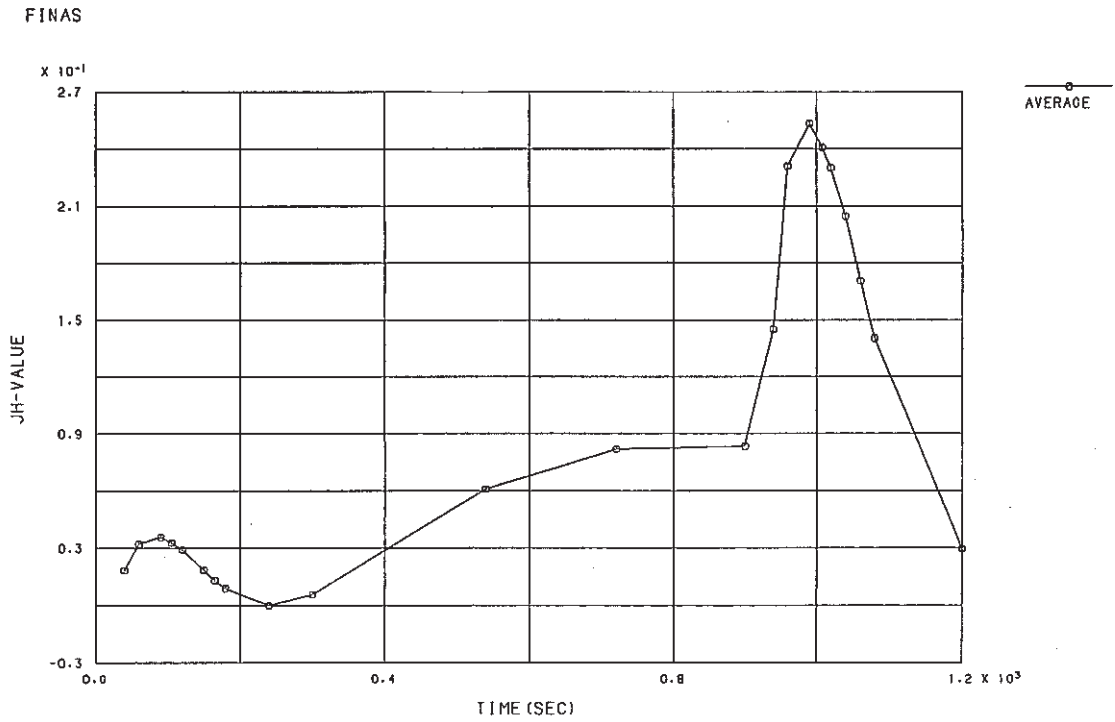


Fig. E.4.2-1 History of \hat{J} -Integral for Conical-Bottom Head, crack depth $a=1$ mm

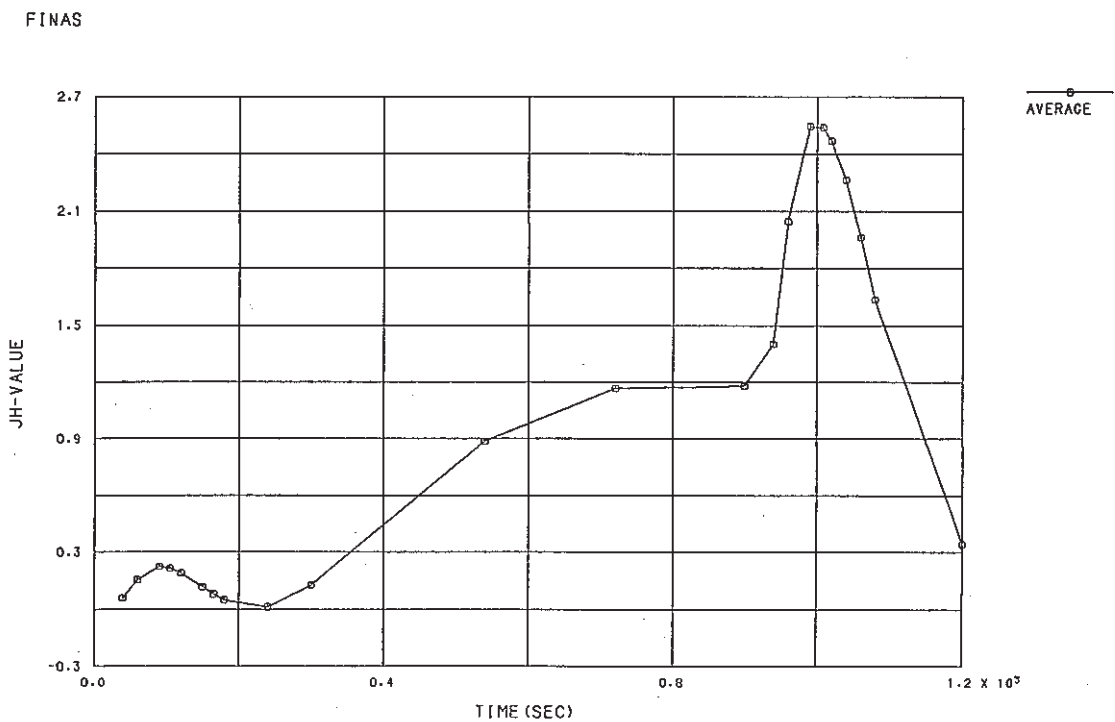


Fig. E.4.2-2 History of \hat{J} -Integral for Conical-Bottom Head, crack depth $a=15$ mm

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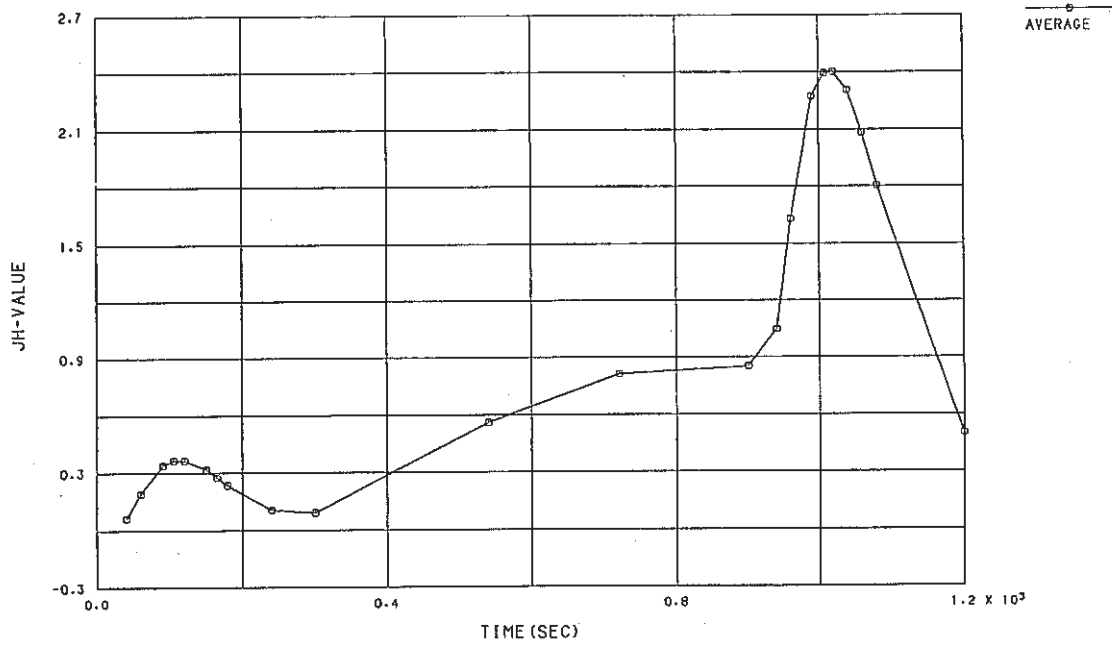


Fig. E.4.2-3 History of \hat{J} -Integral for Conical-Bottom Head, crack depth $a=32$ mm

Table E.5.1-1 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_1=1.45$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	9.50	24.4601	9.7833	20.1898	21.2190	0.0263	0.0271	570.8341	0.45551E-02
2	11.70	37.5631	14.9051	31.3815	32.9591	0.0626	0.0747	545.9108	0.67437E-02
3	15.10	37.1205	15.2052	32.1262	33.7259	0.0849	0.0900	529.0638	0.67846E-02
4	27.00	43.3803	17.9808	38.2593	40.1146	0.0897	0.1491	488.4509	0.78331E-02
5	38.00	50.1100	20.7911	44.3851	46.5032	0.1183	0.2143	454.5385	0.88999E-02
6	51.20	50.3859	20.9587	44.9412	47.0572	0.1192	0.2433	424.9108	0.88354E-02
7	60.00	50.8291	21.1253	45.3936	47.5145	0.1203	0.2619	407.1816	0.88287E-02
8	66.00	49.3512	20.5099	44.1787	46.2329	0.1133	0.2603	397.1580	0.85294E-02
9	90.00	44.8020	18.5369	40.0767	41.8046	0.0918	0.2544	364.0669	0.76107E-02
10	136.50	31.6637	13.0500	28.5765	29.8492	0.0459	0.1878	323.6823	0.52928E-02
11	210.00	17.5968	7.1813	16.0756	16.7772	0.0143	0.1059	285.5597	0.28905E-02
12	300.00	8.3303	3.3322	7.7847	8.1208	0.0033	0.0492	271.0803	0.13492E-02
13	420.00	3.1694	1.1863	3.0763	3.2085	0.0005	0.0173	263.5343	0.50136E-03
14	942.20	-53.9401	-22.2849	45.8675	47.9543	0.1201	-0.1649	359.7741	-0.86576E-02
15	944.80	-58.1123	-24.0491	49.6228	51.8979	0.1414	-0.1537	373.0191	-0.94155E-02
16	952.50	-66.5276	-27.6870	57.3812	60.0663	0.1926	-0.1021	410.8120	-0.11022E-01
17	955.00	-65.6637	-27.4140	56.8408	59.5101	0.1899	-0.0882	418.9628	-0.10958E-01
18	966.00	-63.1954	-26.5188	55.1614	57.7857	0.1821	-0.0460	448.8635	-0.10782E-01
19	972.00	-60.7066	-25.4891	52.8782	55.5153	0.1691	-0.0331	460.6687	-0.10417E-01
20	1000.00	-48.1877	-20.7136	43.0291	45.1446	0.1148	0.0027	506.8590	-0.86409E-02
21	1020.00	-38.7265	-16.2366	33.5843	35.2488	0.0705	-0.0018	520.8035	-0.67689E-02
22	1120.00	-12.7060	-5.2367	10.4778	11.0080	0.0070	-0.0037	557.5583	-0.20864E-02
23	1200.00	-6.9098	-2.8110	5.3116	5.5823	0.0018	-0.0019	570.1221	-0.10058E-02

Table E.5.1-2 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_1=2.9$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	9.50	17.8320	4.3813	22.2059	23.3443	0.0320	0.0376	580.8924	0.60235E-02
2	11.70	30.5459	6.8842	36.9843	38.8589	0.0877	0.1125	560.6020	0.96873E-02
3	15.10	31.5715	7.0359	38.7206	40.6637	0.0951	0.1373	542.8592	0.99397E-02
4	27.00	37.9060	8.3134	46.8210	49.1150	0.1356	0.2280	503.6374	0.11673E-01
5	38.00	43.9994	9.5772	54.4020	57.0240	0.1796	0.3250	471.8086	0.13299E-01
6	51.20	44.6846	9.5915	55.3472	57.9724	0.1825	0.3671	441.9296	0.13267E-01
7	60.00	45.0481	9.6452	55.9009	58.5321	0.1843	0.3924	424.2749	0.13259E-01
8	66.00	43.9651	9.3418	54.5767	57.1338	0.1746	0.3906	413.6544	0.12853E-01
9	90.00	39.8214	8.3430	49.5835	51.8647	0.1416	0.3762	378.9829	0.11448E-01
10	136.50	26.8107	5.6765	35.4525	37.0413	0.0709	0.2737	334.1276	0.7942E-02
11	210.00	14.2473	2.9990	19.8833	20.7541	0.0219	0.1527	295.3441	0.43457E-02
12	300.00	5.9673	1.3135	9.5060	9.9170	0.0050	0.0721	273.7866	0.20165E-02
13	420.00	1.3455	0.4135	3.5402	3.6924	0.0007	0.0274	264.5265	0.73243E-03
14	942.20	-48.2358	-9.9089	56.4833	59.0247	0.1805	-0.1621	340.9558	-0.12801E-01
15	944.80	-51.9508	-10.6695	61.2353	64.0099	0.2133	-0.1415	352.8238	-0.13943E-01
16	952.50	-59.9711	-12.2422	71.5235	74.8318	0.2958	-0.0620	388.0995	-0.16477E-01
17	955.00	-59.4958	-12.1341	71.0655	74.3692	0.2932	-0.0466	396.8063	-0.16414E-01
18	966.00	-57.8730	-11.7864	69.2257	72.4892	0.2832	0.0040	427.9057	-0.16215E-01
19	972.00	-55.5993	-11.2888	66.4964	69.6487	0.2633	0.0163	440.7551	-0.15675E-01
20	1000.00	-48.7881	-9.2578	54.1770	56.8169	0.1802	0.0448	490.9588	-0.13115E-01
21	1020.00	-36.4036	-7.3409	42.1628	44.2381	0.1103	0.0235	508.6528	-0.10290E-01
22	1120.00	-13.1385	-2.6102	12.9505	13.6044	0.0107	-0.0015	553.8414	-0.32229E-02
23	1200.00	-7.9974	-1.5698	6.4749	6.8046	0.0027	-0.0012	568.2815	-0.15923E-02

Table E.5.2-1 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_2=1.55$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	9.50	0.6535	-0.2040	0.6843	0.7196	0.0000	0.0000	592.9980	0.12568E-03
2	11.70	1.5143	-0.4656	1.5293	1.6082	0.0002	0.0002	592.9476	0.28288E-03
3	15.10	1.5286	-0.4552	1.3079	1.3754	0.0001	0.0001	592.2376	0.25147E-03
4	27.00	-0.0080	-0.1221	0.6281	0.6603	0.0000	-0.0002	579.6208	-0.10271E-03
5	38.00	-0.3774	-0.1720	1.1467	1.2048	0.0001	-0.0003	561.0578	-0.19705E-03
6	51.20	-0.8477	-0.1980	1.7155	1.8012	0.0002	-0.0002	535.0950	-0.30230E-03
7	60.00	-0.9519	-0.2513	1.8107	1.9002	0.0002	-0.0001	517.1707	-0.32536E-03
8	66.00	-1.0573	-0.2653	1.9087	2.0024	0.0002	0.0001	505.0300	-0.34760E-03
9	90.00	-1.2370	-0.3153	1.9856	2.0615	0.0002	0.0005	459.3904	-0.37972E-03
10	136.50	-1.1813	-0.3700	1.7074	1.7864	0.0002	0.0010	389.8853	-0.36169E-03
11	210.00	-0.4532	-0.5578	0.4116	0.4300	0.0000	0.0008	324.2186	-0.23016E-03
12	300.00	0.4109	-0.8000	-0.9610	-1.0029	-0.0001	-0.0001	286.2033	-0.83878E-04
13	420.00	1.0078	-0.9696	-0.7790	-0.8126	0.0000	-0.0007	268.3797	0.13652E-04
14	942.20	0.6677	-0.8079	1.5506	1.6173	0.0001	-0.0005	265.2798	0.44549E-04
15	944.80	0.8525	-0.8308	1.8080	1.8859	0.0002	-0.0007	268.6415	0.87939E-04
16	952.50	1.4693	-0.8929	2.6668	2.7827	0.0004	-0.0014	281.5828	0.22724E-03
17	955.00	1.8042	-0.9477	3.0442	3.1768	0.0005	-0.0017	286.6962	0.29325E-03
18	966.00	2.7643	-1.0174	4.0953	4.2766	0.0009	-0.0022	312.6558	0.47813E-03
19	972.00	2.9212	-0.9602	4.2386	4.4278	0.0010	-0.0021	327.7648	0.51067E-03
20	1000.00	2.7516	-0.6616	3.8877	4.0682	0.0009	-0.0016	394.5043	0.50304E-03
21	1020.00	2.3423	-0.5343	3.1991	3.3503	0.0006	-0.0011	434.2411	0.43254E-03
22	1120.00	0.9955	-0.3606	1.2013	1.2613	0.0001	-0.0003	533.1689	0.20092E-03
23	1200.00	0.2801	-0.1706	0.3888	0.4085	0.0000	-0.0001	558.8077	0.71152E-04

Table E.5.2-2 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_2=3.1$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P. STRS	K P. STRN	JH	J	TEMP.	DISP.
1	9.50	0.9161	-0.2952	0.8303	0.8732	0.0000	0.0001	592.9972	0.24143E-03
2	11.70	2.1433	-0.6852	1.7996	1.8925	0.0002	0.0003	592.9090	0.53286E-03
3	15.10	1.9346	-0.7062	1.2243	1.2874	0.0001	0.0001	591.9332	0.40290E-03
4	27.00	-1.1540	-0.2650	2.0066	2.1093	0.0003	-0.0009	578.4582	-0.45679E-03
5	38.00	-2.0358	-0.3012	2.9664	3.1166	0.0006	-0.0020	559.5916	-0.70616E-03
6	51.20	-2.9845	-0.2650	3.8802	4.0739	0.0009	-0.0035	533.4459	-0.94918E-03
7	60.00	-3.2172	-0.2835	4.0651	4.2660	0.0010	-0.0045	515.5080	-0.99940E-03
8	66.00	-3.4069	-0.2645	4.2089	4.4154	0.0011	-0.0051	503.3710	-1.0393E-02
9	90.00	-3.6789	-0.1712	4.2551	4.4586	0.0011	-0.0068	457.8844	-0.10671E-02
10	136.50	-3.4708	0.0432	3.6236	3.7913	0.0008	-0.0076	388.5914	-0.93854E-03
11	210.00	-2.2225	0.1118	1.9610	2.0483	0.0002	-0.0057	323.6272	-0.57104E-03
12	300.00	-0.8511	0.0129	-0.3372	-0.3519	0.0000	-0.0032	285.9476	-0.21375E-03
13	420.00	0.0674	-0.0843	-0.3384	-0.3530	0.0000	-0.0014	268.3045	0.14804E-04
14	942.20	0.6661	0.3207	2.8145	2.9357	0.0004	0.0110	265.3783	0.30804E-03
15	944.80	1.1285	0.2933	3.3039	3.4464	0.0006	0.0130	269.9239	0.42762E-03
16	952.50	2.5807	0.2019	4.8523	5.0633	0.0013	0.0181	283.3829	0.79915E-03
17	955.00	3.2386	0.1164	5.4731	5.7118	0.0017	0.0196	288.6476	0.95646E-03
18	966.00	5.0944	-0.0638	7.0811	7.3949	0.0028	0.0222	314.9448	0.13825E-02
19	972.00	5.4130	-0.0434	7.2573	7.5818	0.0030	0.0214	330.0628	0.14509E-02
20	1000.00	5.1531	0.1049	6.5674	6.8727	0.0025	0.0141	396.4770	0.13925E-02
21	1020.00	4.3600	0.1289	5.3096	5.5607	0.0017	0.0087	435.7552	0.11701E-02
22	1120.00	1.6403	-0.1403	1.8477	1.9399	0.0002	0.0037	533.5775	0.48714E-03
23	1200.00	0.5059	-0.0491	0.6193	0.6507	0.0000	0.0001	558.9938	0.18094E-03

Table E.5.3-1 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_3=0.7$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	9.50	0.1566	-0.0147	0.1416	0.1489	0.0000	0.0000	592.9984	0.17165E-04
2	11.70	0.4262	-0.0442	0.3633	0.3820	0.0000	0.0000	592.9812	0.44151E-04
3	15.10	0.7348	-0.0658	0.4973	0.5229	0.0000	0.0000	592.8561	0.62184E-04
4	27.00	1.7654	-0.2874	0.9923	1.0433	0.0001	0.0000	583.8288	0.12712E-03
5	38.00	2.8623	-0.6782	1.8337	1.9271	0.0002	0.0007	568.9949	0.22962E-03
6	51.20	3.7703	-1.0398	2.5537	2.6820	0.0004	0.0021	544.9304	0.31509E-03
7	60.00	4.1309	-1.1964	2.8591	3.0014	0.0005	0.0033	527.8030	0.34923E-03
8	66.00	4.2635	-1.2622	2.9702	3.1170	0.0005	0.0040	515.9110	0.36095E-03
9	90.00	4.1957	-1.2564	2.9160	3.0563	0.0005	0.0052	469.5841	0.35063E-03
10	136.50	3.1122	-0.9769	1.9604	2.0515	0.0002	0.0070	396.3652	0.24456E-03
11	210.00	1.5954	-0.4877	0.4067	0.4248	0.0000	0.0047	326.7471	0.11381E-03
12	300.00	0.7110	-0.2090	-0.5440	-0.5677	0.0000	0.0022	286.5638	0.45490E-04
13	420.00	0.3006	-0.0855	-0.3886	-0.4053	0.0000	0.0008	268.0447	0.16178E-04
14	942.20	-1.5443	0.1849	1.8357	1.9145	0.0002	-0.0074	262.0204	-0.95099E-04
15	944.80	-1.8667	0.2622	2.0485	2.1365	0.0002	-0.0086	264.5535	-0.11566E-03
16	952.50	-2.9167	0.5534	2.6770	2.7929	0.0004	-0.0123	274.7665	-0.18769E-03
17	955.00	-3.2335	0.6568	2.8663	2.9306	0.0005	-0.0133	278.9469	-0.21018E-03
18	966.00	-4.4484	1.1244	3.5962	3.7542	0.0007	-0.0159	301.3399	-0.30862E-03
19	972.00	-4.9260	1.3455	3.9105	4.0838	0.0009	-0.0161	315.2039	-0.35931E-03
20	1000.00	-5.4335	1.6932	4.2583	4.4545	0.0010	-0.0128	381.2086	-0.43004E-03
21	1020.00	-4.5832	1.4856	3.6269	3.7976	0.0008	-0.0086	423.3104	-0.37955E-03
22	1120.00	-0.5412	0.1229	0.5673	0.5956	0.0000	-0.0006	531.8736	-0.62508E-04
23	1200.00	0.1124	-0.0930	0.1932	0.2030	0.0000	-0.0001	558.8804	-0.75899E-05

Table E.5.3-2 Fracture Mechanics Parameters of Outlet Nozzle, crack depth $a_3=1.4$ mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	9.50	0.2112	-0.0588	0.1999	0.2102	0.0000	0.0000	592.9983	0.40616E-04
2	11.70	0.6281	-0.1312	0.4783	0.5030	0.0000	0.0000	592.9785	0.98176E-04
3	15.10	1.3417	-0.1569	0.6628	0.6970	0.0000	0.0000	592.8249	0.14292E-03
4	27.00	3.1557	-0.4333	1.4116	1.4840	0.0001	-0.0002	583.6407	0.32327E-03
5	38.00	4.9561	-0.9228	2.6051	2.7377	0.0004	0.0001	568.1314	0.57927E-03
6	51.20	6.4478	-1.3632	3.6389	3.8217	0.0008	0.0008	544.6143	0.79369E-03
7	60.00	7.0284	-1.5547	4.0787	4.2816	0.0010	0.0013	527.4746	0.87863E-03
8	66.00	7.2452	-1.6326	4.2423	4.4519	0.0011	0.0016	515.5789	0.90844E-03
9	90.00	7.1140	-1.6632	4.2015	4.4037	0.0011	0.0022	469.2721	0.88612E-03
10	136.50	5.2946	-1.2502	2.9234	3.0592	0.0005	0.0020	396.1351	0.62679E-03
11	210.00	2.7297	-0.6298	1.0085	1.0535	0.0001	0.0010	326.6237	0.29774E-03
12	300.00	1.2024	-0.2723	-0.4932	-0.5147	0.0000	0.0003	286.5119	0.11893E-03
13	420.00	0.4710	-0.1089	-0.2887	-0.3012	0.0000	-0.0001	268.0304	0.38979E-04
14	942.20	-2.8928	0.3231	2.3635	2.4650	0.0003	-0.0035	262.1867	-0.24502E-03
15	944.80	-3.4540	0.4232	2.6487	2.7626	0.0004	-0.0038	264.7535	-0.29873E-03
16	952.50	-5.2773	0.7902	3.5481	3.7016	0.0007	-0.0047	275.0675	-0.48478E-03
17	955.00	-5.8221	0.9125	3.8283	3.9944	0.0008	-0.0048	279.2793	-0.54350E-03
18	966.00	-7.7575	1.4758	4.9563	5.1742	0.0014	-0.0044	301.7667	-0.79439E-03
19	972.00	-8.4727	1.7416	5.4504	5.6920	0.0017	-0.0038	315.6486	-0.90361E-03
20	1000.00	-9.1650	2.1557	6.0480	6.3267	0.0021	-0.0021	381.6227	-0.10887E-02
21	1020.00	-7.6784	1.8930	5.1830	5.4269	0.0016	-0.0012	423.6405	-0.95925E-03
22	1120.00	-0.9753	0.1953	0.8289	0.8702	0.0000	-0.0003	531.9555	-0.16768E-03
23	1200.00	0.1528	-0.0815	0.2563	0.2692	0.0000	-0.0001	558.9138	-0.22880E-04

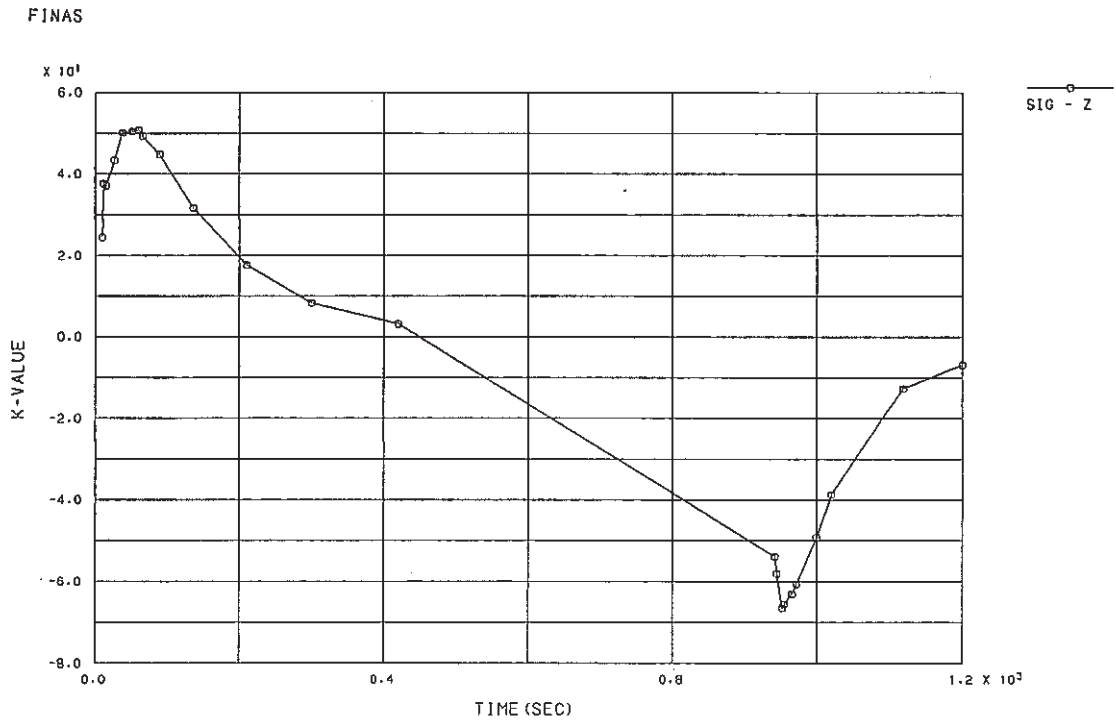


Fig. E.5.1-1 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_1=1.45$ mm

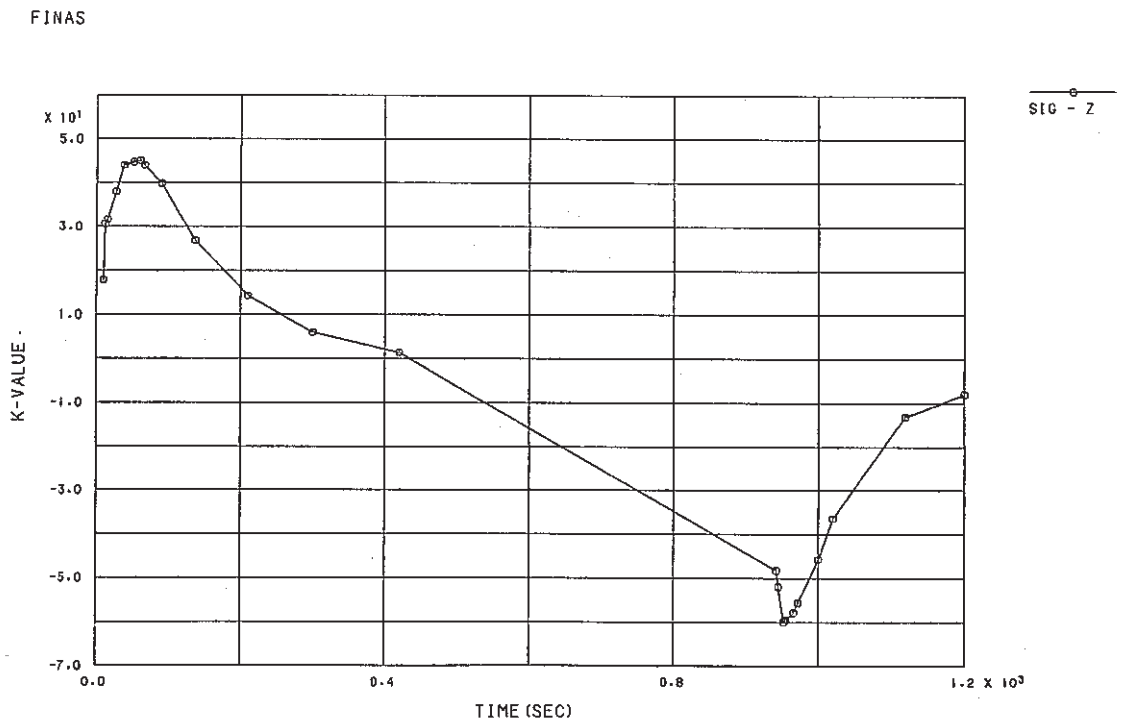


Fig. E.5.1-2 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_1=2.9$ mm

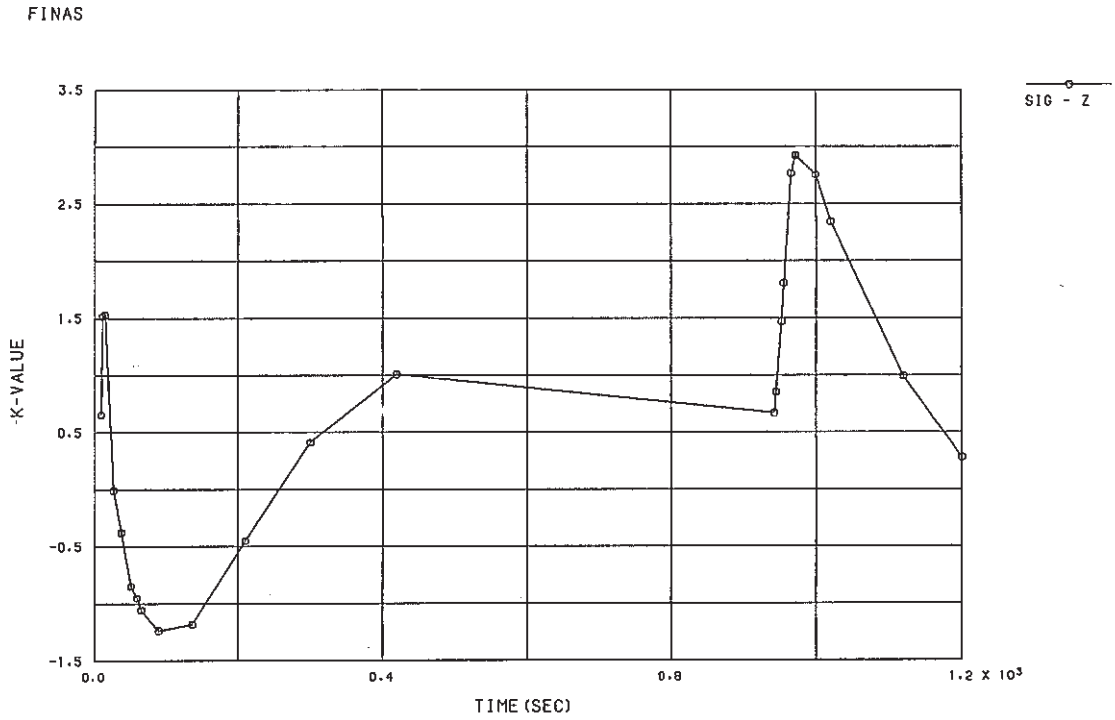


Fig. E.5.2-1 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_2=1.55$ mm

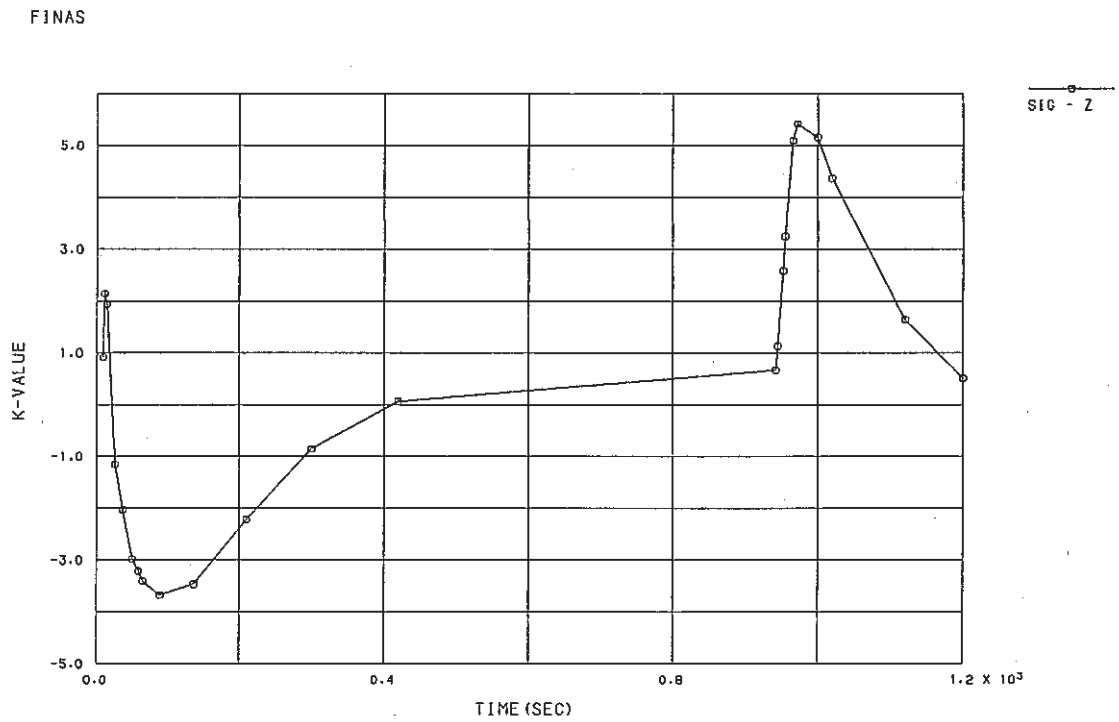


Fig. E.5.2-2 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_2=3.1$ mm

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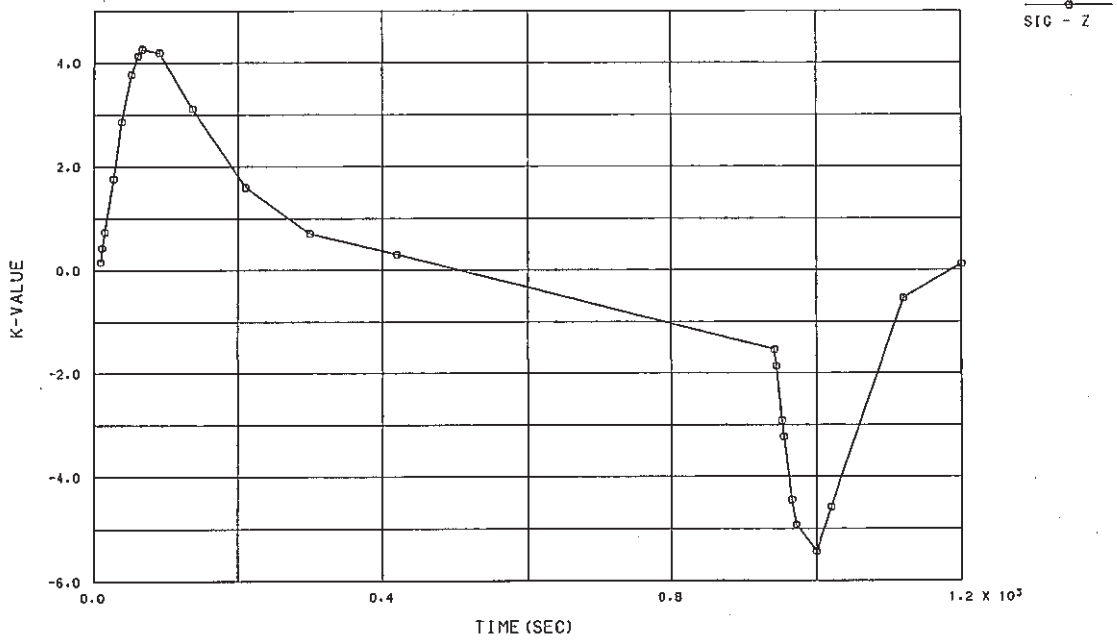


Fig. E.5.3-1 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_2=0.7$ mm

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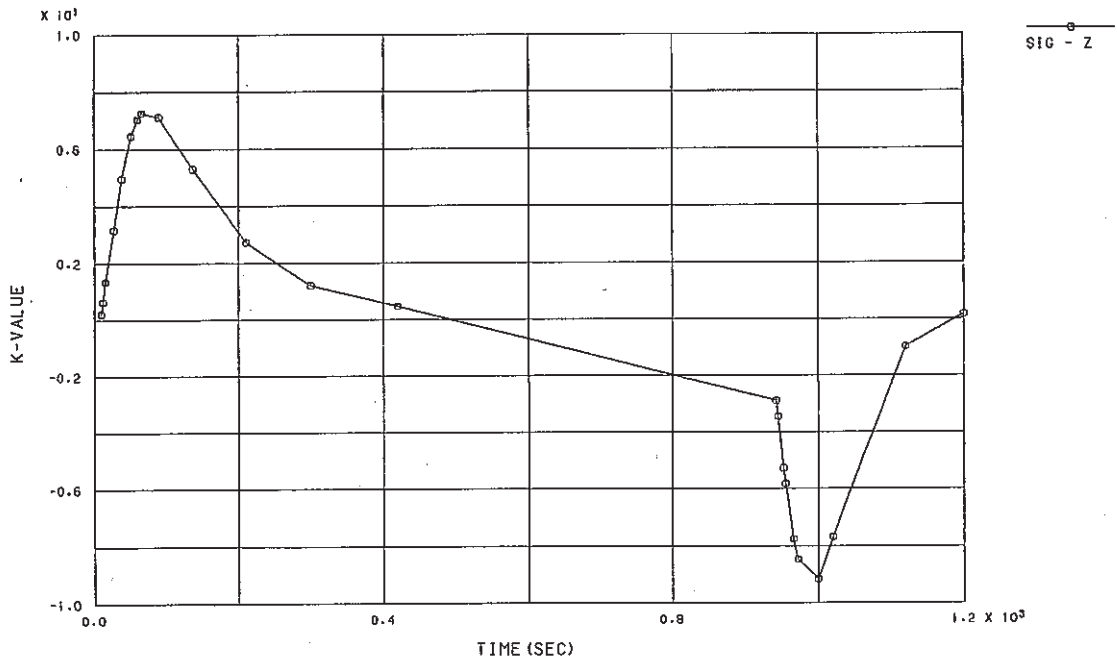


Fig. E.5.3-2 History of Stress Intensity Factor for Outlet Nozzle, crack depth $a_3=1.4$ mm

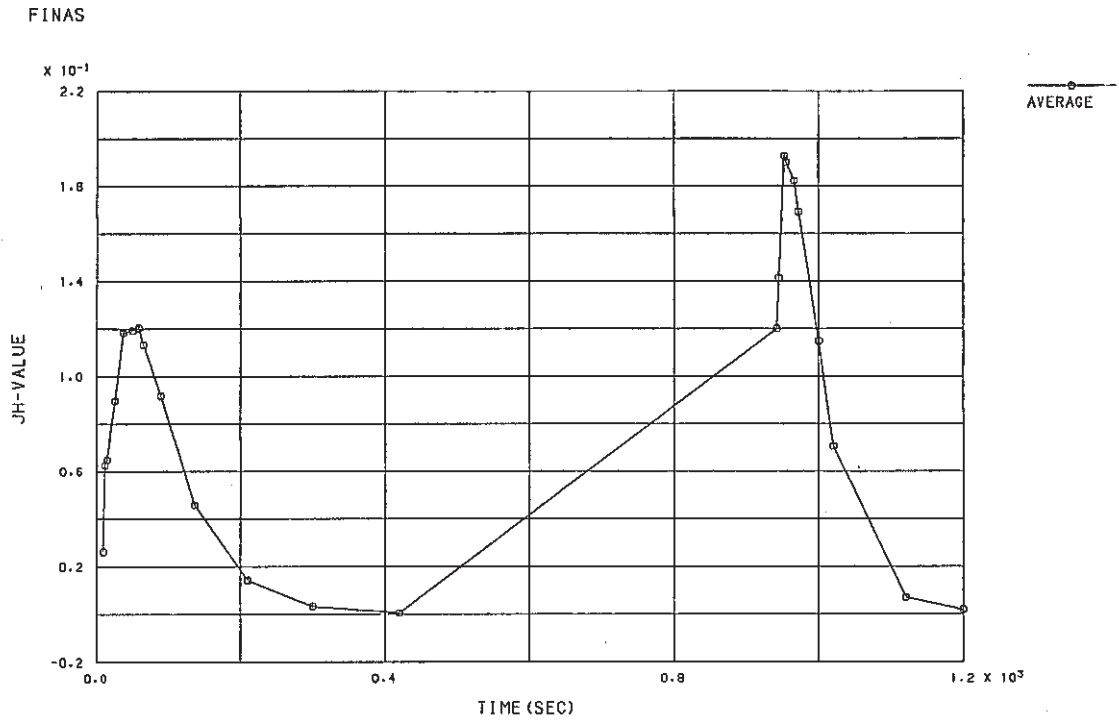


Fig. E.5.4-1 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_1=1.45$ mm

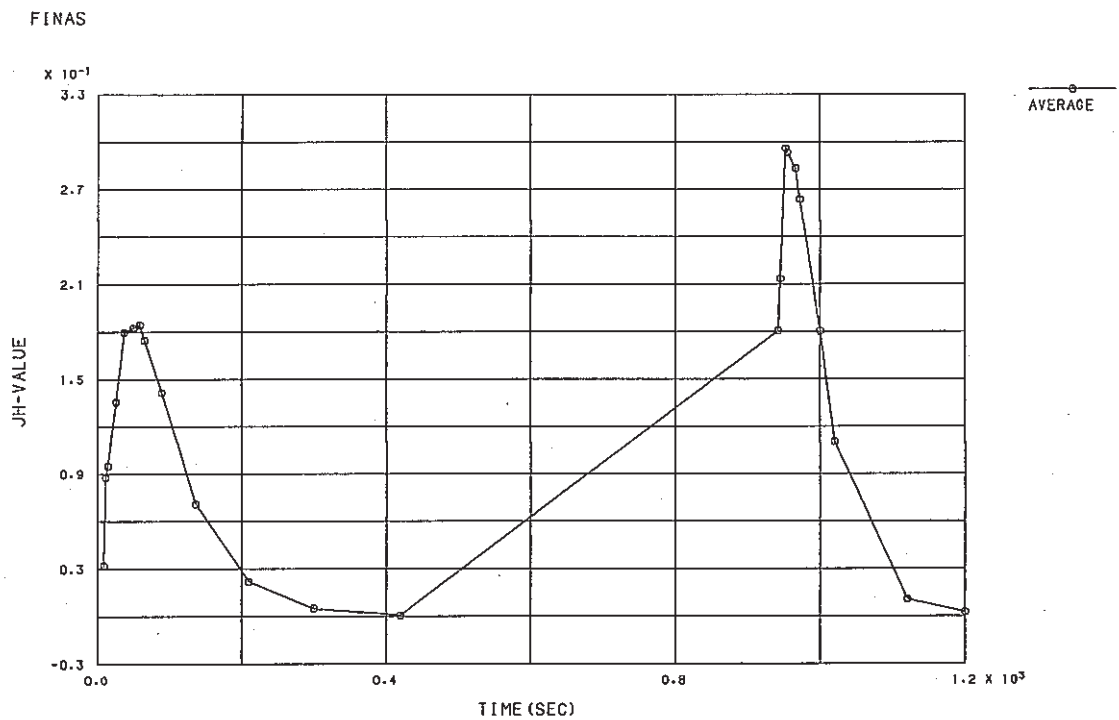


Fig. E.5.4-2 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_1=2.9$ mm

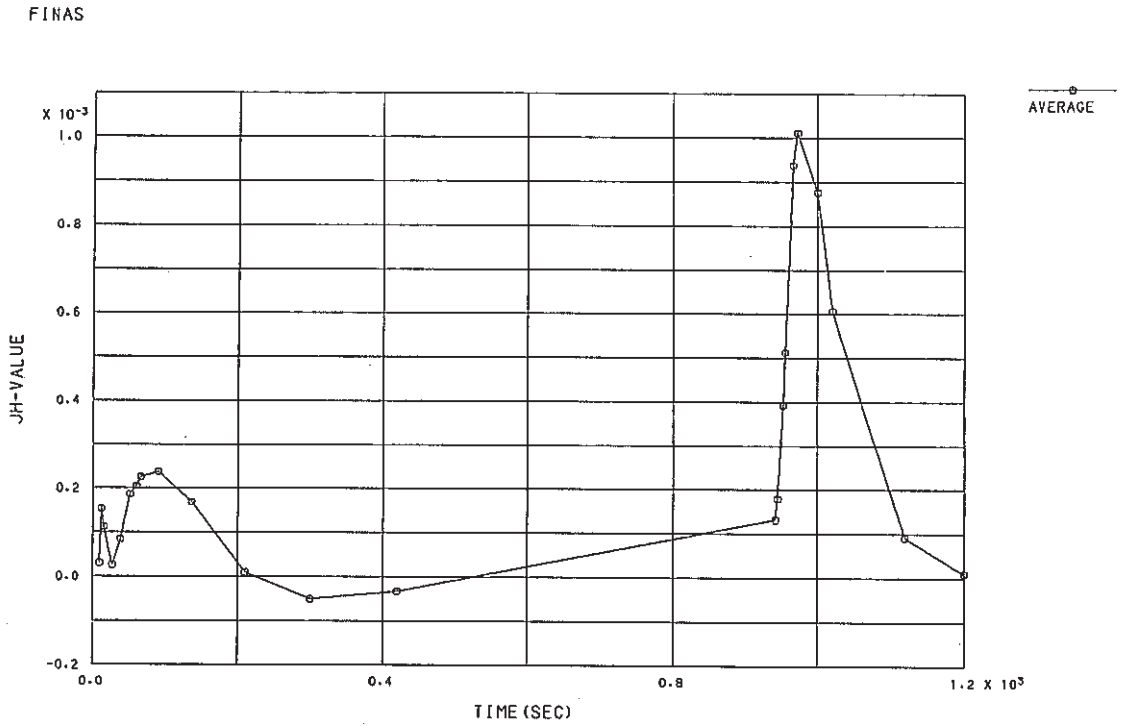


Fig. E.5.5-1 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_2=1.55$ mm

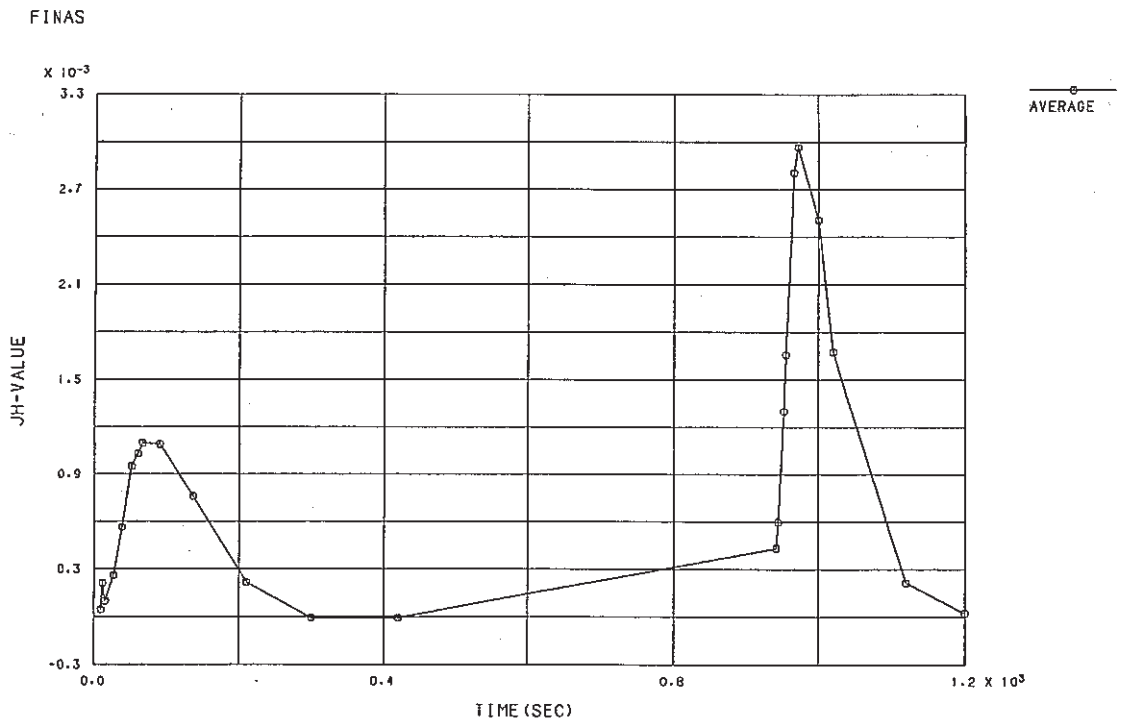


Fig. E.5.5-2 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_2=3.2$ mm

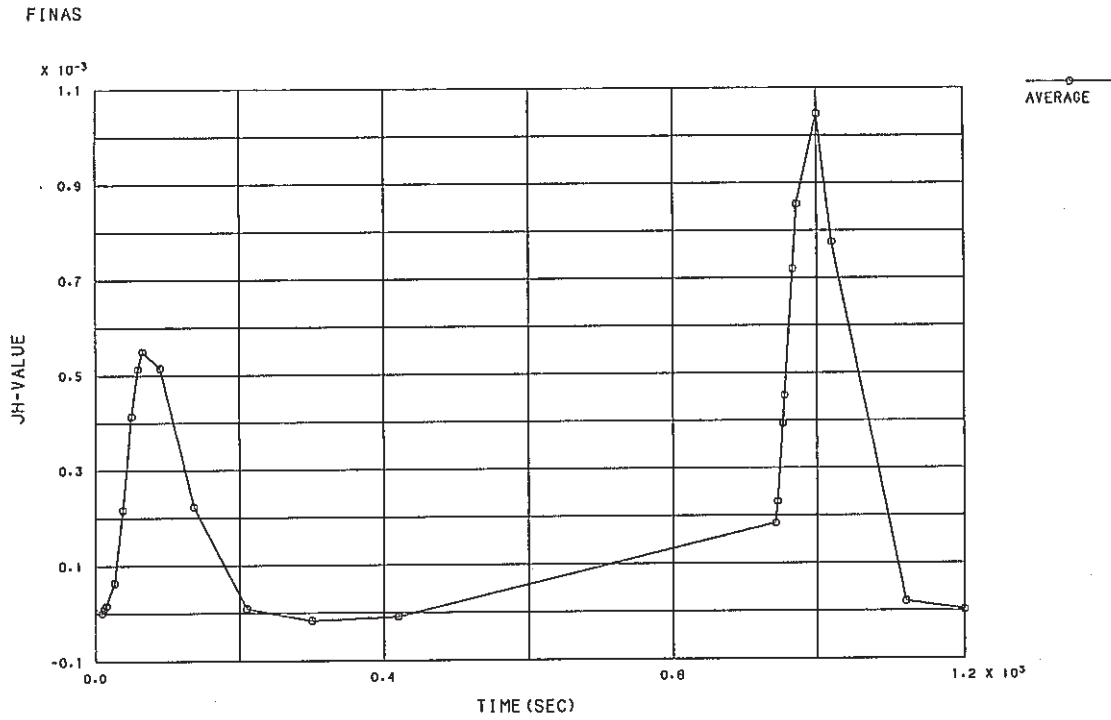


Fig. E.5.6-1 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_2=0.7$ mm

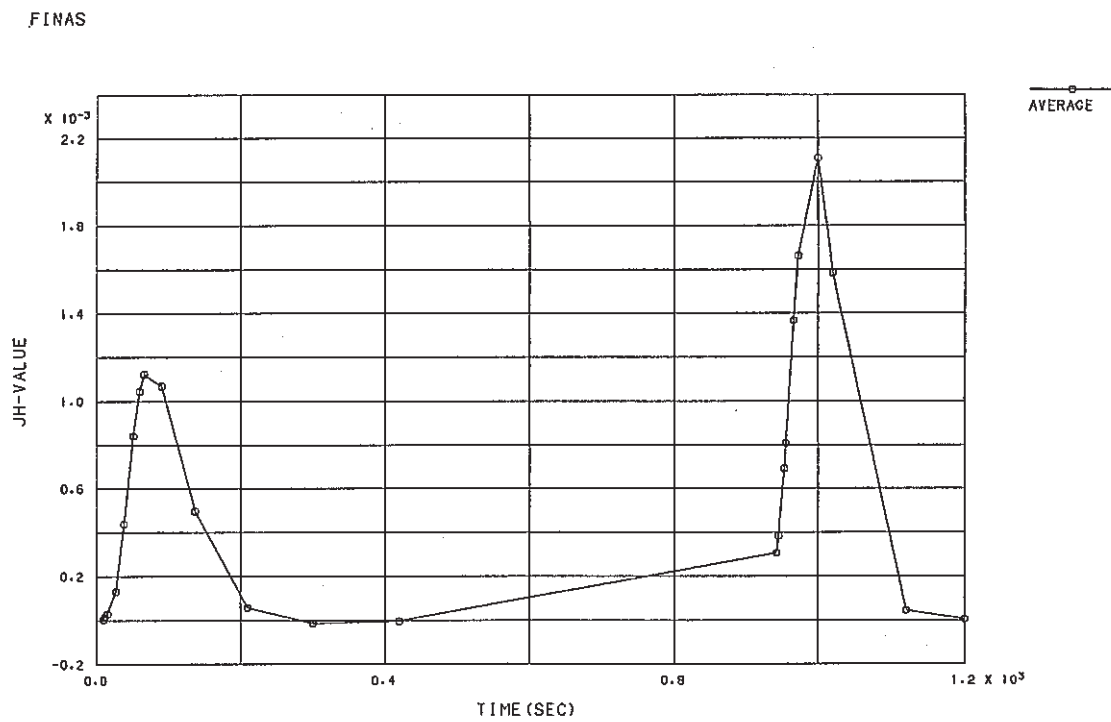


Fig. E.5.6-2 History of \hat{J} -Integral for Outlet Nozzle, crack depth $a_3=1.4$ mm

Table E.6-1 Fracture Mechanics Parameters of Stud Bolt, crack depth a=1 mm

*** CRACK DEPTH = 1.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	120.00	113.9000	25.5300	107.6030	112.6831	0.6856	0.5472	431.2000	0.15610E-01
2	150.00	116.3000	25.9700	109.0684	114.2176	0.7044	0.5365	405.8000	0.15690E-01
3	165.00	114.7000	25.5700	107.3123	112.3786	0.6819	0.5052	395.6000	0.15400E-01
4	180.00	112.1000	25.2000	105.4229	110.4001	0.6581	0.4736	385.9000	0.15110E-01
5	240.00	96.5700	21.6800	90.9862	95.2818	0.4902	0.3013	357.2000	0.13030E-01
6	300.00	78.9200	17.7300	74.9012	78.4374	0.3322	0.1592	337.5000	0.10780E-01
7	720.00	14.8500	3.4070	16.7686	17.5602	0.0167	-0.0323	272.4000	0.27890E-02
8	965.00	-124.6000	-28.9800	104.7399	109.6848	0.6496	0.9090	379.2000	-1.13560E-01
9	980.00	-137.1000	-31.4300	116.4447	121.9422	0.8029	1.0730	402.9000	-1.15180E-01
10	1000.00	-140.9000	-31.8500	119.9809	125.6450	0.8524	1.1110	423.3000	-1.15730E-01
11	1020.00	-138.2000	-31.0800	117.9506	123.5191	0.8238	1.0610	437.8000	-1.15490E-01
12	1056.00	-129.0000	-28.8900	110.1929	115.3952	0.7190	0.9155	457.1000	-1.14490E-01
13	1092.00	-117.0000	-26.1800	99.6925	104.3991	0.5885	0.7481	471.4000	-1.13070E-01
14	1200.00	-89.4700	-19.9900	75.2723	78.8260	0.3355	0.4194	508.8000	-9.97920E-02

Table E.6-2 Fracture Mechanics Parameters of Stud Bolt, crack depth a=7 mm

*** CRACK DEPTH = 7.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	120.00	132.1000	4.6000	135.9245	142.3417	1.0940	0.7139	471.9000	0.36680E-01
2	150.00	137.0000	4.0330	139.9042	146.5093	1.1590	0.7221	445.9000	0.37310E-01
3	165.00	135.8000	3.7910	138.4481	144.9844	1.1350	0.6869	434.8000	0.36750E-01
4	180.00	134.2000	3.6410	136.3587	142.7963	1.1010	0.6474	424.4000	0.36090E-01
5	240.00	118.8000	2.7520	119.7269	125.3794	0.8488	0.4228	390.0000	0.31390E-01
6	300.00	98.9100	2.1220	99.0807	103.7585	0.5813	0.2196	364.7000	0.25980E-01
7	720.00	23.7400	0.3343	24.1134	25.2518	0.0344	-0.0764	279.2000	0.66590E-02
8	965.00	-126.1000	-9.3790	116.8501	122.3667	0.8085	0.7886	333.2000	-0.29360E-01
9	980.00	-148.5000	-7.9700	139.1781	145.7488	1.1470	1.1490	357.5000	-0.34650E-01
10	1000.00	-158.1000	-6.3920	149.9827	157.0636	1.3320	1.3520	380.6000	-0.37120E-01
11	1020.00	-157.4000	-5.4740	150.3201	157.4169	1.3380	1.3630	397.6000	-0.37120E-01
12	1056.00	-147.9000	-4.4950	142.0604	148.7672	1.1950	1.2140	421.2000	-0.35070E-01
13	1092.00	-133.0000	-4.0370	128.7593	134.8361	0.9817	0.9956	439.6000	-0.31810E-01
14	1200.00	-89.0500	-3.1660	95.6905	100.2082	0.5422	0.5342	484.8000	-0.23780E-01

Table E.6-3 Fracture Mechanics Parameters of Stud Bolt, crack depth a=10 mm

*** CRACK DEPTH = 10.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	120.00	112.7000	3.0660	115.0660	120.4984	0.7840	0.5119	487.9000	0.31750E-01
2	150.00	118.0000	2.4570	119.5363	125.1798	0.8461	0.5271	462.2000	0.32570E-01
3	165.00	117.4000	2.2170	118.6287	124.2293	0.8333	0.5047	450.8000	0.32180E-01
4	180.00	116.0000	2.0840	117.0306	122.5558	0.8110	0.4771	440.2000	0.31640E-01
5	240.00	103.5000	1.4110	103.6947	108.5902	0.6367	0.3183	403.7000	0.27710E-01
6	300.00	86.3800	1.0240	86.2604	90.3328	0.4406	0.1677	376.1000	0.22720E-01
7	720.00	20.9400	0.2395	21.9272	22.9624	0.0285	-0.0622	282.1000	0.59450E-02
8	965.00	-98.5200	-7.8520	90.2595	94.5207	0.4824	0.4306	317.3000	-0.23550E-01
9	980.00	-122.0000	-6.2470	112.7607	118.0843	0.7529	0.7279	339.9000	-0.29020E-01
10	1000.00	-134.2000	-4.4680	125.4307	131.3524	0.9316	0.9304	363.0000	-0.31980E-01
11	1020.00	-135.4000	-3.4650	127.5072	133.5259	0.9627	0.9797	380.7000	-0.32400E-01
12	1056.00	-128.3000	-2.5490	121.6162	127.3579	0.8758	0.8833	405.7000	-0.30890E-01
13	1092.00	-116.3000	-2.1000	110.3537	115.5636	0.7211	0.7268	425.7000	-0.28090E-01
14	1200.00	-84.3100	-1.7710	81.2082	85.0421	0.3905	0.3818	474.5000	-0.20900E-01

Table E.6-4 Fracture Mechanics Parameters of Stud Bolt, crack depth a=13 mm

*** CRACK DEPTH = 13.0 ***

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	120.00	89.2300	10.8100	85.2462	89.2707	0.4303	0.3359	501.9000	0.25480E-01
2	150.00	94.1400	10.7300	89.3568	93.5755	0.4728	0.3641	476.6000	0.26370E-01
3	165.00	93.9900	10.4900	88.9970	93.1987	0.4690	0.3581	465.1000	0.26140E-01
4	180.00	93.1000	10.2800	87.9376	92.0892	0.4579	0.3469	454.2000	0.25740E-01
5	240.00	83.8300	8.8460	78.5549	82.2636	0.3654	0.2639	415.2000	0.22720E-01
6	300.00	70.5000	7.2850	65.7392	68.8428	0.2559	0.1714	386.5000	0.18900E-01
7	720.00	18.1500	1.8930	17.5798	18.4098	0.0183	-0.0217	284.7000	0.49970E-02
8	965.00	-69.8600	-13.5400	59.9199	62.7487	0.2126	0.0189	304.9000	-0.17120E-01
9	980.00	-91.0800	-14.1000	79.2931	83.0367	0.3723	0.2020	325.1000	-0.22240E-01
10	1000.00	-103.9000	-13.5500	91.6244	95.9501	0.4971	0.3640	347.5000	-0.25390E-01
11	1020.00	-106.7000	-12.7600	94.7238	99.1958	0.5313	0.4238	365.4000	-0.26140E-01
12	1056.00	-102.2000	-11.4300	91.2827	95.5923	0.4934	0.4098	391.4000	-0.25180E-01
13	1092.00	-92.6300	-10.1700	83.0180	86.9374	0.4081	0.3402	412.9000	-0.22940E-01
14	1200.00	-66.3000	-7.5550	60.4111	63.2631	0.2161	0.1724	465.1000	-0.16960E-01

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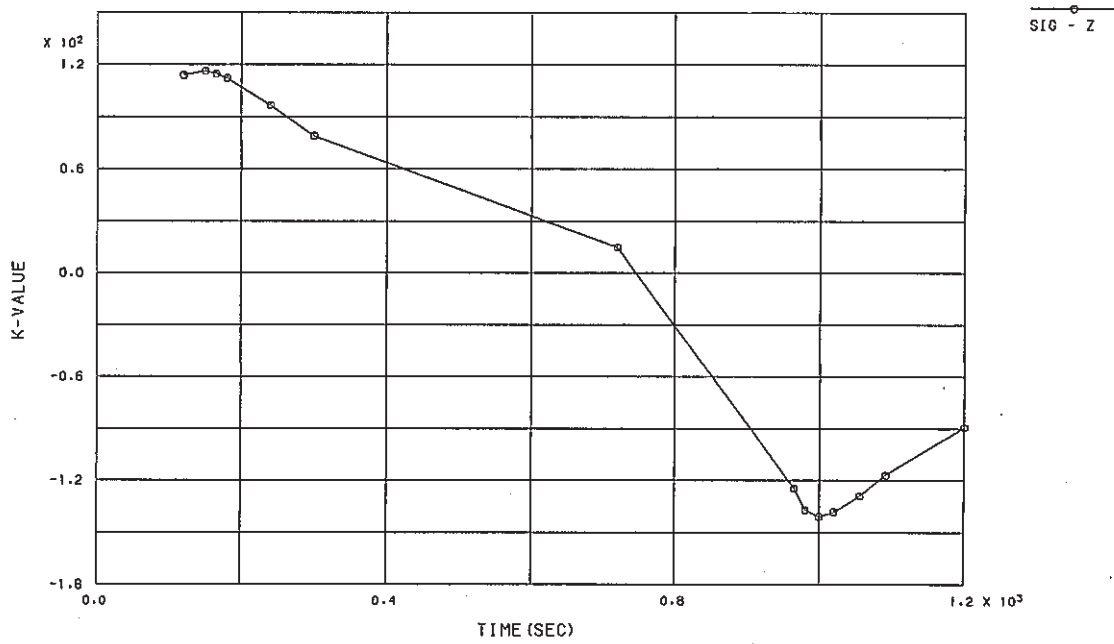


Fig. E.6.1-1 History of Stress Intensity Factor for Stud Bolt, crack depth a=1 mm

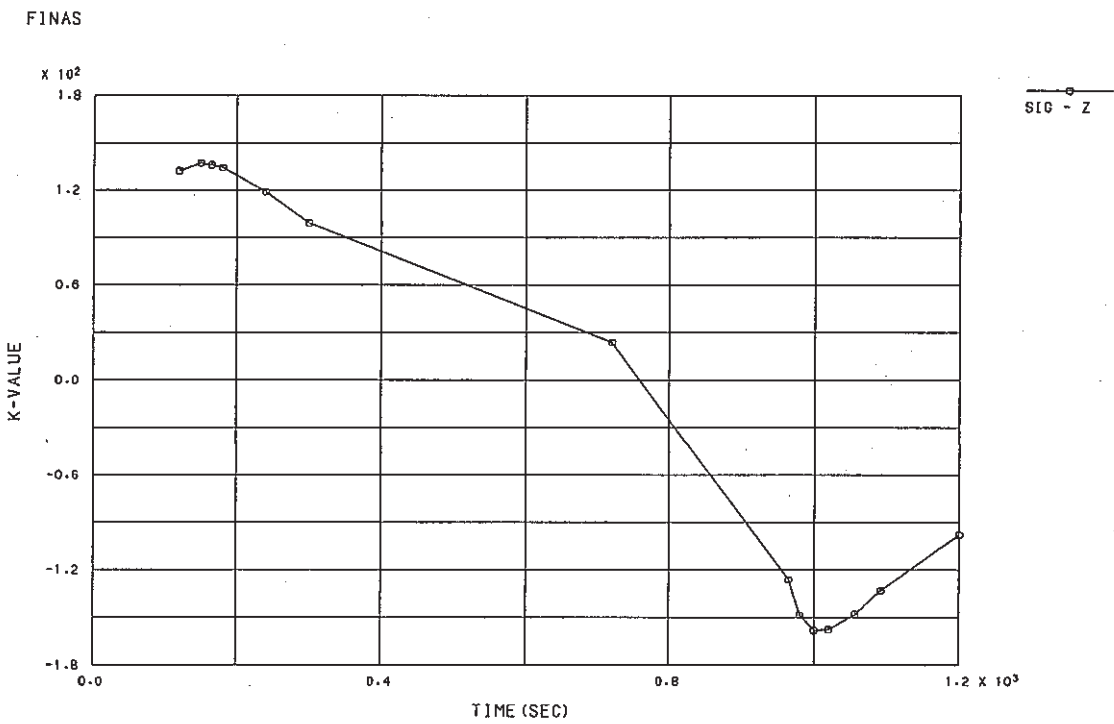


Fig. E.6.1-2 History of Stress Intensity Factor for Stud Bolt, crack depth a=7 mm

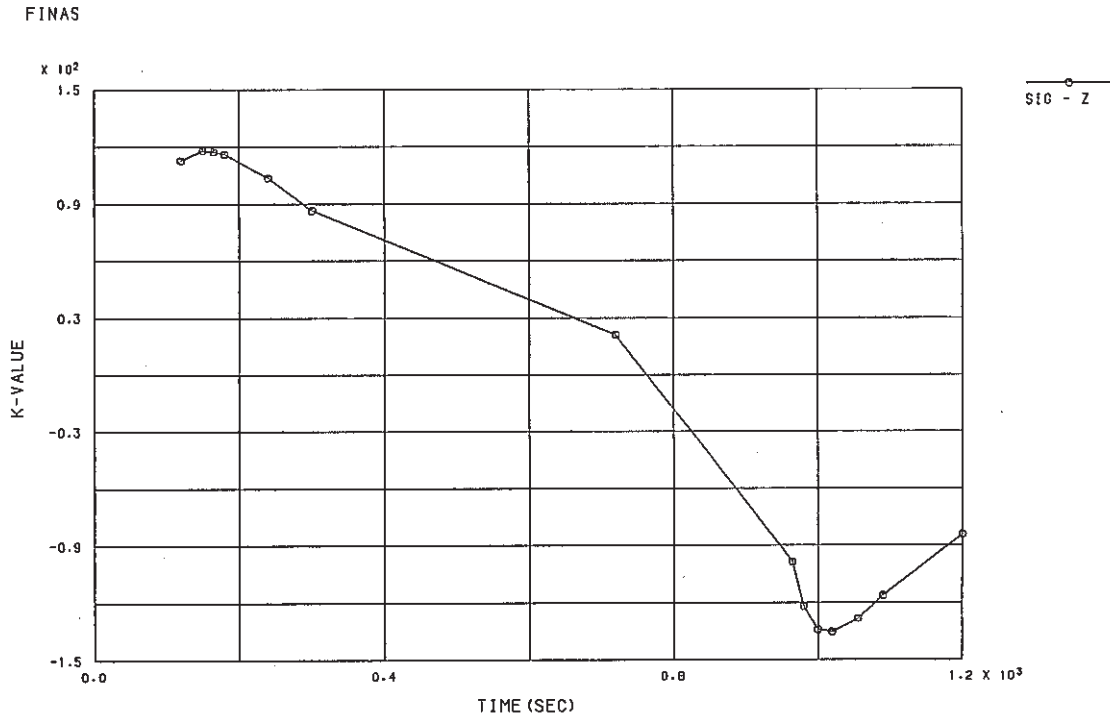


Fig. E.6.1-3 History of Stress Intensity Factor for Stud Bolt, crack depth a=10 mm

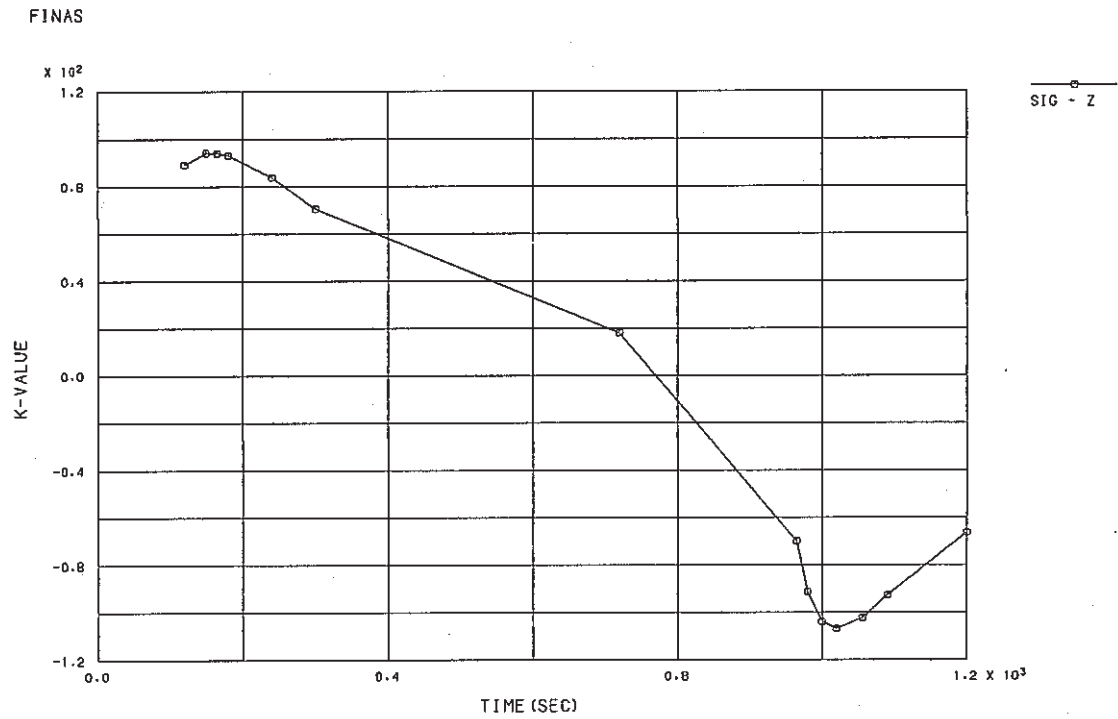


Fig. E.6.1-4 History of Stress Intensity Factor for Stud Bolt, crack depth a=13 mm

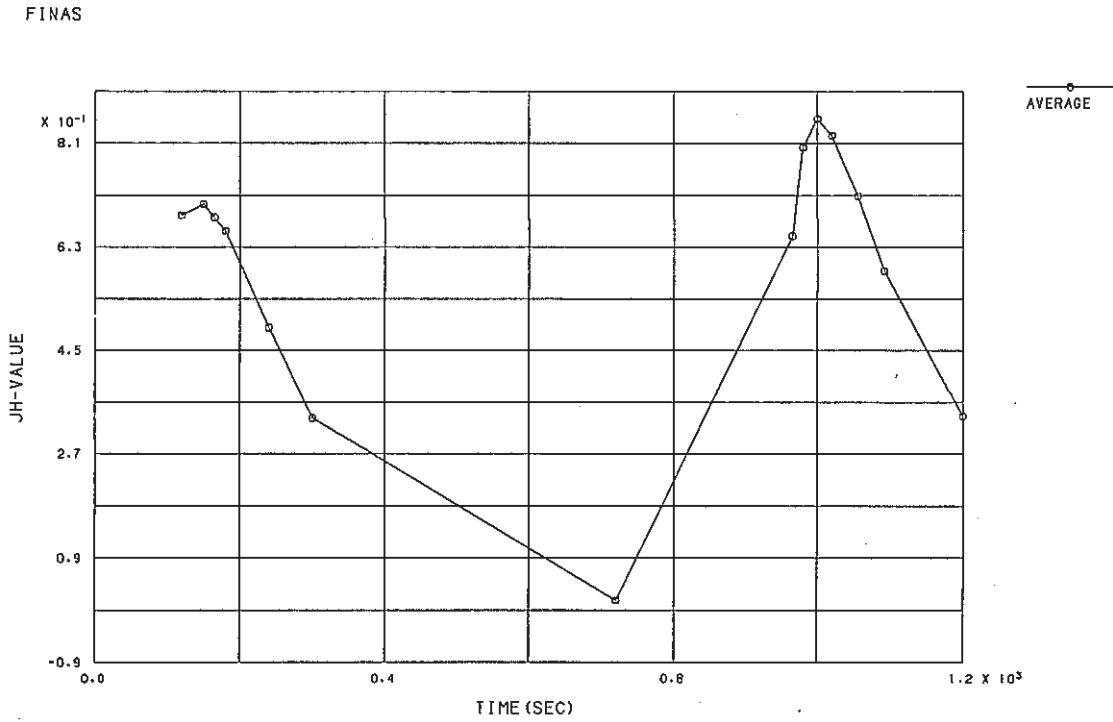


Fig. E.6.2-1 History of \hat{J} -Integral for Stud Bolt, crack depth $a=1$ mm

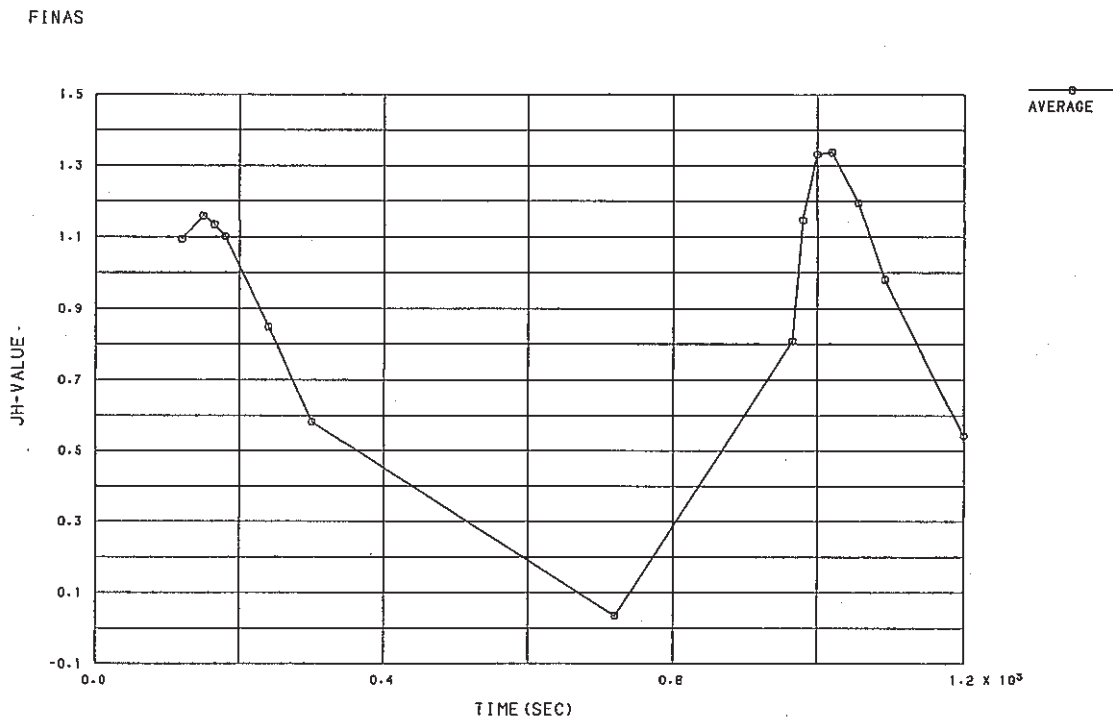


Fig. E.6.2-2 History of \hat{J} -Integral for Stud Bolt, crack depth $a=7$ mm

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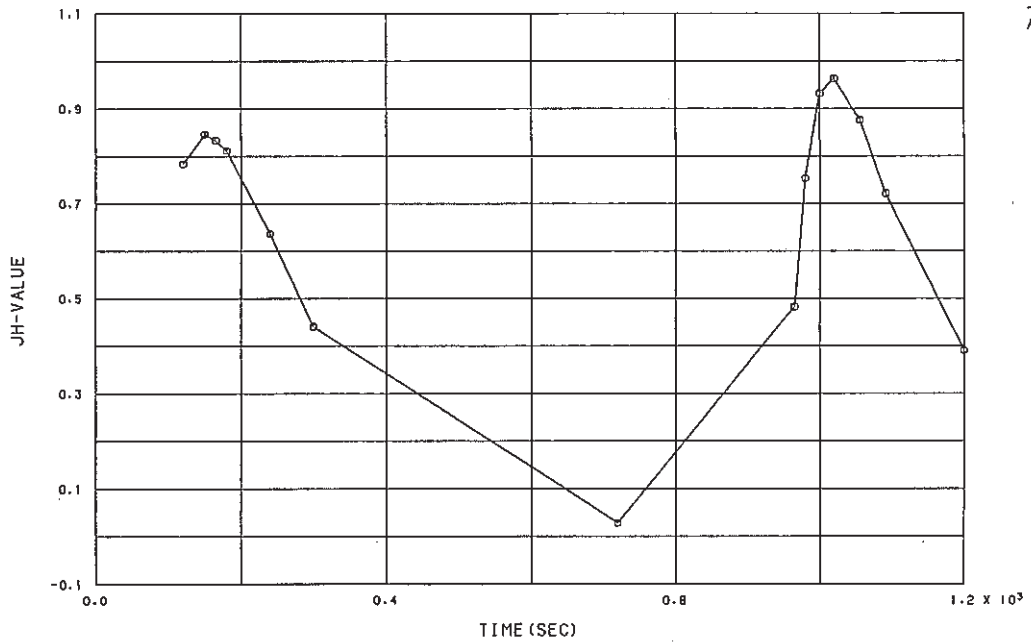


Fig. E.6.2-3 History of \hat{J} -Integral for Stud Bolt, crack depth $a=10$ mm

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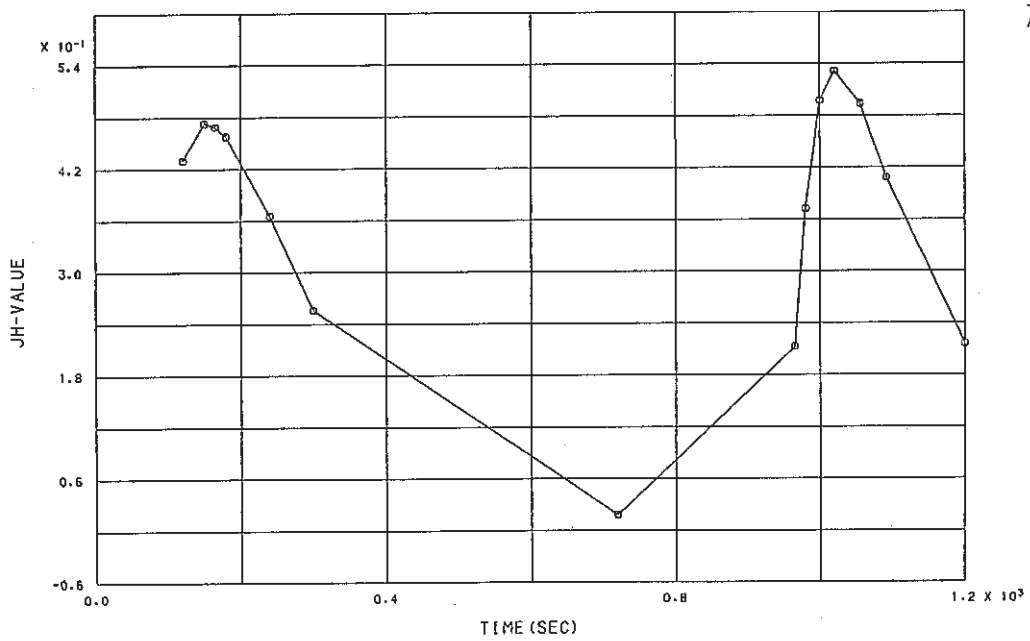


Fig. E.6.2-4 History of \hat{J} -Integral for Stud Bolt, crack depth $a=13$ mm

Table E.7.1-1 Fracture Mechanics Parameters at Cold Shock
of Instrumental Nozzle
(crack radius r=9.6 mm)

STEP = 2
TIME = 150.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K		JH	J	TEMP.	DISP.
				P.STRS	P.STRN				
A	20.000	70.2954	2.1977	67.3911	70.5610	0.2676	0.2027	422.6805	0.55713E-02
B	30.000	83.7927	8.9122	82.6481	86.5356	0.4024	0.1338	421.8362	0.10376E-01
C	40.000	89.9657	12.9176	88.8474	93.0265	0.4651	0.1699	419.1572	0.11141E-01
D	50.000	92.3843	16.1220	91.2848	95.5786	0.4909	0.1761	414.8073	0.11407E-01
E	60.000	90.6955	18.5719	89.4568	93.6646	0.4715	0.1457	408.7832	0.11122E-01
F	70.000	78.0726	14.9733	74.5841	78.0923	0.3277	0.2412	401.8867	0.60977E-02

Table E.7.1-2 Fracture Mechanics Parameters at Hot Shock
of Instrumental Nozzle
(crack radius, r=9.6 mm)

STEP = 6
TIME = 1000.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K		JH	J	TEMP.	DISP.
				P.STRS	P.STRN				
A	20.000	-82.8769	-2.7668	73.7144	77.1480	0.3160	0.3629	400.2505	-.55454E-02
B	30.000	-98.3351	-10.5182	89.1614	93.3146	0.4623	0.7330	401.1197	-.10342E-01
C	40.000	-106.1376	-15.3546	96.5691	101.0673	0.5423	0.8335	404.0058	-.11117E-01
D	50.000	-109.9963	-19.3183	100.1791	104.8455	0.5836	0.8898	408.7390	-.11414E-01
E	60.000	-108.9119	-22.5142	99.2841	103.9089	0.5732	0.8816	415.3059	-.11171E-01
F	70.000	-95.4282	-18.4519	84.9739	88.9320	0.4199	0.4987	422.7964	-.61405E-02

Table E.7.2-1 Fracture Mechanics Parameters at Cold Shock
of Instrumental Nozzle
(crack radius $r=12.8$ mm)

STEP TIME = 2
= 150.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K		JH	J	TEMP.	DISP.
				P.STRS	P.STRN				
A	10.000	94.9628	2.7513	90.7323	95.0269	0.4892	0.4646	437.1773	0.77618E-02
B	20.000	99.5143	7.9547	98.2419	102.8921	0.5735	0.2666	438.3294	0.15240E-01
C	30.000	102.6330	12.0139	100.7547	105.5238	0.6032	0.2793	437.2572	0.15607E-01
D	40.000	106.9172	16.4357	104.8285	109.7904	0.6530	0.3010	433.7912	0.16168E-01
E	50.000	112.7056	20.8763	110.6911	115.9304	0.7281	0.3352	428.0712	0.16942E-01
F	60.000	119.7206	25.2175	118.0115	123.5974	0.8276	0.3811	420.0411	0.17881E-01
G	70.000	125.7316	28.9526	124.3267	130.2116	0.9185	0.4200	410.7441	0.18710E-01
H	80.000	125.3038	30.3089	118.5719	124.1843	0.8355	0.8023	399.2559	0.99232E-02

Table E.7.2-2 Fracture Mechanics Parameters at Hot Shock
of Instrumental Nozzle
(crack radius, $r=12.8$ mm)

STEP TIME = 6
= 1000.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K		JH	J	TEMP.	DISP.
				P.STRS	P.STRN				
A	10.000	-108.1301	-3.2666	97.4624	101.9613	0.5483	0.6137	384.6187	-.76452E-02
B	20.000	-112.7466	-9.0828	103.7813	108.5719	0.6217	0.9863	383.1437	-.15046E-01
C	30.000	-116.4489	-13.7471	107.0405	111.9815	0.6514	1.0401	384.1469	-.15431E-01
D	40.000	-122.1977	-18.9644	112.4570	117.6481	0.7300	1.1314	387.8399	-.16042E-01
E	50.000	-130.3448	-24.4104	120.1813	125.7290	0.8338	1.2646	394.0991	-.16894E-01
F	60.000	-140.9122	-30.1173	129.9619	135.9610	0.9750	1.4361	402.9461	-.17923E-01
G	70.000	-150.6576	-35.1814	138.4929	144.8858	1.1072	1.5982	413.1788	-.18848E-01
H	80.000	-153.7518	-37.7733	135.3513	141.5992	1.0575	1.2352	425.7259	-.10012E-01

Table E.7.3-1 Fracture Mechanics Parameters at Cold Shock
of Instrumental Nozzle
(crack radius r=16.0 mm)

STEP = 2
TIME = 150.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
A	2.500	86.0905	-2.5207	85.8757	89.9595	0.4411	0.4204	447.9711	0.74073E-02
B	10.000	89.7914	4.0163	88.9164	93.1448	0.4728	0.2385	451.0571	0.14027E-01
C	20.000	88.9751	7.4256	87.0139	91.1519	0.4528	0.2165	452.6312	0.13798E-01
D	30.000	91.3114	11.2169	88.8614	93.0872	0.4723	0.2249	451.4773	0.14050E-01
E	40.000	97.2885	15.5930	94.7455	99.2511	0.5369	0.2583	447.3842	0.14859E-01
F	50.000	106.7003	20.5440	104.2957	109.2555	0.6506	0.3186	440.4621	0.16178E-01
G	60.000	119.2375	26.1073	117.1291	122.6992	0.8205	0.4103	430.5331	0.17959E-01
H	70.000	132.7245	31.4653	131.1285	137.3643	1.0284	0.5258	418.8581	0.19902E-01
I	80.000	147.3846	37.1351	146.4363	153.4001	1.2825	0.6868	404.1631	0.22099E-01
J	87.500	144.2563	36.6332	144.4023	151.2693	1.2471	1.2272	391.8098	0.11947E-01

Table E.7.3-2 Fracture Mechanics Parameters at Hot Shock
of Instrumental Nozzle
(crack radius, r=16.0 mm)

STEP = 6
TIME = 1000.000

POSI.	THETA	K-1 SIG-Y	K-2 TAU-XY	JH --> K P.STRS	P.STRN	JH	J	TEMP.	DISP.
A	2.500	-96.0425	2.5328	92.5573	96.8015	0.4920	0.5331	373.2517	-.72217E-02
B	10.000	-98.5072	-4.4533	92.2688	96.4998	0.4889	0.8040	369.5208	-.13637E-01
C	20.000	-96.9275	-8.1890	89.6170	93.7264	0.4612	0.7799	367.3319	-.13384E-01
D	30.000	-99.7563	-12.3933	92.0716	96.2935	0.4863	0.8155	368.2649	-.13658E-01
E	40.000	-107.5105	-17.4354	99.5790	104.1452	0.5694	0.9290	372.5649	-.14537E-01
F	50.000	-120.0368	-23.4046	111.6164	116.7346	0.7154	1.1248	380.1680	-.15968E-01
G	60.000	-137.1799	-30.4782	127.7690	133.6279	0.9375	1.4109	391.2210	-.17901E-01
H	70.000	-156.9739	-37.8215	145.6963	152.3772	1.2190	1.7527	404.1940	-.20000E-01
I	80.000	-178.7470	-45.9082	165.7977	173.4004	1.5786	2.1434	420.3989	-.22365E-01
J	87.500	-181.1323	-46.4859	169.2032	176.9621	1.6441	1.8622	433.8309	-.12136E-01

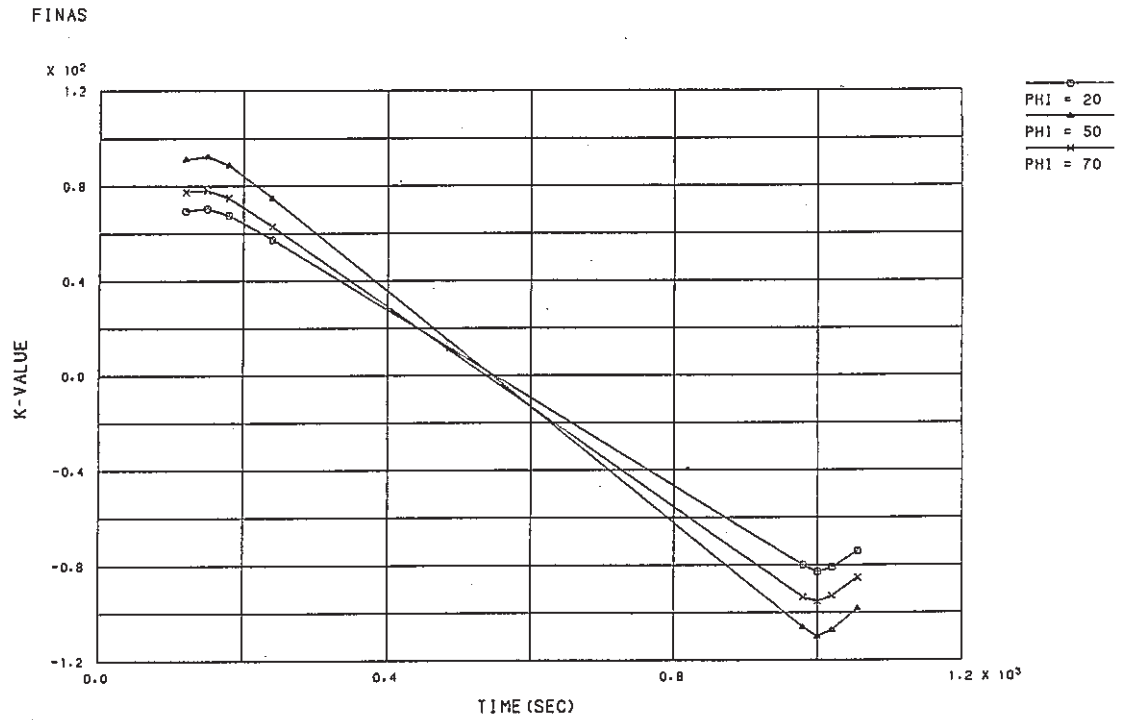


Fig. E.7.1-1 History of Stress Intensity Factor for Instrumental Nozzle (crack radius $r=9.6$ mm)

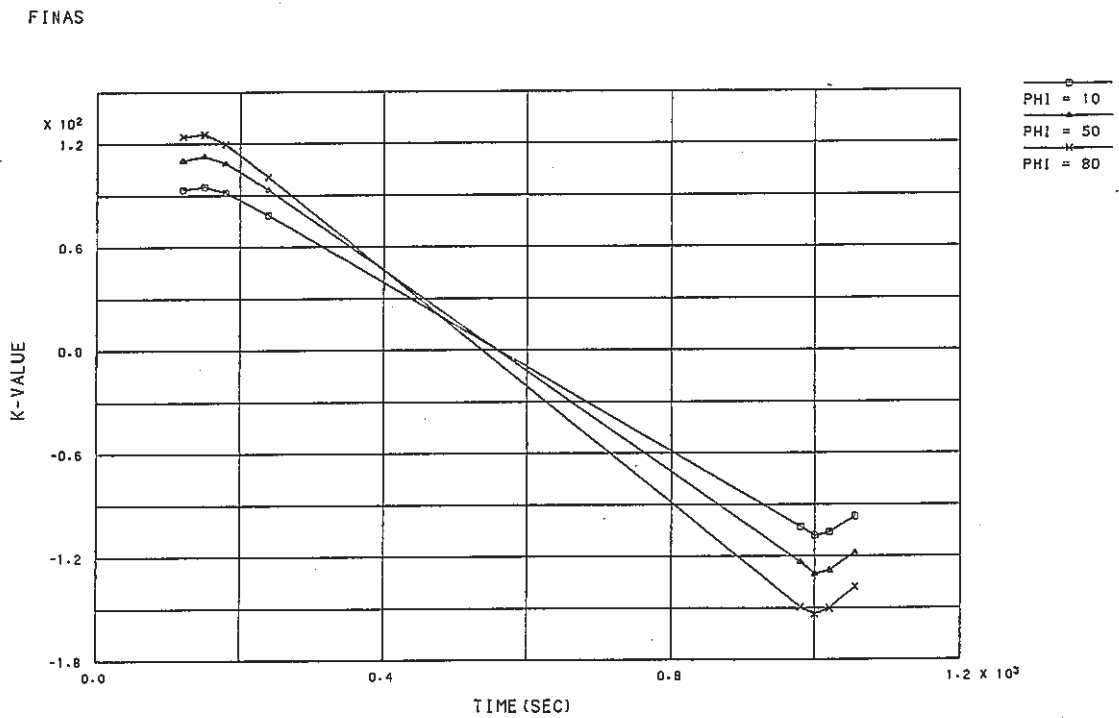


Fig. E.7.1-2 History of Stress Intensity Factor for Instrumental Nozzle (crack radius $r=12.8$ mm)

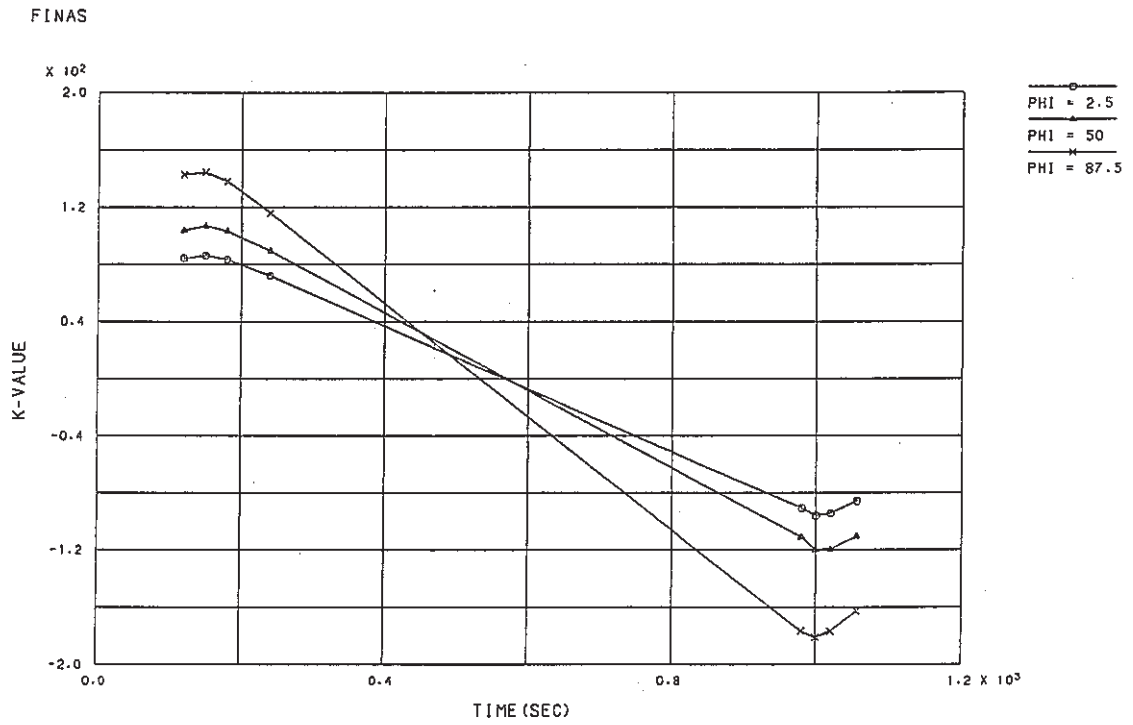


Fig. E.7.1-3 History of Stress Intensity Factor for Instrumental Nozzle (crack radius $r=16.0$ mm)

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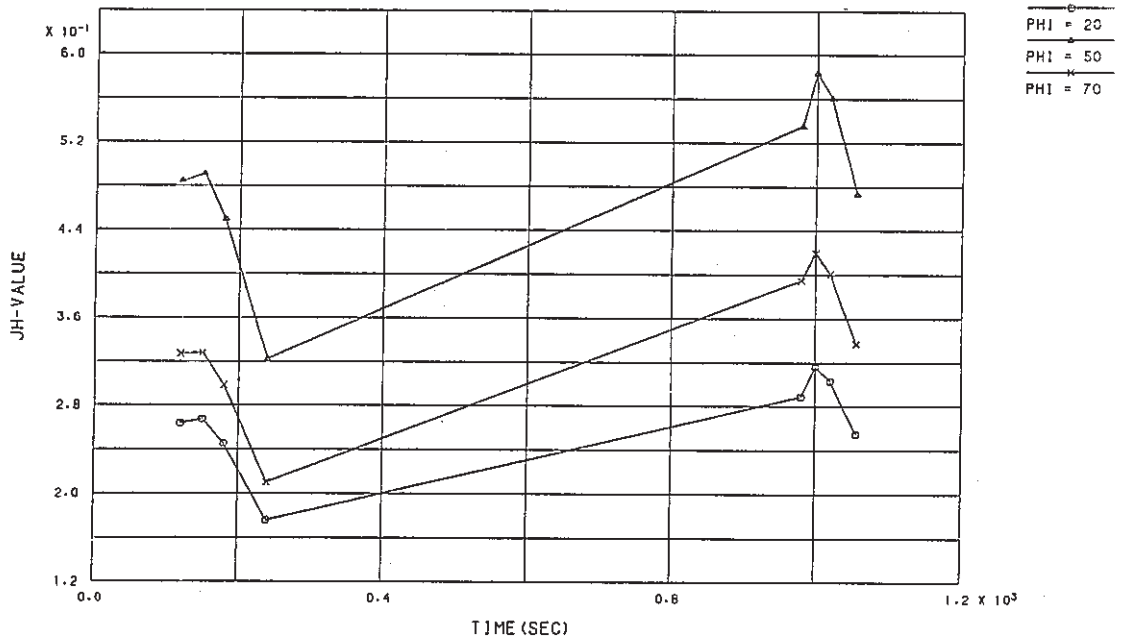


Fig. E.7.2-1 History of \hat{J} -Integral for Instrumental Nozzle (crack radius $r=9.6$ mm)

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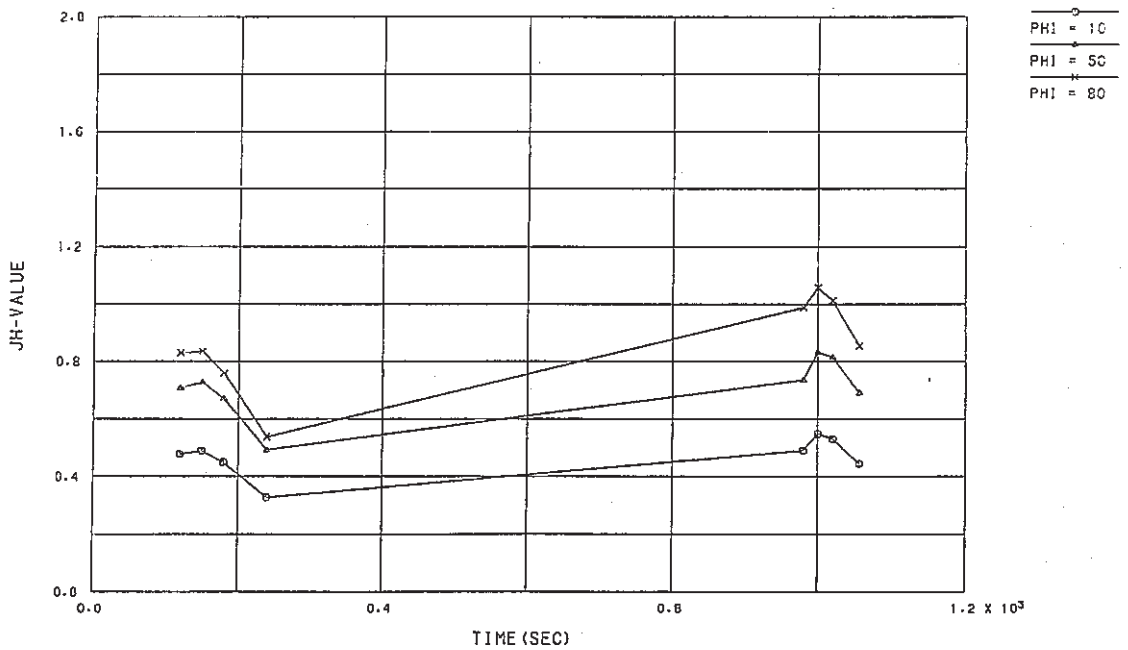


Fig. E.7.2-2 History of \hat{J} -Integral for Instrumental Nozzle (crack radius $r=12.8$ mm)

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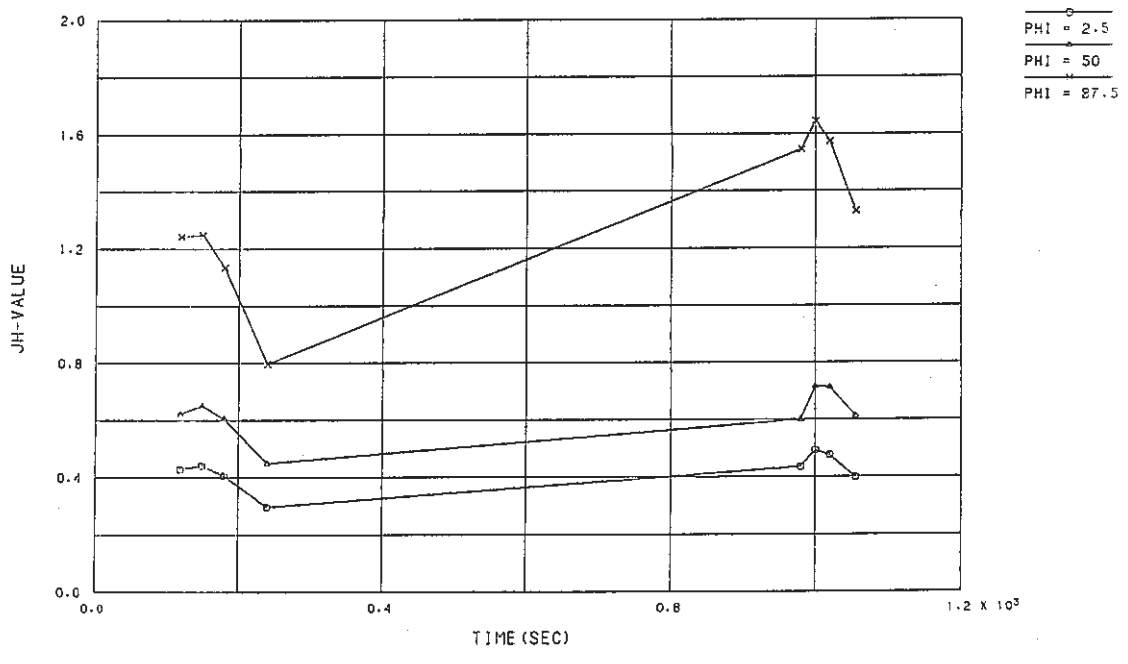


Fig. E.7.2-3 History of \hat{J} -Integral for Instrumental Nozzle (crack radius $r=16.0$ mm)

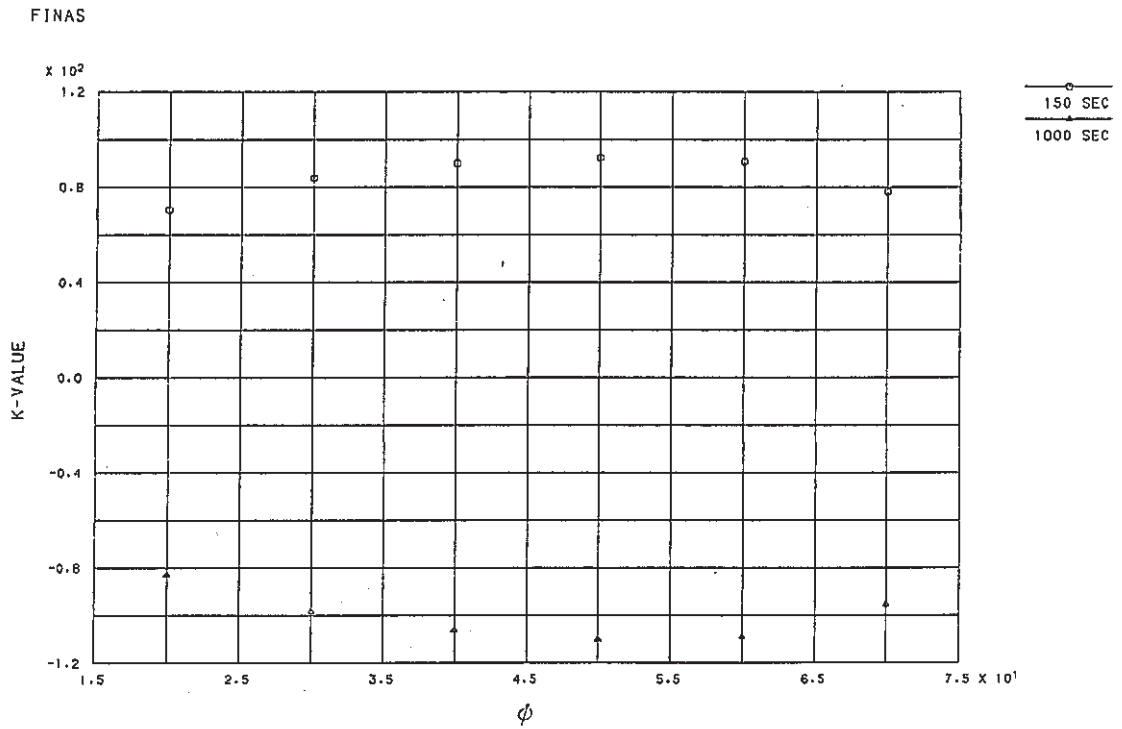


Fig. E.7.3-1 K_I Distribution along Crack Front at Cold and Hot Shock for Instrumental Nozzle (crack radius $r=9.6$ mm)

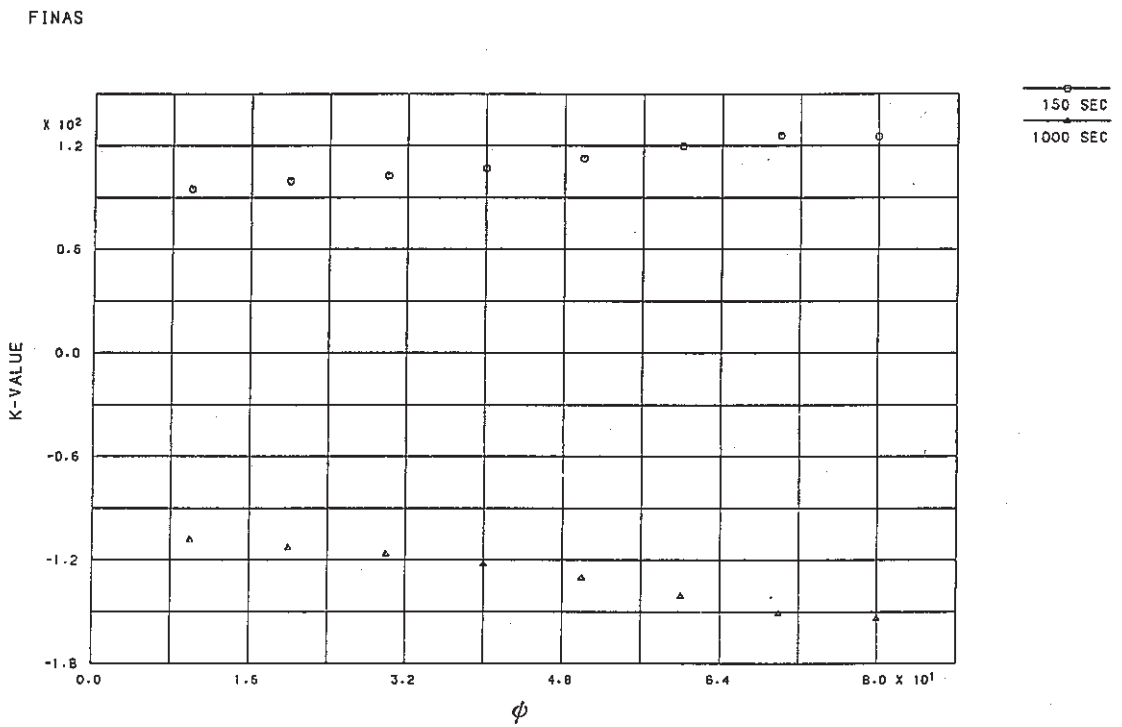


Fig. E.7.3-2 K_I Distribution along Crack Front at Cold and Hot Shock for Instrumental Nozzle (crack radius $r=12.8$ mm)

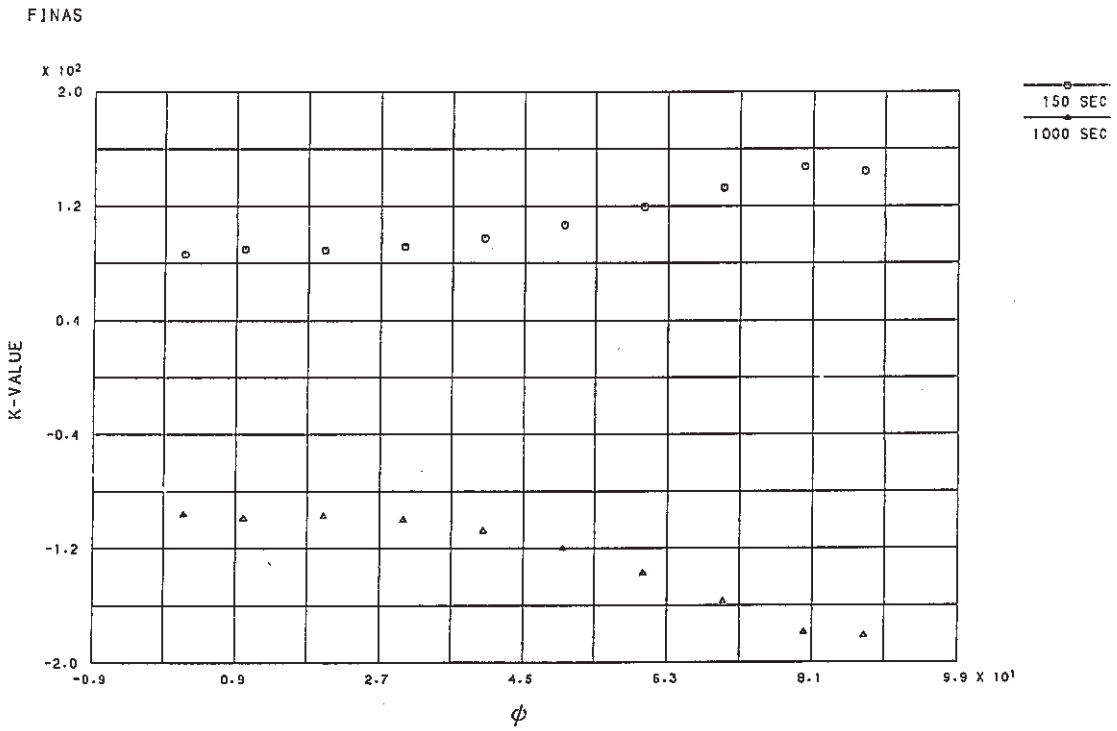


Fig. E.7.3-3 K_I Distribution along Crack Front at Cold and Hot Shock for Instrumental Nozzle (crack radius $r=16.0$ mm)

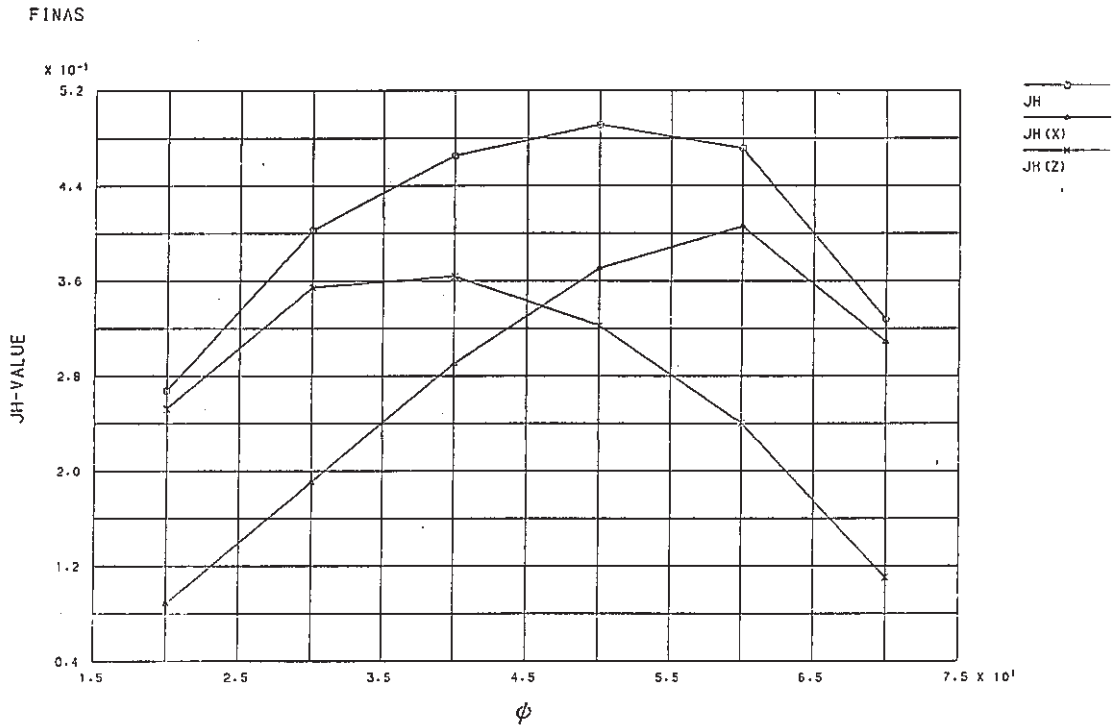


Fig. E.7.4-1 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Cold Shock for Instrumental Nozzle (crack radius $r=9.6$ mm)

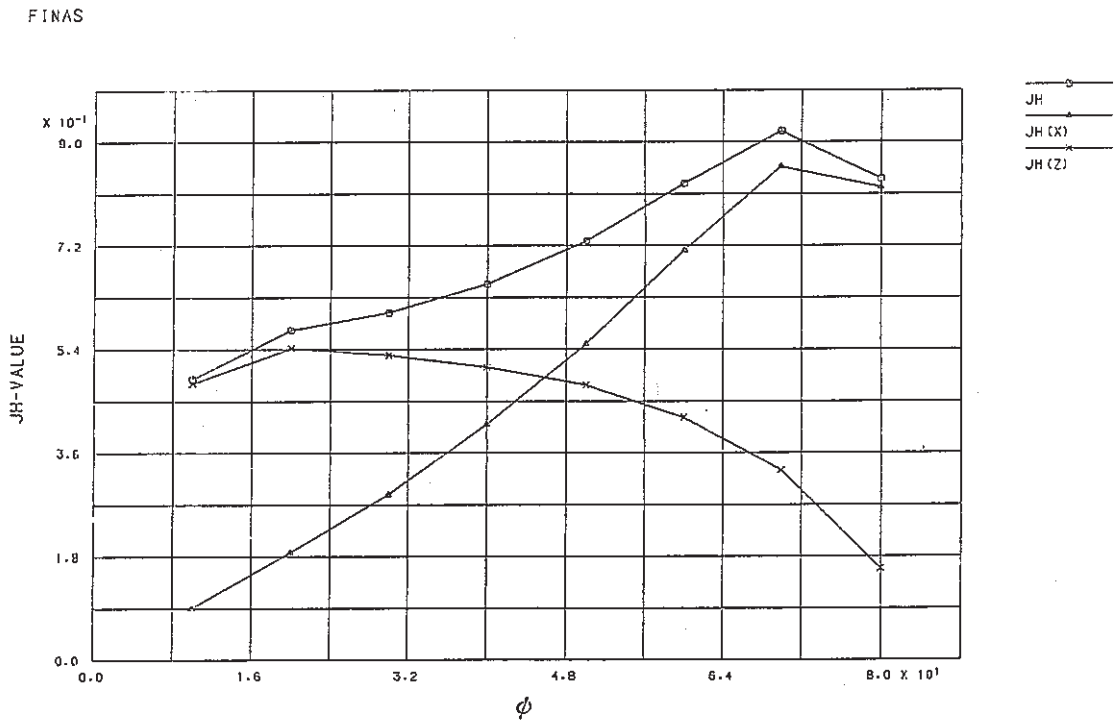


Fig. E.7.4-2 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Cold Shock for Instrumental Nozzle (crack radius $r=12.8$ mm)

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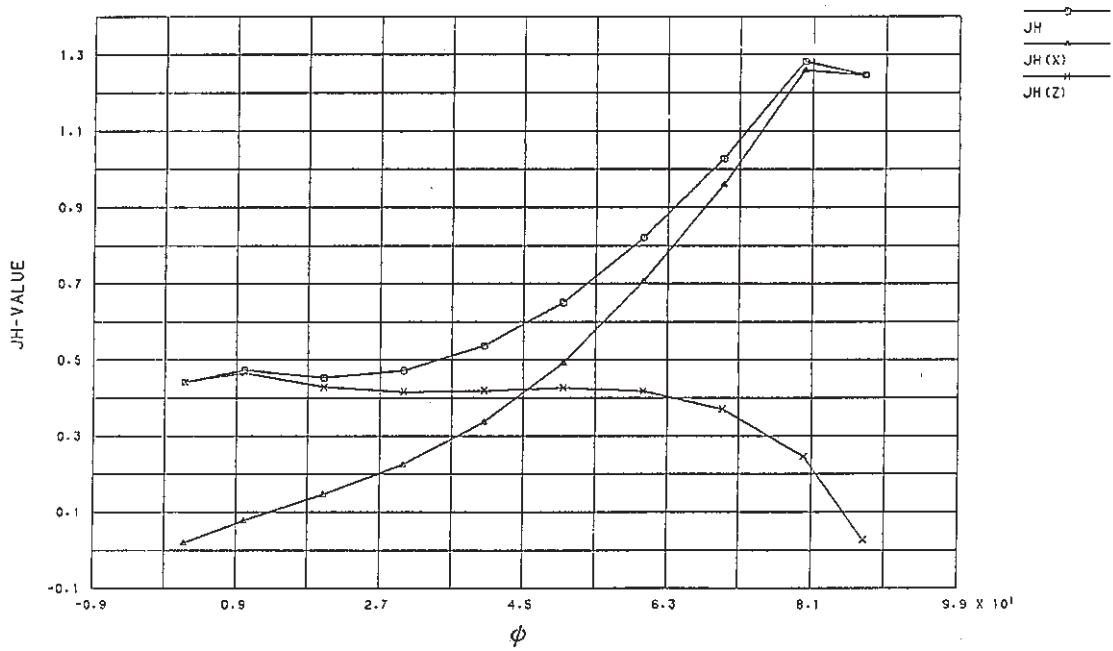


Fig. E.7.4-3 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Cold Shock for Instrumental Nozzle (crack radius $r=16.0$ mm)

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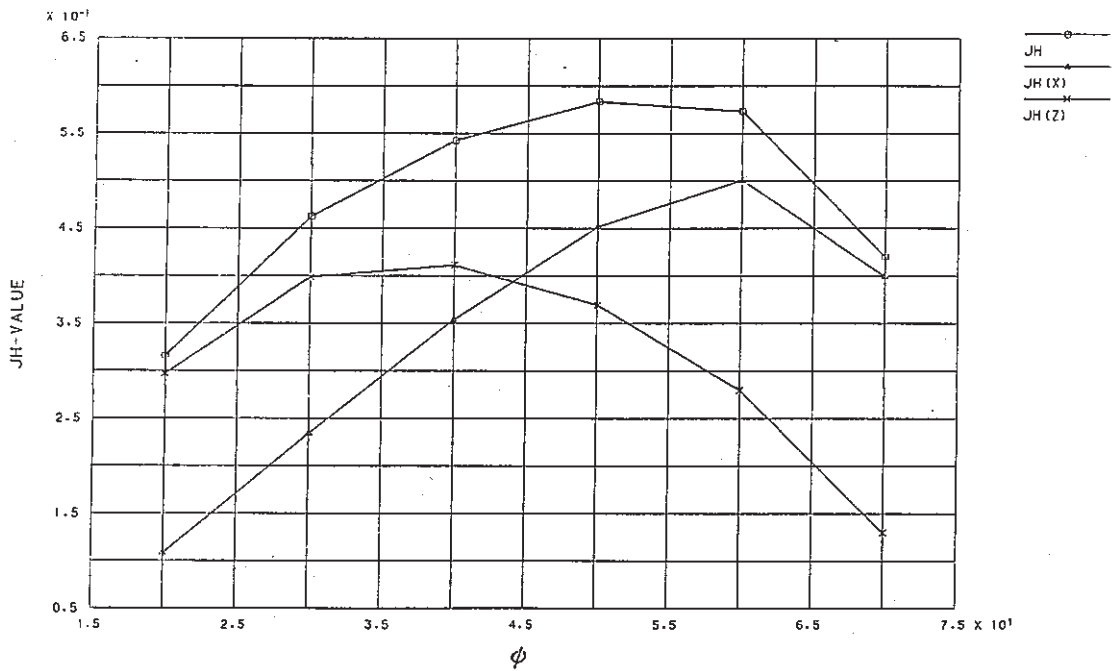


Fig. E.7.4-4 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Hot Shock for Instrumental Nozzle (crack radius $r=9.6$ mm)

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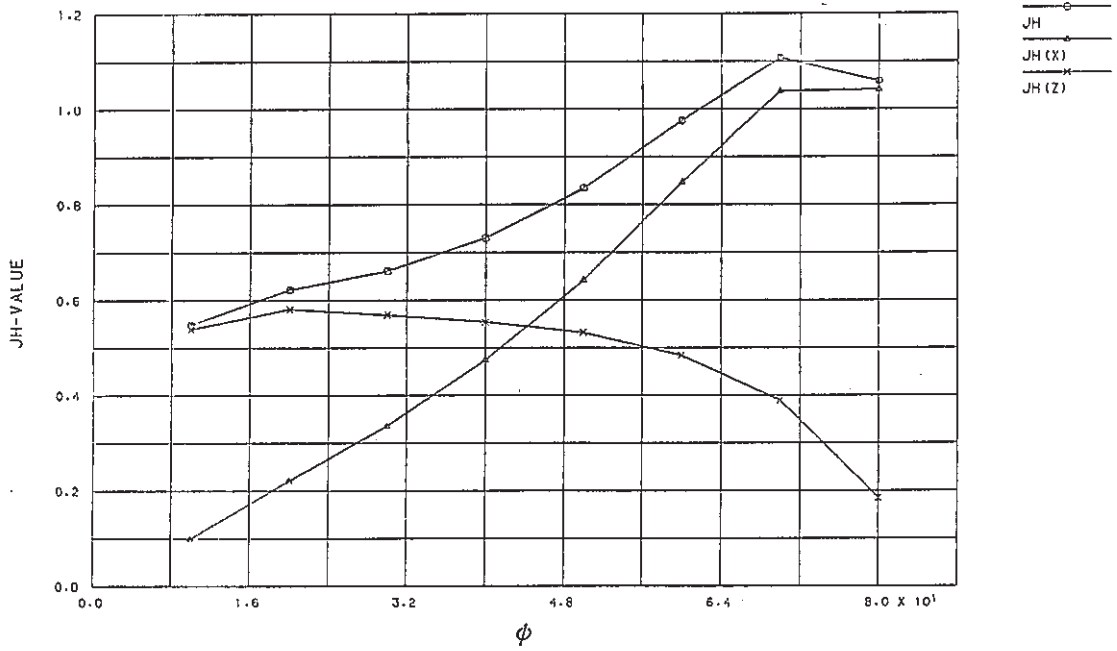


Fig. E.7.4-5 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Hot Shock for Instrumental Nozzle (crack radius $r=12.8$ mm)

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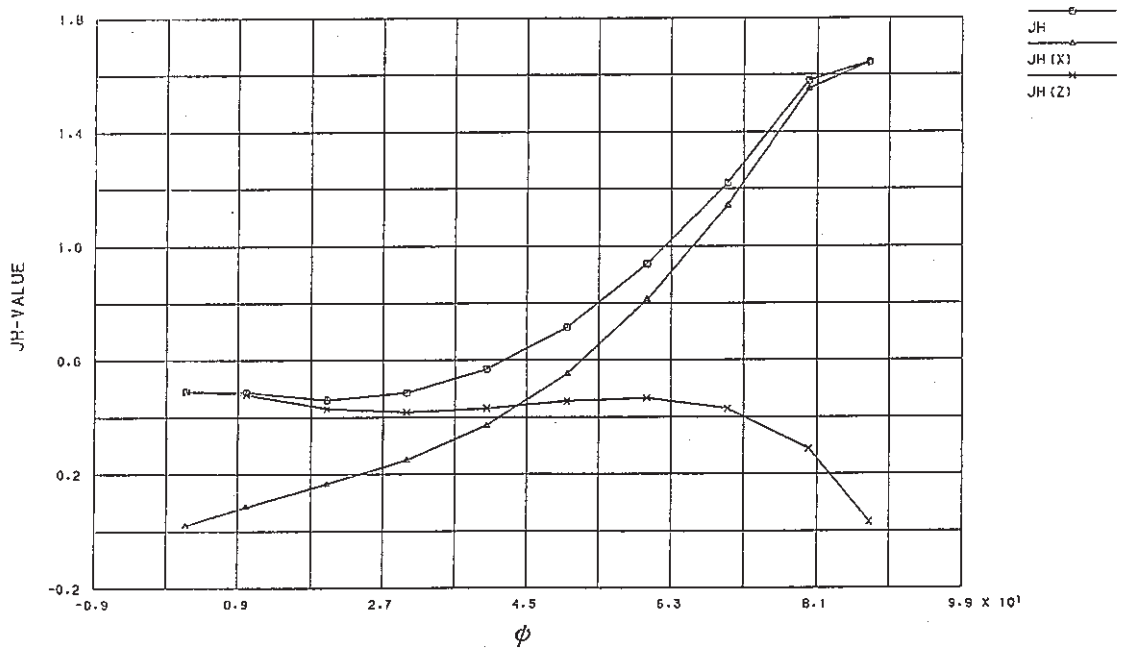


Fig. E.7.4-6 \hat{J}_X -and \hat{J}_Z -Integral Distribution along Crack Front at Hot Shock for Instrumental Nozzle (crack radius $r=16.0$ mm)

附録F 弾塑性解析に基づく破壊力学パラメータの解析結果

附録F 弾塑性解析に基づく破壊力学パラメータの解析結果

最終溶接部の3つのき裂深さについて実施した弾塑性解析より破壊力学パラメータを計算した。Table.F-1～Table.F-3は、それぞれき裂深さ1mm、15mm及び27mmについて計算した結果である。J積分より求めた K_I が、直接法により求めた K_I 値と異なるところがある。これはき裂先端の塑性域の拡がりにより、き裂先端の応力場が K_I によって特徴づけられなくなっているためである。本解析結果では、特にき裂深さ1mmの場合に両 K_I 値間の差が大きい。き裂深さ1mmの場合では、J積分に用いた積分経路が内表面の要素を含んでおり、き裂の存在によるき裂先端近傍の応力・ひずみ場の特異性を評価するばかりでなく、内表面から受ける熱過渡の影響を十分含んだ形で評価している。このため浅いき裂では、両 K_I 値間の差が大きくなると考えられる。

Fig.F-1～Fig.F-6に、各き裂深さにおける K_I 値とJ積分値の時間に対する変化を示す。弾塑性解析はORNL推奨の硬化則を用いているため、ここでもコールド、ホット及びコールドショックの1.5サイクルについて計算した。

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Table F-1 Fracture Mechanics Parameters of Finally Welded
Joint, crack depth $a=1$ mm

STEP	TIME	K-1	K-2	JH --> K		JH	J	TEMP.	DISP.
		SIG-Z	TAU-RZ	P.STRS	P.STRN				
1	20.80	8.8599	1.5938	6.5835	6.9207	0.0028	0.0019	578.8940	0.90694E-03
2	60.00	20.6914	6.4649	65.4830	68.7008	0.2656	0.1249	505.7612	0.14836E-01
3	144.00	44.5616	10.7710	92.5301	96.8535	0.4999	0.2108	407.3550	0.23819E-01
4	152.00	44.6799	10.7973	92.9762	97.3082	0.5028	0.2080	400.8445	0.23856E-01
5	174.00	43.0912	9.7003	85.1621	89.0929	0.4186	0.1691	384.4451	0.23343E-01
6	196.00	35.8675	9.1363	79.5396	83.1840	0.3631	0.1103	371.8772	0.23012E-01
7	240.00	22.4609	6.4195	48.7940	51.0017	0.1353	-0.0206	350.4580	0.21611E-01
8	300.00	4.2145	2.7571	-50.5388	-52.7961	-0.1437	-0.1853	328.4817	0.19767E-01
9	540.00	-46.2911	-7.8250	-86.8336	-90.5990	-0.4150	-0.5121	278.7532	0.14527E-01
10	900.00	-85.5139	-13.3752	-71.7616	-74.8249	-0.2802	-0.5373	252.4841	0.10145E-01
11	940.00	-94.1938	-21.8172	75.9552	79.3399	0.3240	0.1062	324.5503	-.72580E-02
12	960.00	-44.8910	-14.7816	110.5202	115.5883	0.7014	0.6209	373.2969	-.15937E-01
13	975.00	-40.8896	-14.2183	120.7104	126.3243	0.8462	0.7731	397.4622	-.19065E-01
14	990.00	-47.7744	-15.4239	123.5019	129.2863	0.8935	0.8067	412.8369	-.19912E-01
15	1005.00	-51.6526	-16.1688	122.9164	128.7036	0.8913	0.8023	424.8840	-.19888E-01
16	1020.00	-46.8796	-15.4426	119.5021	125.1544	0.8478	0.7895	435.5149	-.19592E-01
17	1065.00	-33.9454	-12.2246	101.5830	106.4447	0.6215	0.6797	459.5935	-.18298E-01
18	1800.00	71.0711	10.2181	-56.1487	-59.0093	-0.2034	0.0106	569.7244	-.60486E-02
19	2400.00	79.1327	12.1040	-51.9667	-54.6253	-0.1750	-0.0102	577.1572	-.49738E-02
20	4200.00	79.7727	11.7785	-50.9198	-53.5266	-0.1682	-0.0121	578.3586	-.48845E-02
21	7200.00	79.2374	11.7425	-44.2809	-46.5552	-0.1277	-0.0209	584.1414	-.48623E-02
22	7251.00	190.0083	19.5846	67.7337	71.0944	0.2872	0.2260	522.7454	0.10336E-01
23	7273.00	189.3809	30.6465	98.7744	103.5708	0.5967	0.3823	484.9097	0.16906E-01
24	7300.00	155.5452	28.9708	113.0285	118.4099	0.7652	0.4578	450.5110	0.20470E-01
25	7338.00	146.1525	27.7155	117.5815	123.0916	0.8104	0.4783	414.0894	0.21348E-01
26	7345.00	145.2028	27.6192	118.0358	123.5513	0.8136	0.4794	407.4963	0.21403E-01
27	7352.00	144.4326	27.5261	118.4191	123.9368	0.8158	0.4801	400.9858	0.21442E-01
28	7374.00	143.0124	26.9210	114.9216	120.2263	0.7624	0.4567	384.5867	0.20987E-01
29	7396.00	133.6890	25.5008	106.2969	111.1676	0.6485	0.3971	372.0186	0.20501E-01
30	8100.00	27.5282	3.3538	-90.4429	-94.3038	-0.4451	-0.2508	252.6255	0.91675E-02

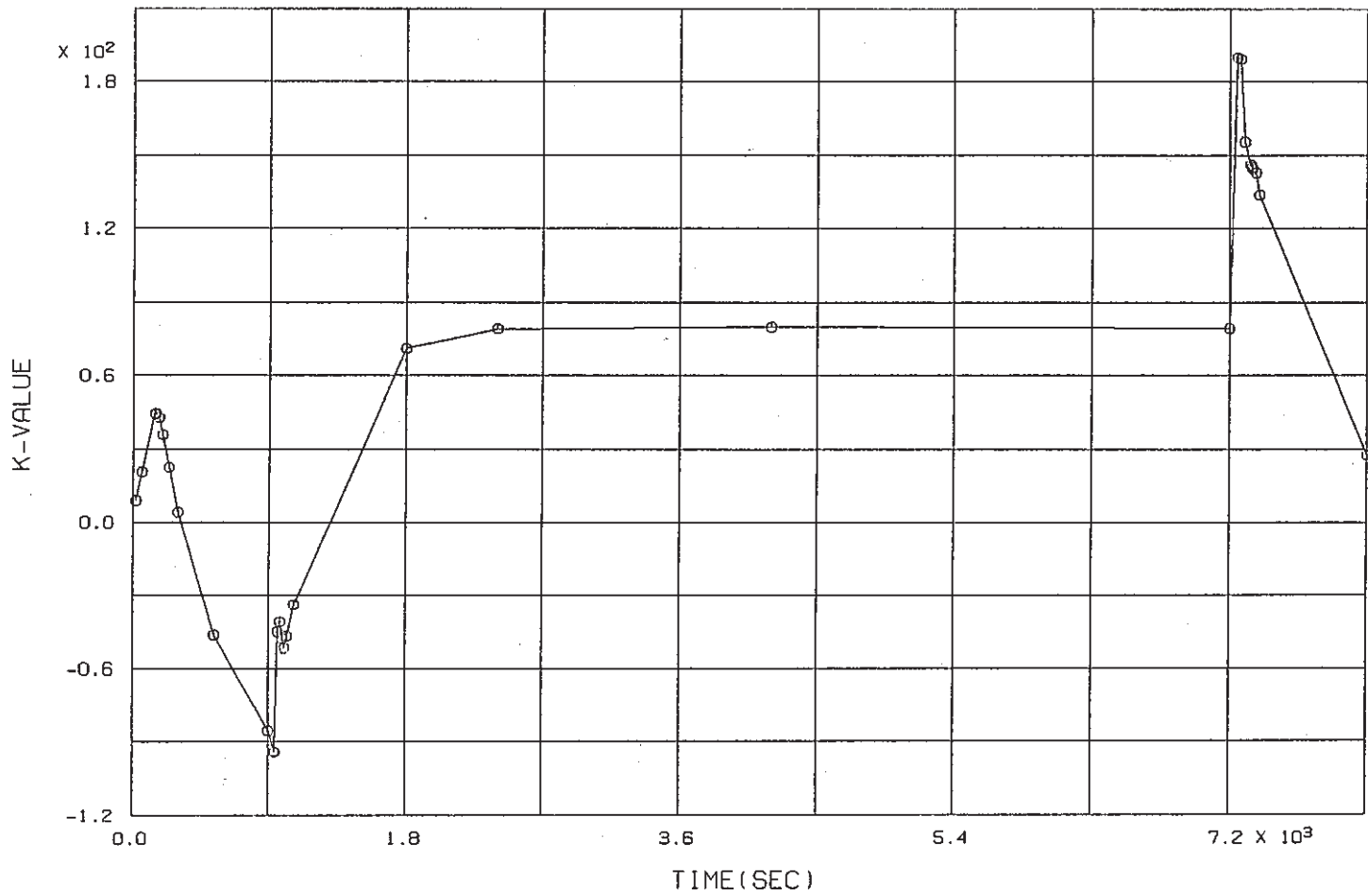
Table F-2 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=15 mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS P.STRN		JH	J	TEMP.	DISP.
1	20.80	5.9165	0.2564	6.6486	6.9901	0.0029	0.0027	583.8694	0.24996E-02
2	60.00	118.2814	6.5603	107.0155	112.4411	0.7346	0.5487	561.0063	0.45961E-01
3	144.00	180.7699	15.3733	194.5411	203.9763	2.3116	1.5667	482.7488	0.93406E-01
4	152.00	181.5164	15.5065	195.6381	205.0923	2.3287	1.5934	476.4348	0.93821E-01
5	174.00	182.0992	15.3961	191.6155	200.7802	2.2098	1.5909	458.4495	0.92579E-01
6	196.00	173.9995	14.3126	182.0988	190.7358	1.9760	1.4825	441.8945	0.90159E-01
7	240.00	155.8262	11.4062	145.9971	152.8360	1.2488	1.1732	413.1418	0.83388E-01
8	300.00	129.1402	7.0513	96.2560	100.6881	0.5338	0.7392	380.3513	0.73677E-01
9	540.00	49.3142	-5.1770	-139.3238	-145.4503	-1.0794	-0.2989	302.1492	0.47441E-01
10	900.00	-9.7288	-9.5055	-139.5033	-145.4823	-1.0619	-0.6970	259.2385	0.30979E-01
11	940.00	-146.1349	-11.1340	-48.5594	-50.6515	-0.1292	-0.7888	267.9175	-.81136E-02
12	960.00	-214.2840	-10.5310	146.9350	153.3603	1.1956	-0.2406	292.8035	-.44555E-01
13	975.00	-246.9288	-7.8872	187.8989	196.2088	1.9718	0.2338	311.7861	-.62723E-01
14	990.00	-270.8530	-8.7730	205.0646	214.2265	2.3667	0.5360	328.9946	-.72156E-01
15	1005.00	-275.0908	-8.5240	206.7600	216.0791	2.4222	0.6315	343.8875	-.73631E-01
16	1020.00	-273.7847	-8.0432	203.8128	213.0708	2.3679	0.6708	357.1130	-.72766E-01
17	1065.00	-256.5491	-6.5040	181.0587	189.4492	1.8983	0.6138	391.3267	-.67876E-01
18	1800.00	-51.5908	19.6918	-74.5307	-78.3199	-0.3575	-0.0223	566.0146	-.63182E-02
19	2400.00	-37.5617	20.5635	-69.7291	-73.2966	-0.3152	-0.0052	577.2480	-.19580E-02
20	4200.00	-37.2105	20.4980	-68.6568	-72.1721	-0.3058	-0.0050	578.6130	-.19065E-02
21	7200.00	-37.9462	20.2419	-65.7306	-69.1055	-0.2812	-0.0046	583.6426	-.23245E-02
22	7251.00	80.6103	20.9641	86.8799	91.3043	0.4867	0.4816	568.9849	0.35438E-01
23	7273.00	153.7363	24.2574	145.5697	152.8970	1.3482	1.1243	548.2290	0.58422E-01
24	7300.00	191.1575	26.9872	183.5777	192.6843	2.1095	1.7032	522.4258	0.73820E-01
25	7338.00	204.0171	29.2453	202.8064	212.6763	2.5214	2.0604	488.7710	0.80273E-01
26	7345.00	205.5943	29.2854	204.1830	214.0837	2.5458	2.0974	482.3916	0.80725E-01
27	7352.00	206.9059	29.3587	205.3260	215.2462	2.5645	2.1303	476.0776	0.81050E-01
28	7374.00	206.6374	29.1996	205.0206	214.8244	2.5292	2.1515	458.0920	0.80158E-01
29	7396.00	201.1936	27.9220	192.8091	201.9526	2.2148	2.0206	441.5374	0.77090E-01
30	8100.00	29.6456	3.7156	-117.7641	-122.8104	-0.7566	-0.3281	258.8811	0.19279E-01

Table F-3 Fracture Mechanics Parameters of Finally Welded Joint, crack depth a=27 mm

STEP	TIME	K-1 SIG-Z	K-2 TAU-RZ	JH --> K P.STRS	K P.STRN	JH	J	TEMP.	DISP.
1	20.80	4.8820	-1.2622	4.7809	5.0265	0.0015	0.0014	583.9966	0.18566E-02
2	60.00	91.1363	-20.6529	76.3087	80.2137	0.3775	0.3226	577.6704	0.34841E-01
3	144.00	117.7322	-18.7409	123.1201	129.2147	0.9466	0.7790	518.6484	0.66002E-01
4	152.00	118.3637	-18.8628	123.9629	130.0781	0.9560	0.7934	512.5771	0.66310E-01
5	174.00	118.3309	-16.4732	122.2024	128.1700	0.9189	0.7930	494.7793	0.65683E-01
6	196.00	112.0126	-18.2121	115.1338	120.7006	0.8070	0.7280	477.3740	0.63596E-01
7	240.00	97.9686	-17.2410	92.1281	96.5041	0.5068	0.5358	445.2681	0.57957E-01
8	300.00	76.5309	-15.7919	42.9983	45.0076	0.1080	0.2492	407.6040	0.49791E-01
9	540.00	9.8618	-10.2533	-93.4801	-97.6217	-0.4887	-0.4785	314.8066	0.27091E-01
10	900.00	-35.0988	-5.4256	-93.6060	-97.6267	-0.4789	-0.8132	262.8750	0.13437E-01
11	940.00	-139.6387	34.9813	34.5574	36.0405	0.0652	-0.7422	261.4490	-0.14602E-01
12	960.00	-203.8533	50.1196	127.9381	133.4509	0.8966	-0.1914	268.1421	-0.40852E-01
13	975.00	-225.8462	47.3369	158.1185	164.9705	1.3753	0.1620	277.6167	-0.53917E-01
14	990.00	-234.4630	48.0238	171.5877	179.0759	1.6280	0.3720	289.3977	-0.60815E-01
15	1005.00	-238.2940	47.7172	176.4271	184.1856	1.7310	0.4797	302.2544	-0.63453E-01
16	1020.00	-240.0792	45.7754	176.3228	184.1372	1.7391	0.5253	315.3406	-0.63712E-01
17	1065.00	-215.0226	51.7653	164.1137	171.5492	1.5322	0.5554	352.7173	-0.58741E-01
18	1800.00	-53.8373	28.0071	-54.4807	-57.2473	-0.1907	0.0029	563.9436	-0.71138E-02
19	2400.00	-43.3294	26.4001	-53.3391	-56.0681	-0.1844	-0.0013	577.3333	-0.35242E-02
20	4200.00	-43.2077	26.4049	-52.4991	-55.1872	-0.1788	-0.0020	578.6665	-0.35240E-02
21	7200.00	-44.0028	26.4608	-51.1649	-53.7917	-0.1704	-0.0043	583.4968	-0.38889E-02
22	7251.00	37.3540	8.0379	43.8694	46.1177	0.1250	0.2417	580.3757	0.23362E-01
23	7273.00	100.5778	-10.5985	91.7525	96.4303	0.5435	0.6247	570.9521	0.41519E-01
24	7300.00	141.5230	-24.7981	117.7040	123.6461	0.8844	0.9701	553.4504	0.54145E-01
25	7338.00	159.3253	-30.5954	130.9457	137.4480	1.0745	1.2226	524.2004	0.59778E-01
26	7345.00	160.8166	-30.8597	132.1784	138.7195	1.0907	1.2558	518.1453	0.60131E-01
27	7352.00	161.6670	-31.2998	133.1332	139.6988	1.1023	1.2848	512.0742	0.60359E-01
28	7374.00	163.2247	-33.0995	132.6552	139.1313	1.0824	1.3187	494.2761	0.59763E-01
29	7396.00	157.6030	-29.6911	127.8302	134.0090	0.9945	1.2761	476.8711	0.57462E-01
30	8100.00	20.7926	-22.6561	-59.5654	-62.1232	-0.1939	-0.1464	262.3718	0.81906E-02

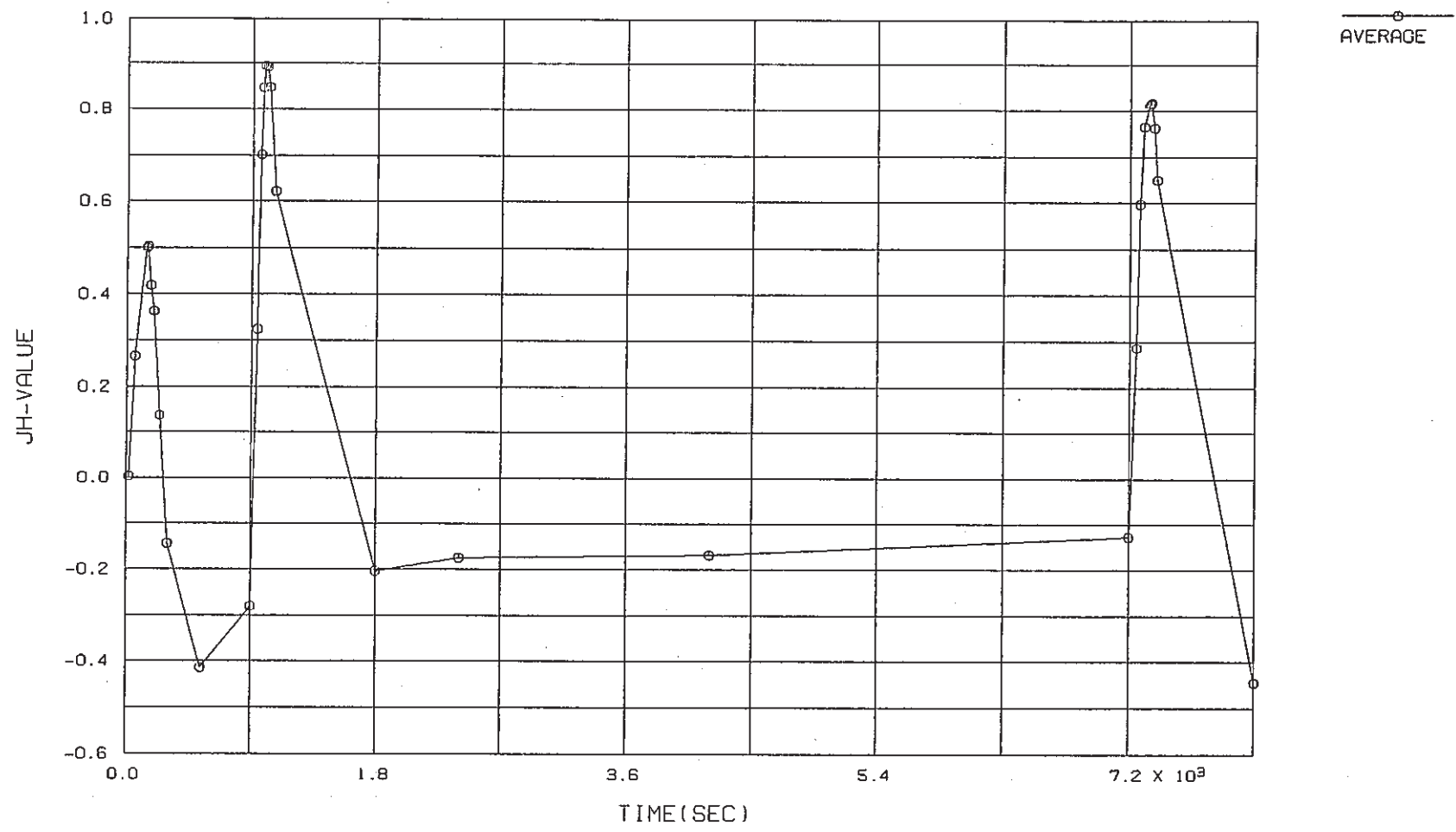
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Fig. F-1 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=1 mm

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Fig. F-2 History of \hat{J} -Integral for Finally Welded Joint, crack depth a=1 mm

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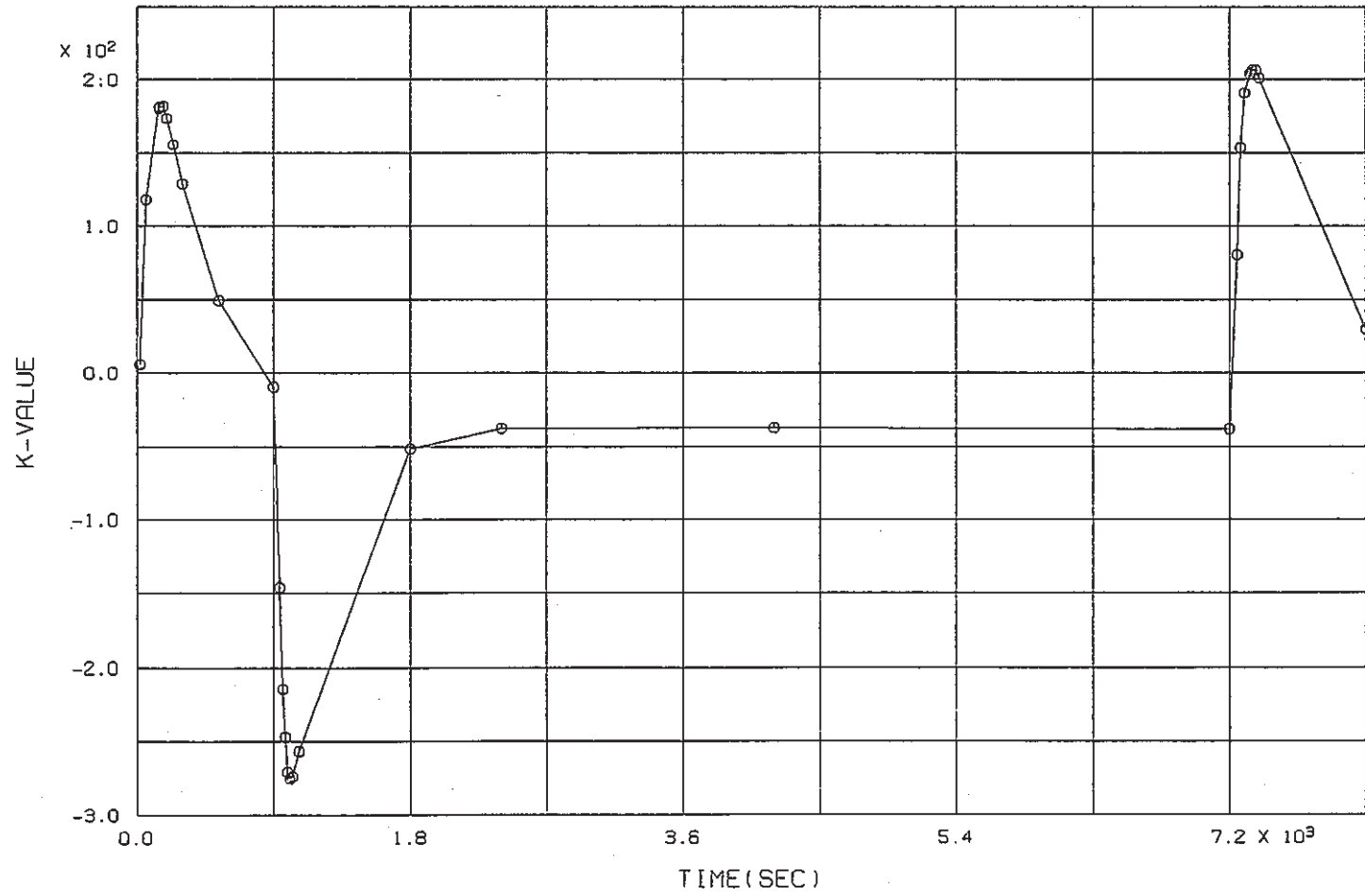


Fig. F-3 History of Stress Intensity Factor for Finally Welded Joint, crack depth a=15 mm

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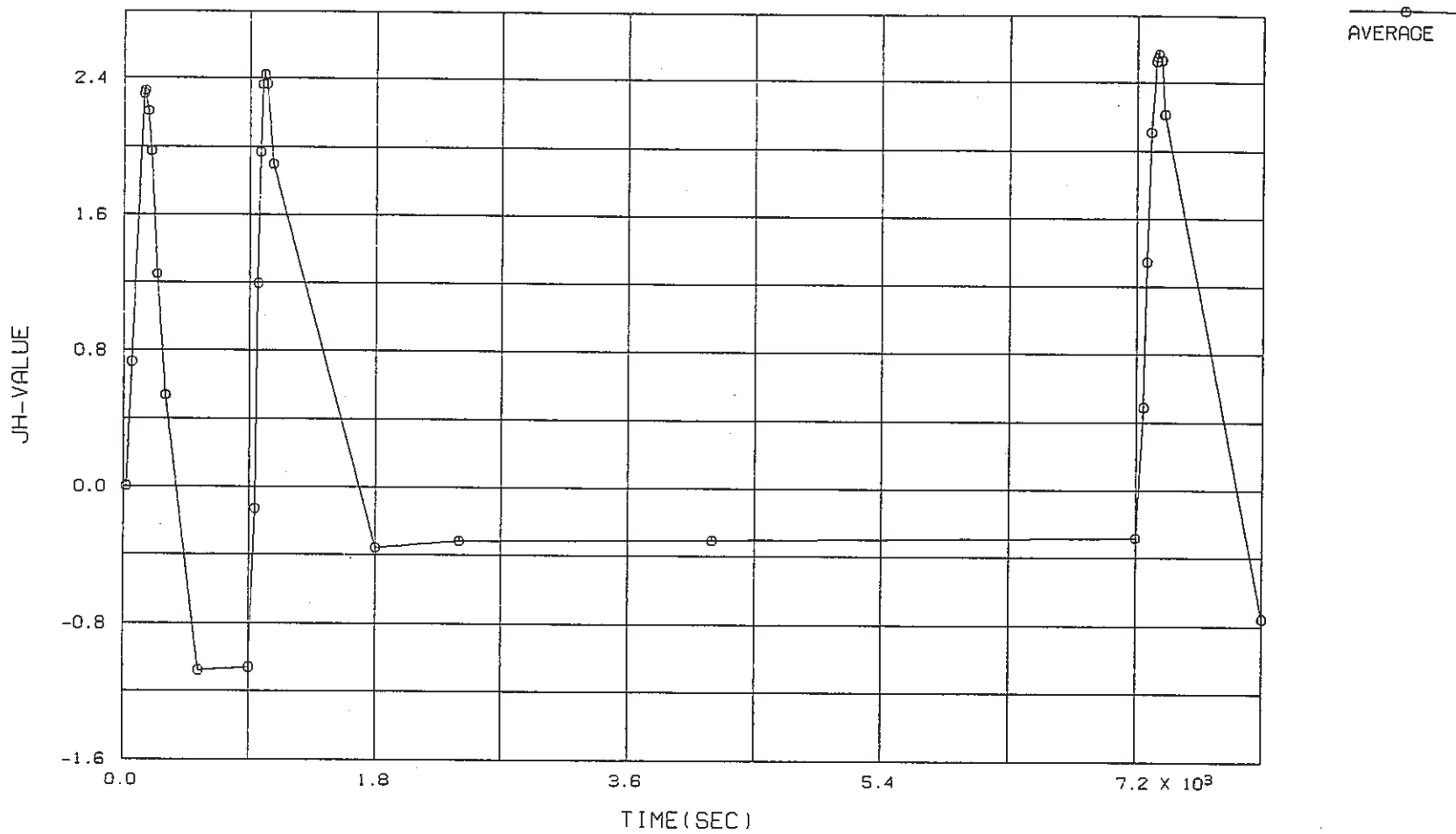


Fig. F-4 History of \hat{J} -Integral for Finally Welded Joint, crack depth a=15 mm

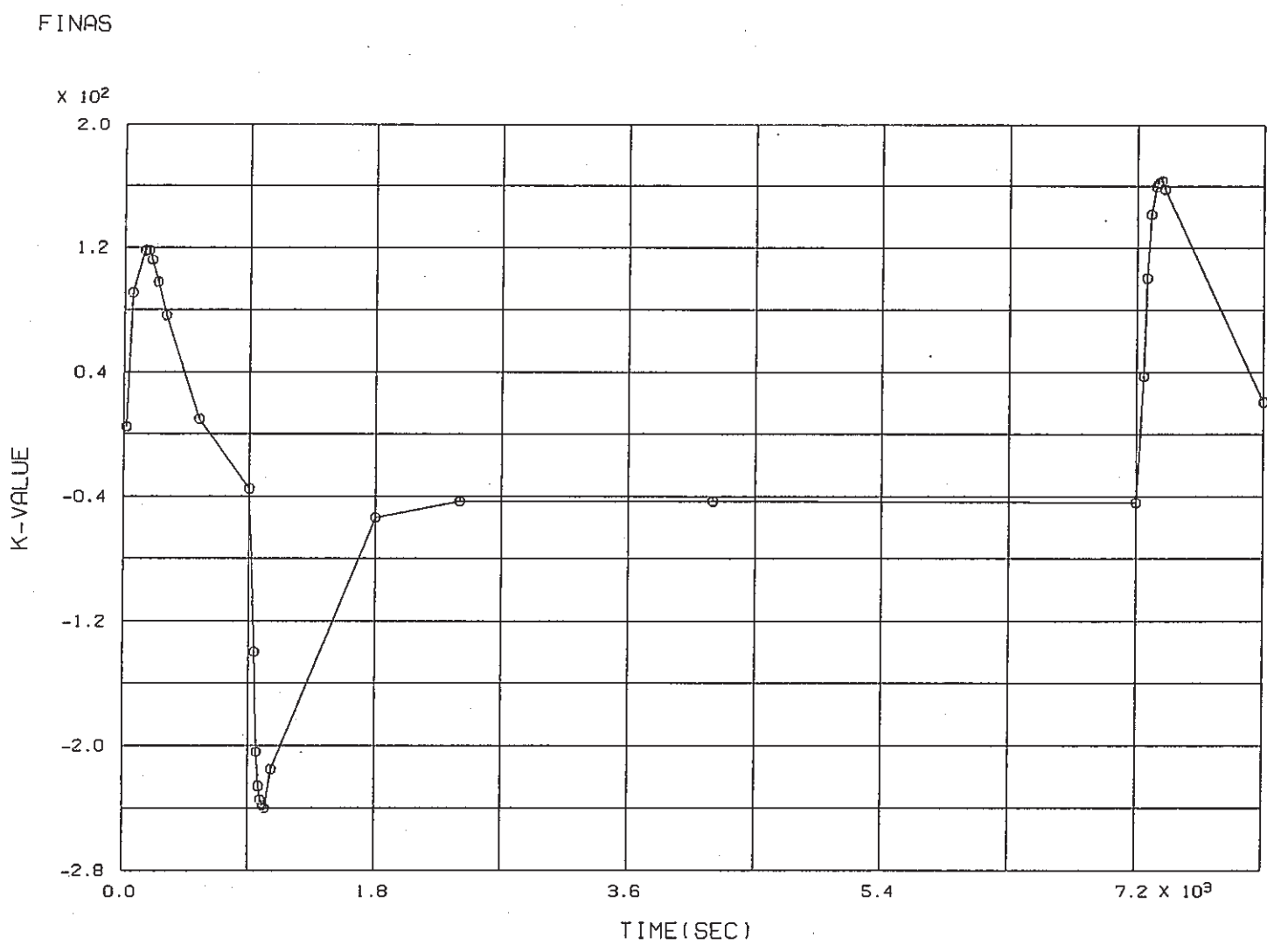


Fig. F-5 History of Stress Intensity Factor for Finally Welded Joint, crack depth $a=27$ mm

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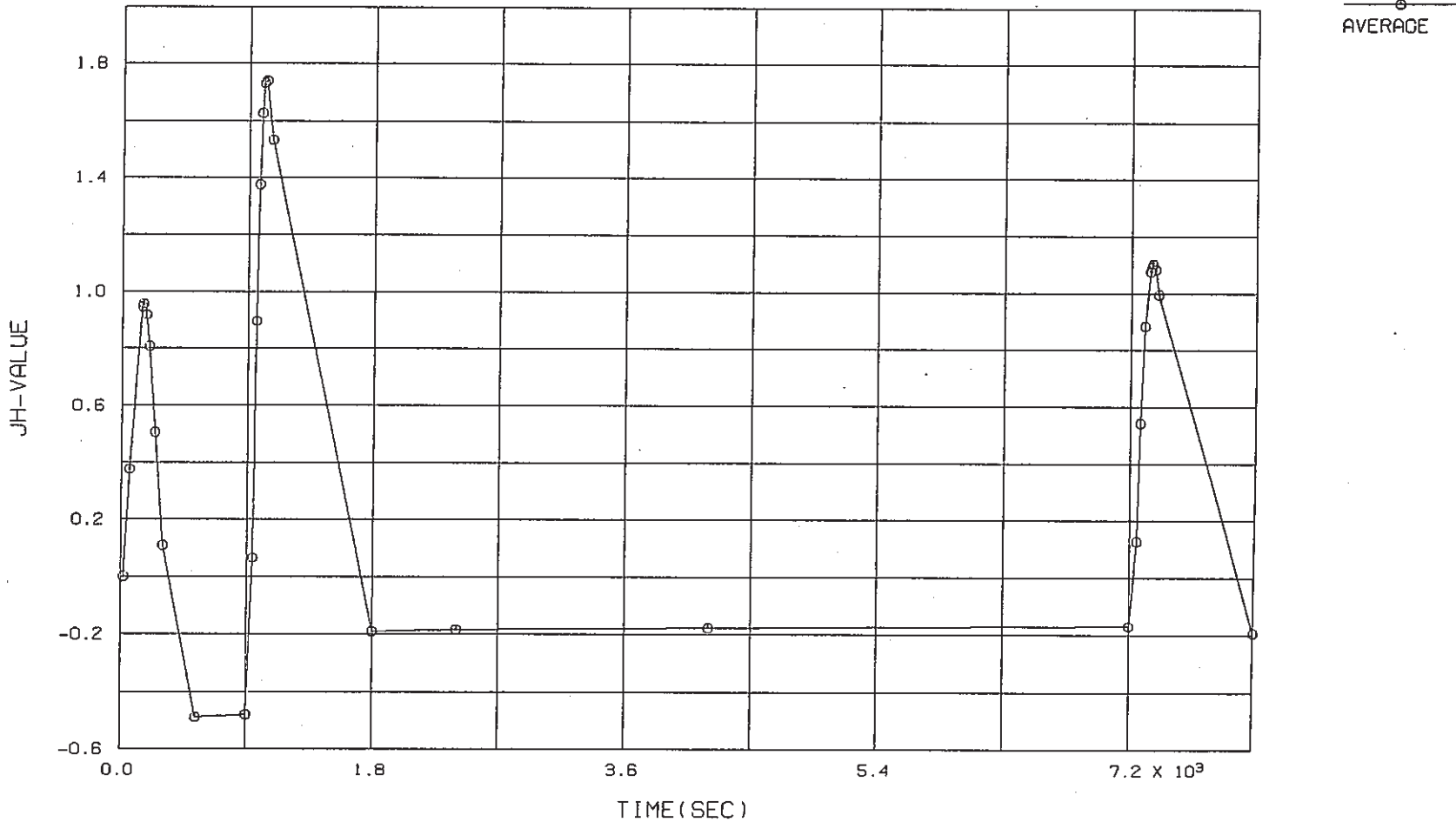


Fig. F-6 History of \hat{J} -Integral for Finally Welded Joint, crack depth a=27 mm

附錄 G 破面觀察結果

附録G 破面観察結果

本解析で対象としたき裂の破面観察結果を示す。ここでは出口ノズル部以外のき裂について実施した破面の巨視的な観察結果を示すが、出口ノズル部及びこれらのき裂の微視的な観察結果については、「原子炉容器モデル熱過渡強度試験」に関連する報告書^{(G-1), (G-2)}をみられたい。これらのき裂はほとんど全て粒界割れであり、典型的なクリープ疲労き裂である。

(1) 最終溶接部

上部胴、下部胴の最終溶接部には、Fig.G-1に示すように2本の周方向全周き裂が発生した。本解析では、このうち下部胴部に発生したき裂について解析している。これらのき裂が発生した位置は、最終溶接部近傍の形状を詳細にモデル化した応力解析結果と一致しており、形状不連続により発生したき裂と思われる。

(2) 入口ノズル部

入口ノズル部では多数の微細き裂が発生していたが、解析では3つの周方向全周き裂を想定した。Fig.G-2に示す破面はき裂 a_2 に対応している。

(3) シンニング部

上部胴シンニング部でも多数の微細き裂が発生した。Fig.G-3に示すように2つの周方向全周き裂、周方向亀甲状き裂及び軸方向亀甲状き裂が発生した。本解析では、このうち周方向全周き裂2つについて解析している。Fig.G-3に示すように a_2 き裂の上部で周方向優勢の亀甲状き裂、下部で軸方向優勢の亀甲状き裂が発生したが、これは第5報「伝熱・応力解析と強度評価」で述べたように応力成分 σ_θ 、 σ_z の大小関係と対応している。Fig.C3.3にき裂の深さが変化した時の内表面に沿う応力分布を示したが、き裂深さの浅い1mmの場合には、 a_2 き裂発生位置で軸方向応力 σ_z が周方向応力 σ_θ より大きく、かつ極値を示している。また a_2 き裂下部では $\sigma_\theta > \sigma_z$ 、 a_2 き裂上部では $\sigma_z > \sigma_\theta$ である。 a_1 き裂については、応力解析結果をみると軸方向応力の極値を示していないが、このき裂は溶接部であることから、解析モデルで模擬できなかった形状不連続や材料の不均質により周方向き裂が発生したものと思われる。

(4) コニカル胴・下部鏡部

コニカル胴・下部鏡の溶接部近傍に発生したき裂は、Fig.G-4に示すように深さ32mm程度の周方向全周き裂である。このき裂は、熱過渡による表面応力に構造的な温度分布に起因する大きなたが締め応力が重畳する場所であり、他のき裂発生箇所と異なり、ホットショック中に高応力が発生すると思われる。このためクリープき裂進展の寄与が大きく深いき裂が発生したと思われる。

(5) スタッドボルト

スタッドボルトの隅肉溶接止端部には、Fig.G-5に示すように全周にわたって、き裂が発生しており、その深さは周方向にわたって、ほぼ均一であった。また、さらにこの全周き裂から放射状

にき裂が発生しており、胴部内表面側に長い形状となっていた。この放射状き裂は、Fig.C 6.7 に示したように全周き裂の外側で半径方向応力が緩和されて、周方向応力が大きくなることと良く対応する。

(6) 計装ノズル

計装ノズルコーナ部に発生した放射状のき裂を Fig.G-6 に示す。き裂はほぼ 40° 間隔で生じており、破面形状は母材側に長いだ円状であるが、解析では円弧状のき裂でモデル化した。

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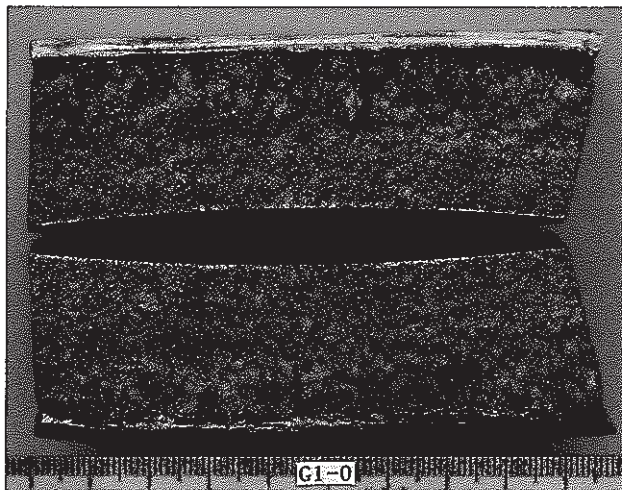
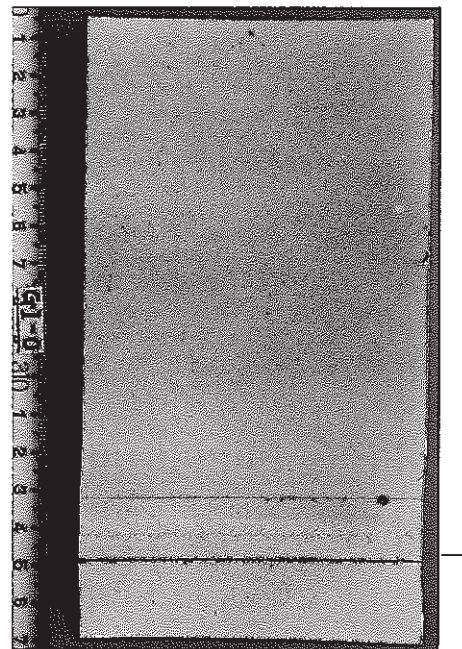
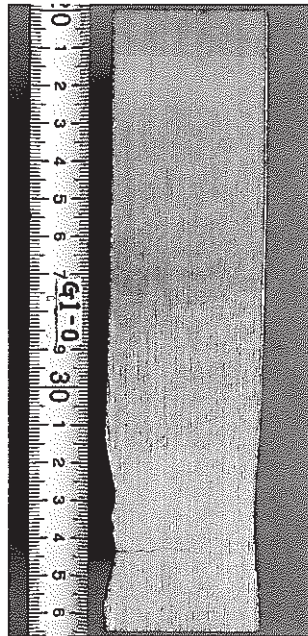
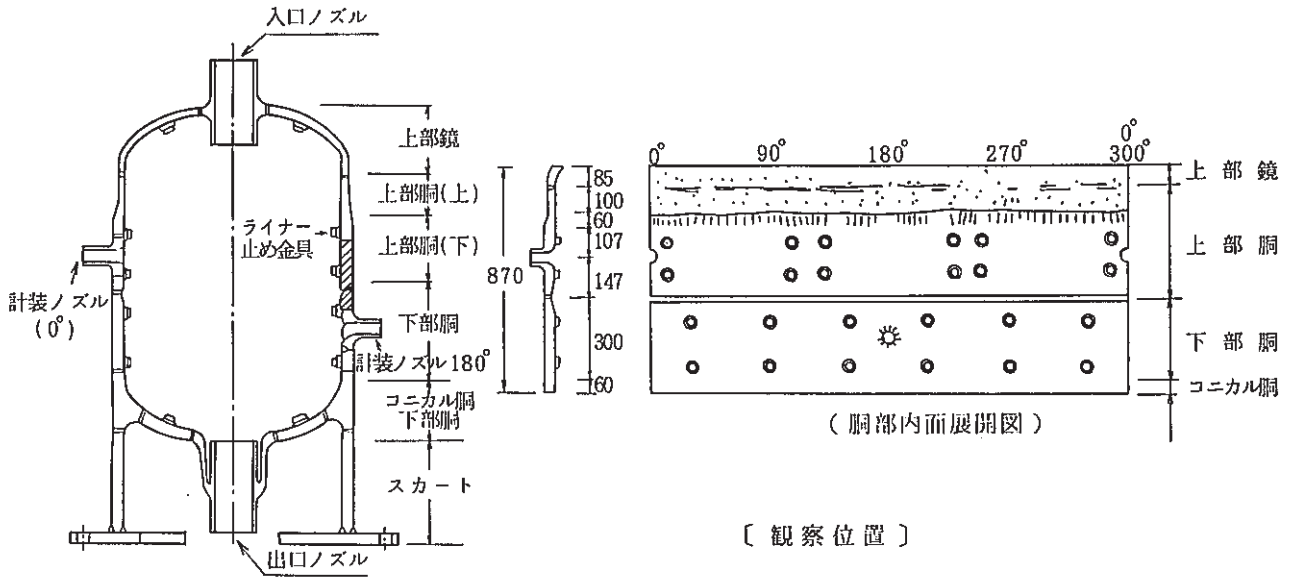
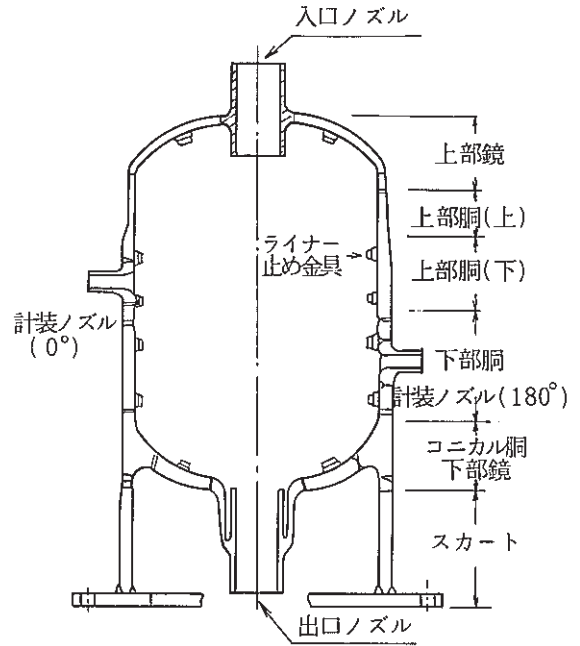
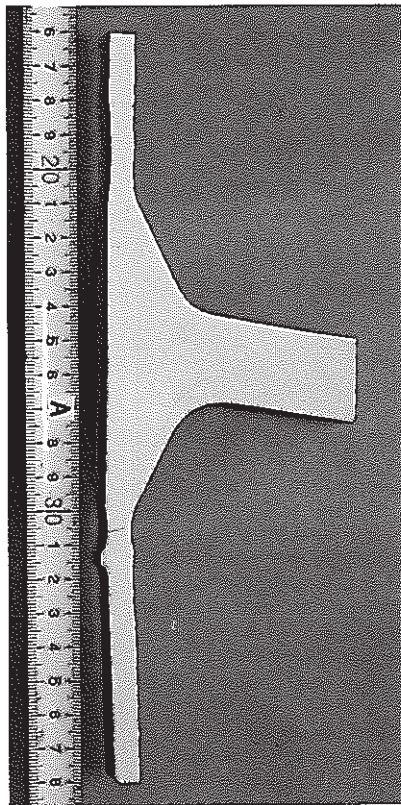


Fig. G-1 Macroscopic Profiles of Finally Welded Joint



Fig. G-1 Macroscopic Profiles of Finally Welded Joint (Cont'd)



[観察位置]

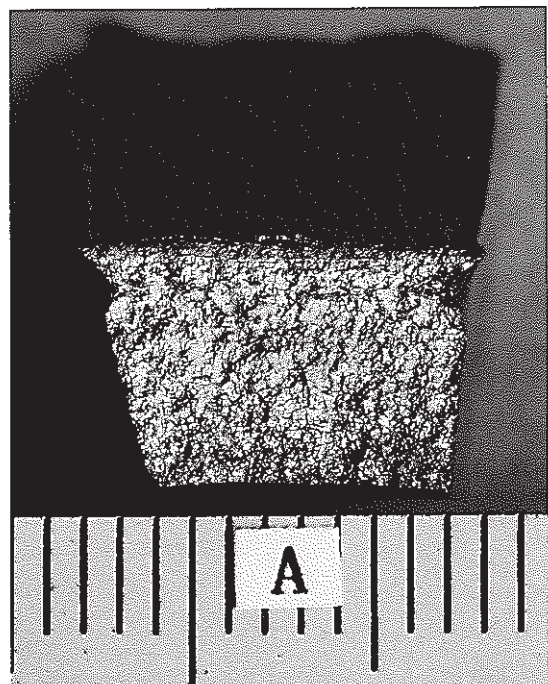
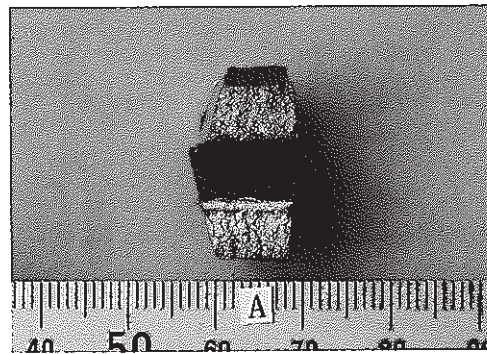


Fig. G-2 Macroscopic Profiles of Inlet Nozzle

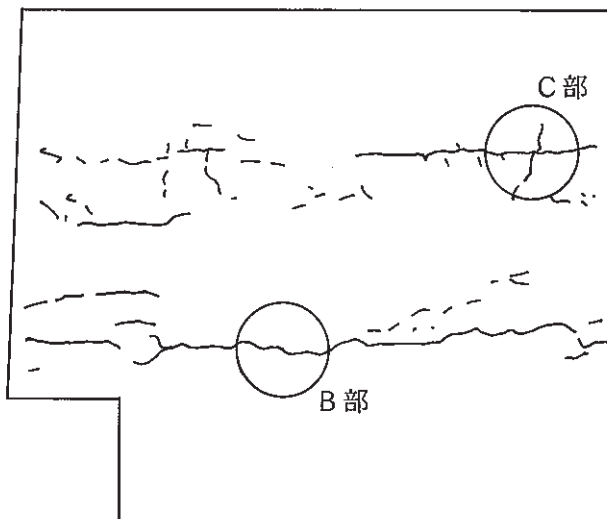
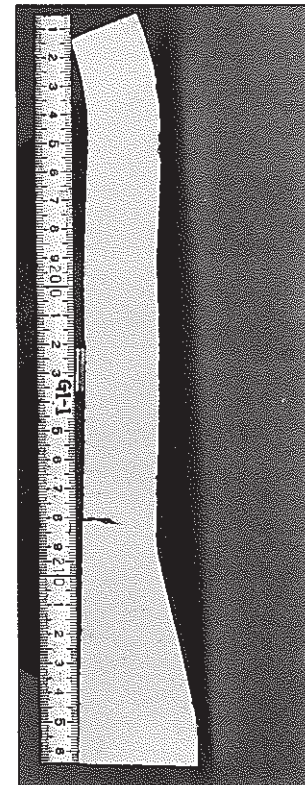
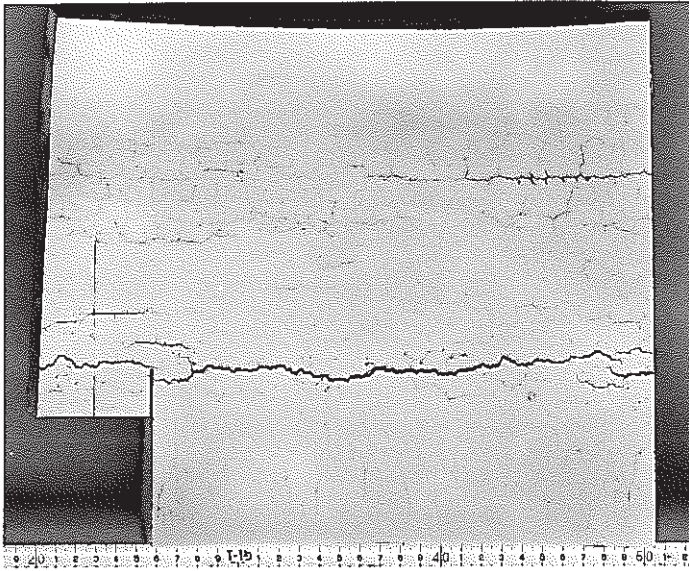
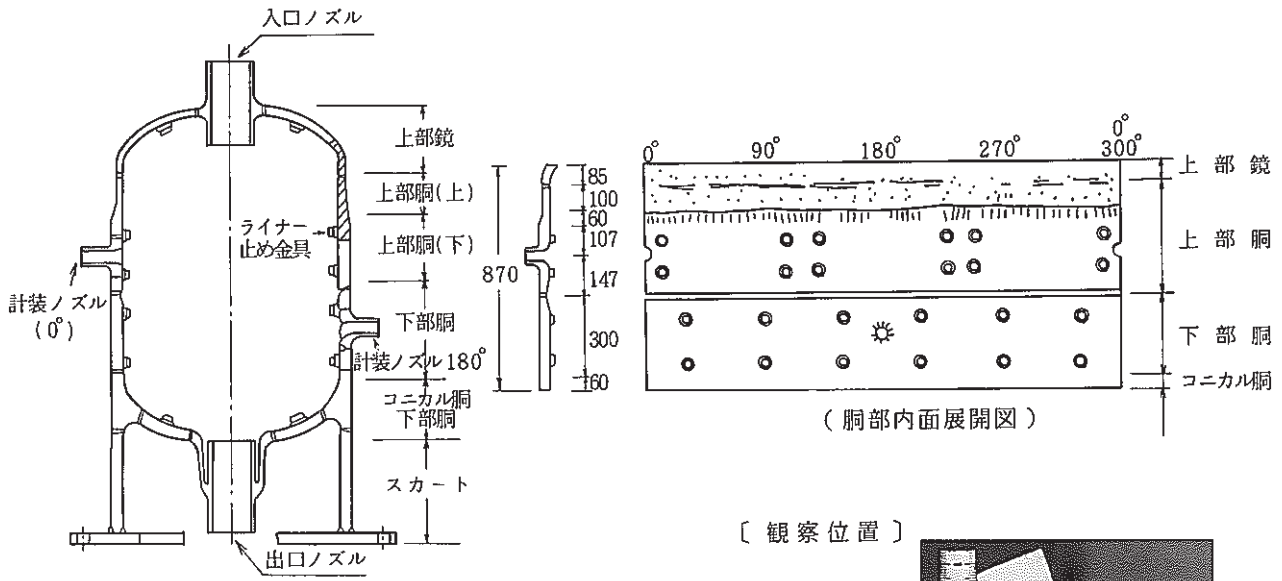


Fig. G-3 Macroscopic Profiles of Thinning Portion

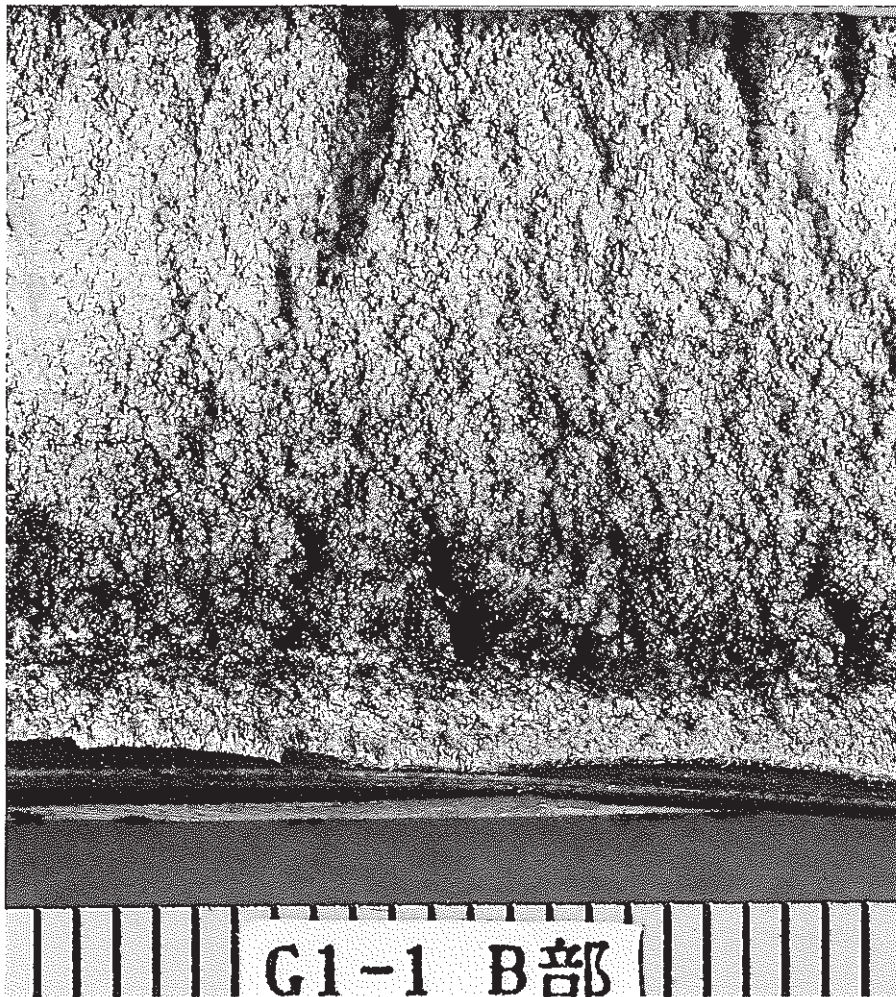
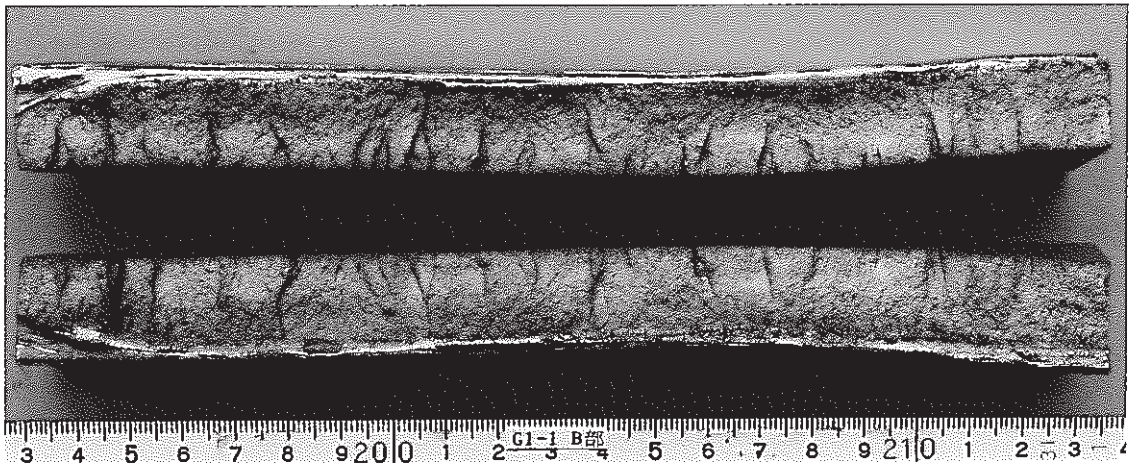


Fig. G-3 Macroscopic Profiles of Thinning Portion
(crack a₂) (cont'd)

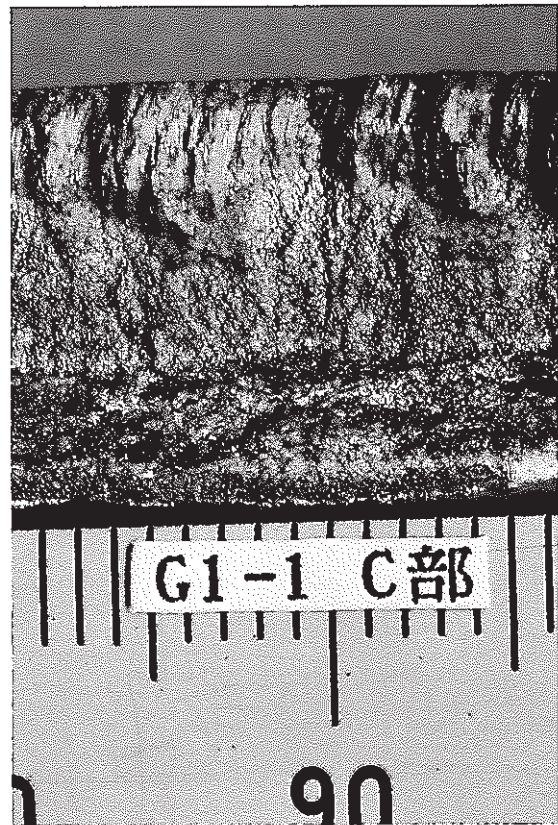
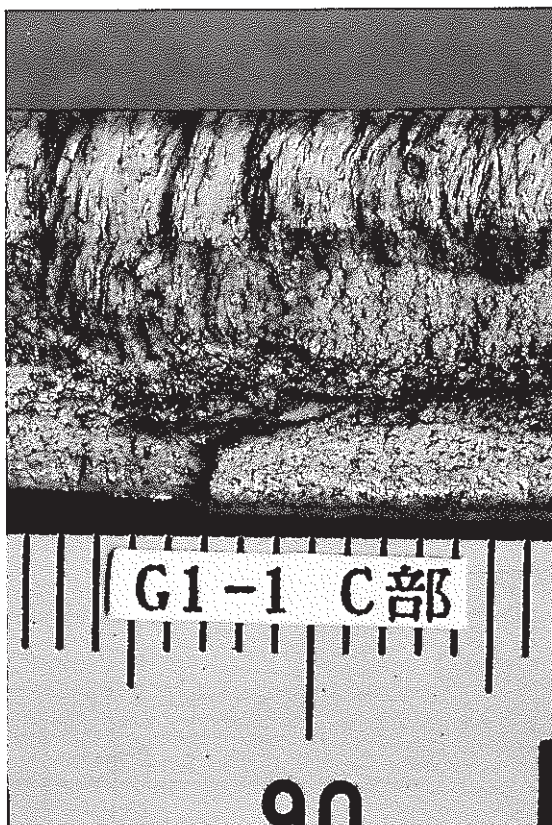
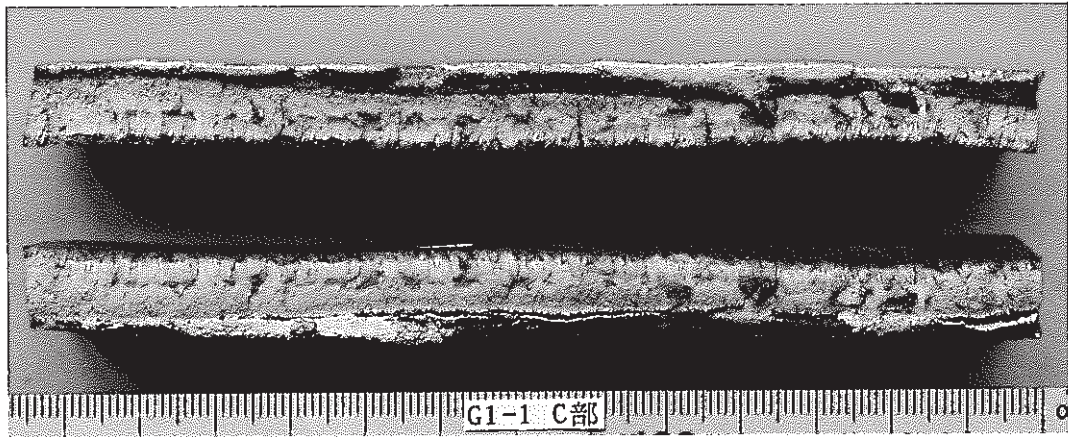


Fig. G-3 Macroscopic Profiles of Thinning Portion
(crack a₁) (cont'd)

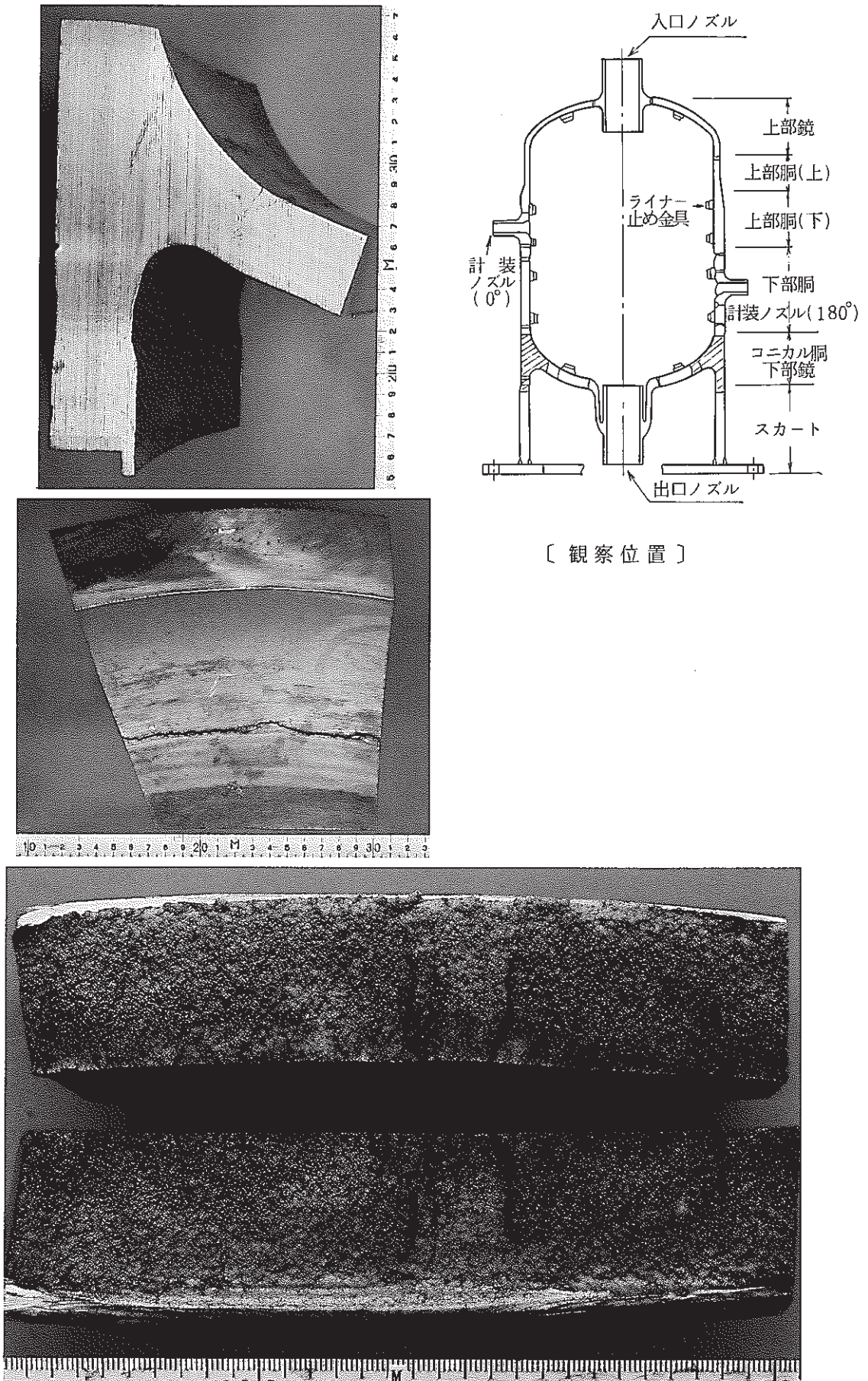


Fig. G-4 Macroscopic Profiles of Conical-Bottom Head

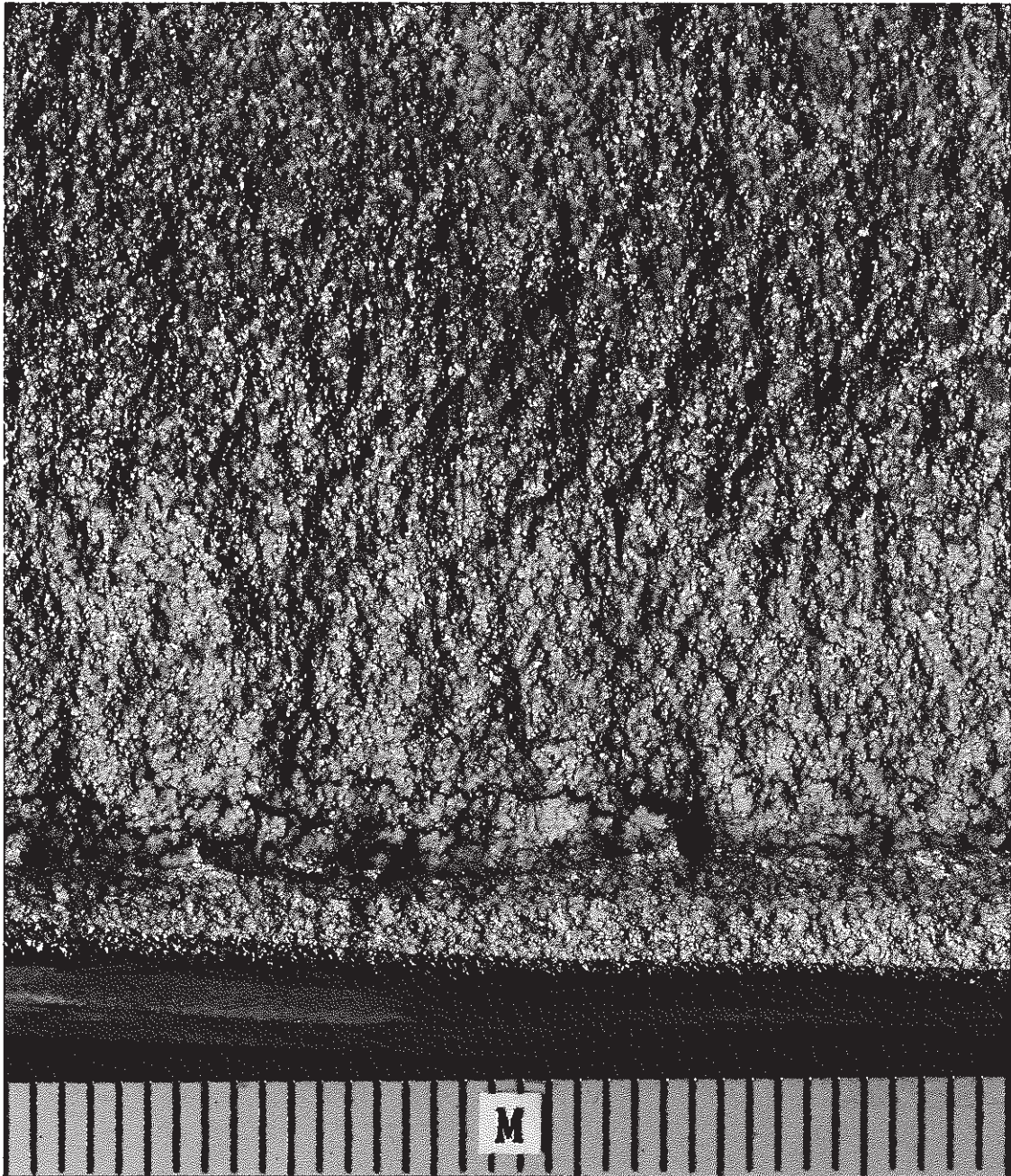


Fig. G-4 Macroscopic Profiles of Conical-Bottom Head (Cont'd)

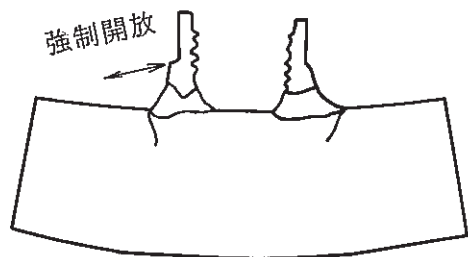
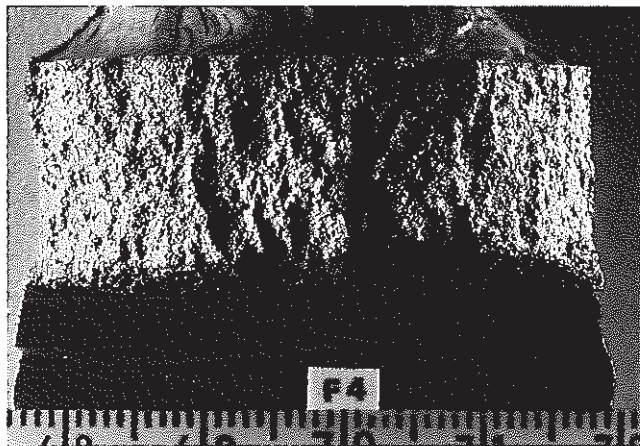
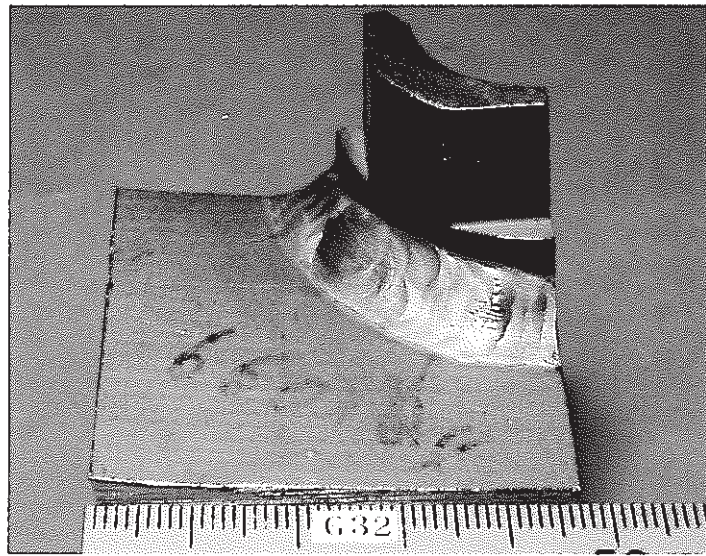


Fig. G-5 Macroscopic Profiles of Stud Bolt

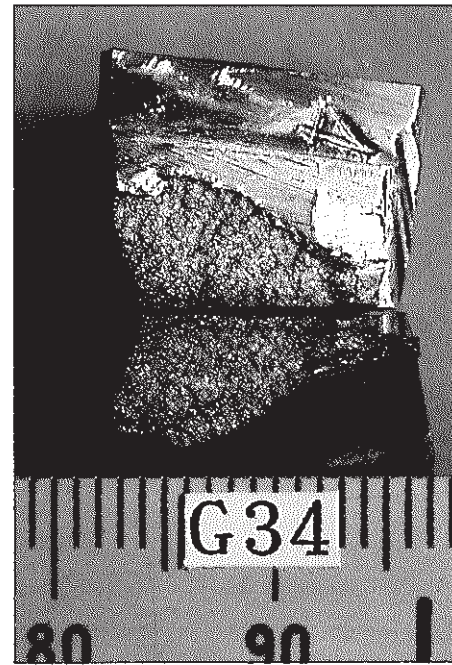
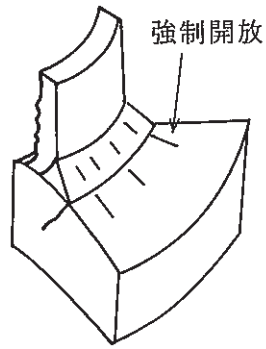
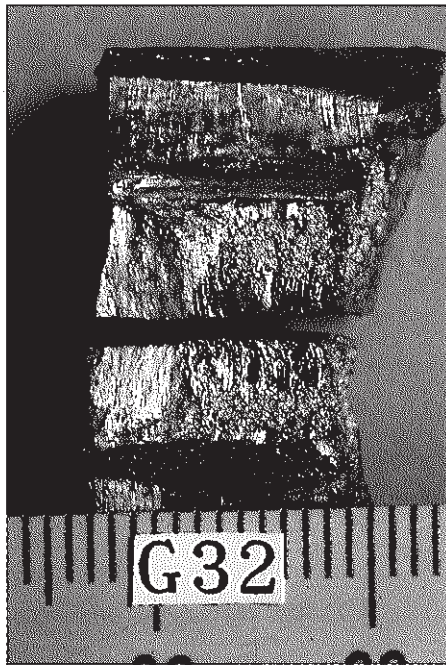
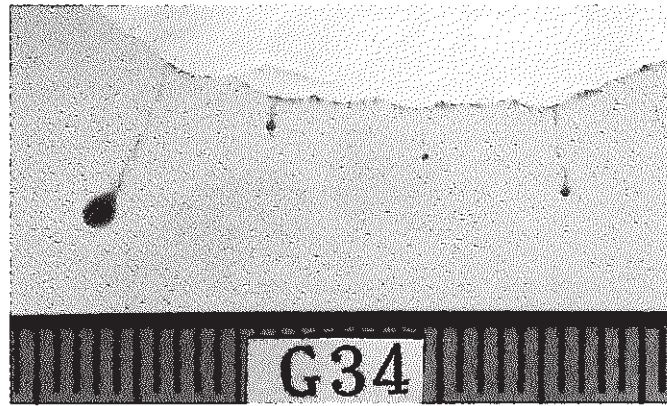
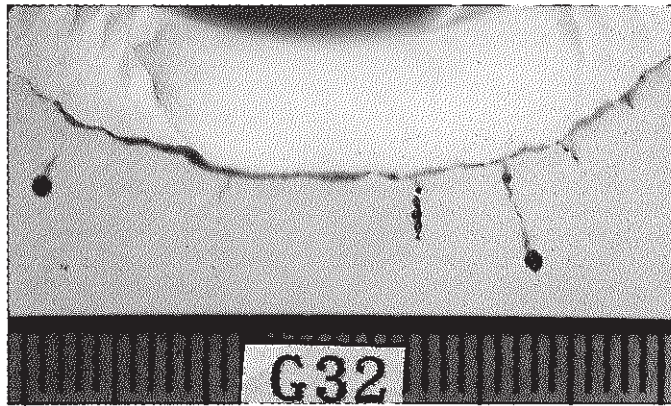


Fig. G-5 Macroscopic Profiles of Stud Bolt (Cont'd)

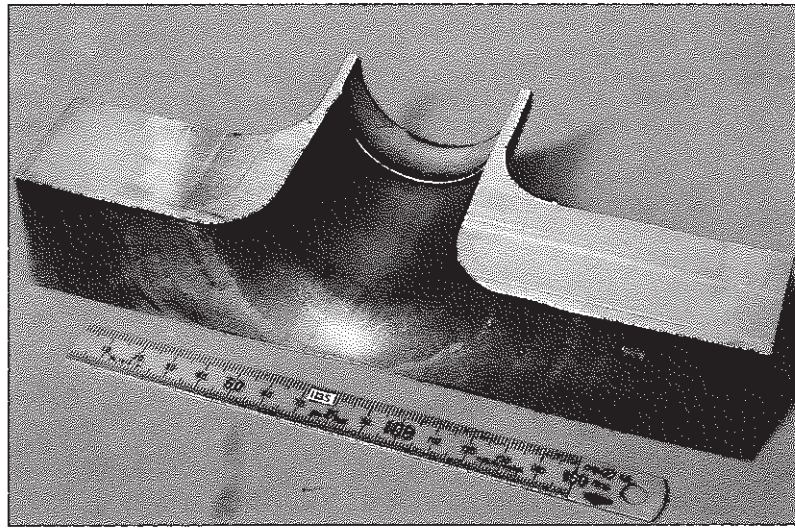


Fig. G-6 Macroscopic Profiles of Instrumental Nozzle

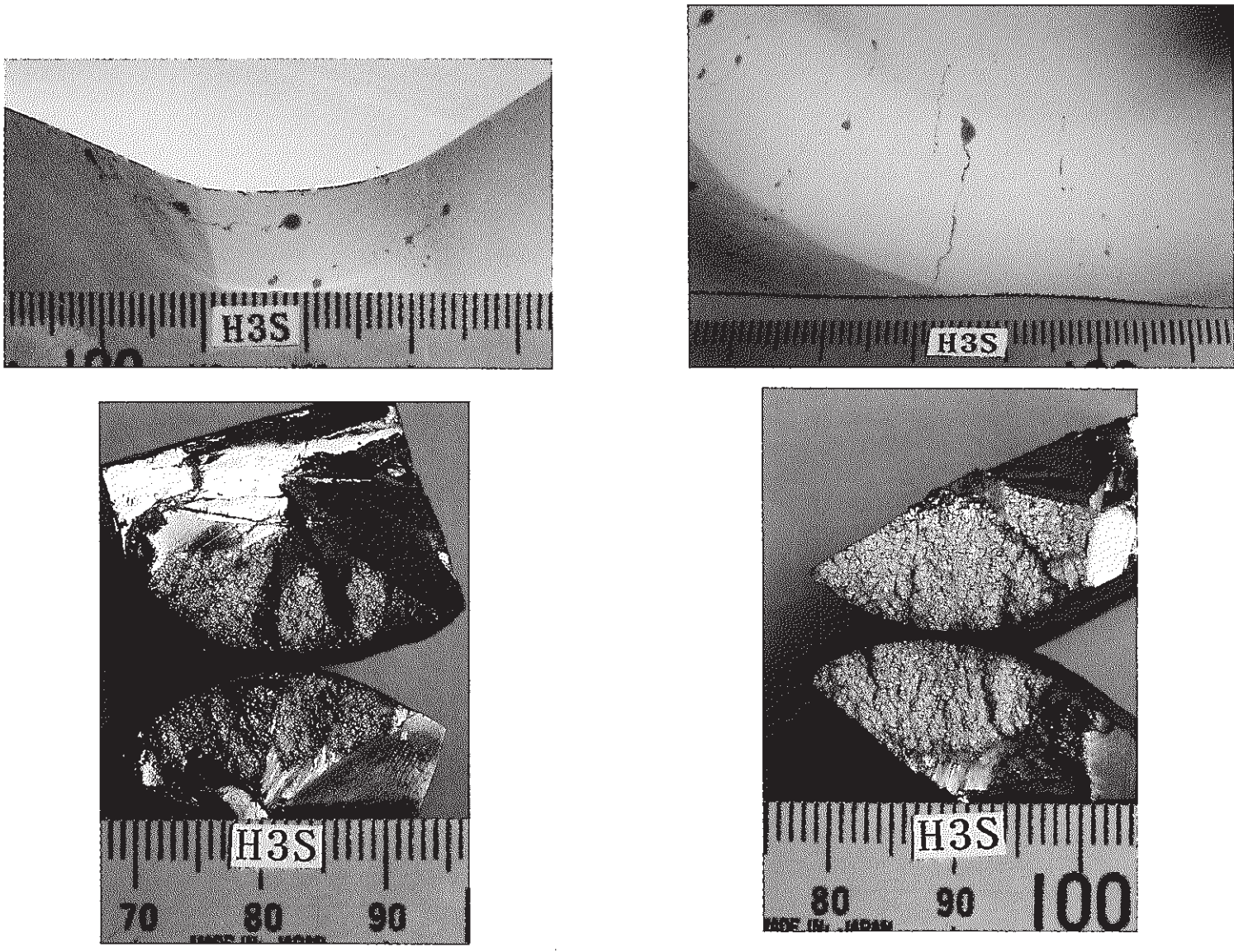


Fig. G-6 Macroscopic Profiles of Instrumental Nozzle (Cont'd)