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JOINING TECHNOLOGY DEVELOPMENT OF ADVANCED
MATERIALS/SS304 BY FRICTION WELDING

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Joining Technology Development of Advanced Materials/SS304
by Friction Welding

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A friction welding is one of the most popular welding method for joint of different materials. In the JMTR(Japan Materials Testing Reactor), intensive studies have been made on various materials and stainless steel joints fabricated by friction welding method and used for structural materials as pressure boundaries of irradiation capsule against the primary coolant of the JMTR. Niobium alloy is one of advanced materials because of the heat resisting and low activation material. The friction welding can be applied to joints of niobium alloy/SS304. In the present work, the welding technique and characteristics of friction welded Nb1%Zr/SS304 were investigated under un-irradiated and irradiated specimens.

The study items for Nb1%Zr/SS304 joints fabricated by friction welding are as follows: the measurement of tensile strength, torsion fatigue strength, burst strength and hardness,, metallography and XMA analysis for neutron-un-irradiated specimens. The measurement of tensile strength and hardness, metallography and XMA anyalysis for neutron-irradiated specimens.

The results obtained were as follows: A suitable fabricating condition were obtained from experiments for friction welding of Nb1%Zr/SS304. From un-irradiated data, tensile strength of Nb1%Zr/SS304 joints was equal to the strength of Nb1%Zr alloy. Fatigue strength of Nb1%Zr/SS304 joints was similar to the strength of Nb1%Zr alloy and burst positions by burst test were the parts of Nb1%Zr alloy. From post-irradiation examination, all specimens have broken at the part of Nb1%Zr alloy, and the strength of irradiated specimens increased comparing with that of un-irradiated specimens. The hardness of irradiated specimens also increased comparing with that of un-irradiated specimens.

Keywords : Friction Welding, Nb1%Zr/SS304 Joint, Tensile Strength, Torsion Fatigue Strength, Burst Strength, Hardness, Metallography, XMA Analysis

摩擦圧接法による先進材料とSS304の接合技術開発

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(1995年2月6日受理)

摩擦圧接法は、異種材接合において最も一般的な接合方法である。JMTRでは、照射キャプセルの圧力バンドリのような構造材として摩擦圧接法により製作した種々の材料とステンレス鋼の接合材の研究が行われている。ニオブ合金は、耐熱性かつ低放射化材料のため先進材料の1つである。この摩擦圧接法が、ニオブ合金とSS304の接合材の製作に適応できる。本報告は、Nb1%Zr/SS304接合材の技術開発及び未照射時と中性子照射後におけるNb1%Zr/SS304接合材の機械的特性評価について述べたものである。

摩擦圧接法により制作したNb1%Zr/SUS304接合材の技術開発として、未照射時におけるNb1%Zr/SUS304接合材の引張強度、疲労強度、バースト強度等の機械的特性評価、金相観察及びXMA分析を実施した。また、中性子照射後におけるNb1%Zr/SUS304接合材の引張強度等の機械的特性評価、金相観察及びXMA分析を実施した。

その結果、未照射時におけるNb1%Zr/SUS304接合材の引張強度及び疲労強度は、Nb1%Zr合金母材の強度とほぼ同等な強度が得られた。また、バースト試験の結果では、バースト位置はNb1%Zr/合金母材部分であった。中性子照射後におけるNb1%Zr/SUS304接合材の引張試験の結果、Nb1%Zr合金の母材部分で破断した。照射したNb1%Zr/SUS304接合材の引張強度は、未照射Nb1%Zr/SUS304接合材の強度と比較して増加する傾向があり、さらに、硬さも増加する傾向が観察された。これらの試験により、Nb1%Zr/SUS304接合材の中性子照射後の機械的特性に関する知見を得ることができ、異材継手として中性子環境下で使用できることが明らかとなった。

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1. Introduction

Technology development for Jointing advanced materials and stainless steel have been investigated for diffusion bonding, brazing, roll bonding, explosive bonding, and hot isostatic pressing (HIP) [1]. On the other hand, a friction welding is one of most popular welding methods for the joint of different materials used as a tube[2-7]. In the JMTR (Japan Materials Testing Reactor), investigations on joints of various materials and stainless steel fabricated by friction welding method and used for structural components as pressure boundaries of an irradiation capsule against the primary coolant of the JMTR, were carried out[8-11].

Niobium and low alloy forms of niobium (Nb1%Zr) have been studied since the early 1930's. Niobium is one of advanced materials from the view point of good heat resisting and its low activation[12]. Additionally, niobium is the same group metal in the periodic table as vanadium. Vanadium is one of advanced materials for the fusion materials[13]. It seems that several kinds of data for Nb1%Zr/SS304 joints can be applicable to the friction welding of vanadium alloy and SS316.

In the present work, characteristics of Nb1%Zr/SS304 joints are investigated under neutron-un-irradiated and irradiated conditions. Tensile, torsion fatigue and burst strength, and hardness of Nb1%Zr/SS304 joints have been measured under neutron-un-irradiated conditions and tensile and hardness of Nb1%Zr/SS304 joints have been measured under neutron-irradiated conditions. Metallographical observation and XMA analysis have been also performed under both conditions. These properties are described in this papers.

2. Characteristics of Nb1%Zr/SS304 Joints under Neutron-un-irradiated Condition

2.1 Welding Conditions

In this work, SS304 and Nb1%Zr alloy rods of 15mm diameter were used as the first trail, of which chemical compositions are shown in Table 1. Physical properties of SS304 and Nb1%Zr alloy are shown in Table 2.

Conditions of friction welding for Nb1%Zr/SS304 joint ars shown in Fig.1. As the shape of Nb1%Zr alloy, a cone of 110 degree was excellent. The welding were made with a rotational speed of 2000 rpm under a friction pressure of 1.5~2.0MPa. Upset pressure was 2.5~3.0MPa and welding time was 0.1sec. After friction welding, the burr glowled at welding was removed by lathe to make test specimens.

1. Introduction

Technology development for Jointing advanced materials and stainless steel have been investigated for diffusion bonding, brazing, roll bonding, explosive bonding, and hot isostatic pressing (HIP) [1]. On the other hand, a friction welding is one of most popular welding methods for the joint of different materials used as a tube[2-7]. In the JMTR (Japan Materials Testing Reactor), investigations on joints of various materials and stainless steel fabricated by friction welding method and used for structural components as pressure boundaries of an irradiation capsule against the primary coolant of the JMTR, were carried out[8-11].

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2.2 Characteristics of Nb1%Zr/SS304 Joints

Tensile, torsion fatigue and burst strengths, and hardness of Nb1%Zr/SS304 joints fabricated by friction welding have been measured under neutron-un-irradiated condition. Metallographical observation and XMA analysis have been also performed.

a) Tensile strength

Tensile test were carried out for five specimens (TypeA~E) fabricated by friction welding at room temperature, 573K, 773K and 973K.

The specimens used are shown in Figs.2-5. Specimens were prepared with the type of rods and pipes. Tensile tests were performed for specimens A and B at room temperature, and specimens C and D at 973K. Photographs of specimens before/after the tensile tests are shown in Figs.6-13.

In the tensile tests at room temperature, all specimens broke at the part of joint section. The results of tensile tests at 293k are tabulated in Table 3. The tensile strengths were 217~286 MPa and 228~256 MPa for rod type and pipe type specimens, respectively. In this case, the tensile strength of Nb1%Zr/SS304 joints was 91~95% of that of base material(Nb1%Zr alloy).The tensile strength of Nb1%Zr/SS304 joints was almost equal to that of the base materials.

On the other hand, in the tensile tests at 973K, rod type specimens broke at the part of joint section, and pipe type specimens at the part of the base material. The results of tensile tests at 973K are summarized in Table 4. Tensile strengths were 118~157 MPa and 206~225 MPa for rod type and pipe type specimens, respectively. The tensile stress of pipe type specimen is almost twice as high as that of rod type specimen.

Tensile tests with specimen type E (Fig.14) were conducted at room temperature, 573K and 773K. The results of the tensile tests are tabulated in Table 5 ~ Table 7, and photographs before/after tensile tests are shown in Fig.15 ~ Fig.18.

In the tensile tests at room temperature, all specimens broke at the part of base material. Tensile strengths were 277~307 MPa, and elongations were 17.3~18.0%. The tensile strength of Nb1%Zr/SS304 joints is equal to the that of Nb1%Zr alloy.

In the tensile tests at 573K and 773K, two specimens broke at the part of Nb1%Zr alloy. Tensile strengths of Nb1%Zr/SS304 joints were 186~206 MPa, and elongation were 17.3~18.3% at 573K. On the other hand, the tensile strengths of Nb1%Zr/SS304 joints were 207~208 MPa, and elongations were 16.8 ~ 17.0% at 773K.

The results of tensile tests are shown in Fig.19. The tensile strength of Nb1%Zr/SS304 joints was almost equal to the that of the base materials at high temperature (see Fig.A-3).

b) Torsion fatigue test

The specimen of torsion fatigue test is shown in Fig.20. The results of torsion fatigue test are shown in Table 8, and the S-N curve obtain from the test is shown in Fig.21. Photographs of

the specimens before/after torsion test are shown in Fig.22 ~ Fig.25. From the results shown above, the torsion fatigue strength of Nb1%Zr/SS304 joints is similar to that of Nb1%Zr alloy.

c) Burst test

The specimen subjected to burst test is shown in Fig.26. To increase the internal pressure of the specimens, water was supplied from the end of Nb1%Zr part which was connected to a hydraulic pump. Conditions of burst test are as follows:

- 1) Temperature : Room Temperature
- 2) Pressure : increased up to 29.4MPa, then step by step with 1.0MPa.

The result of burst test is shown in Table 9. In the test, all specimens have broken at the part of Nb1%Zr alloy. Stress equation of the thin tube is expressed as

$$\sigma = PD/200t, \quad (I.1)$$

σ , P, D and t are fracture stress[MPa], pressure[MPa], diameter[mm] and thickness[mm] of pipe, respectively. The burst stresses were 340~361 MPa which were equal to the strength of base material(Nb1%Zr alloy). Photographs of test specimens before/after burst test are shown in Fig.27 and Fig.28. The burst positions are at base material(Nb1%Zr alloy) away from the joint section by 12mm.

d) Metallographical observation

Metallographical observation was carried out for the specimen fabricated by friction welding. Surface treatment of the specimen was as follows:

- 1) Mechanical polishing
- 2) Electrical etching of SS304

Etching solution : $\text{HCl}(31\text{cm}^3) + \text{HNO}_3(1.7\text{cm}^3) + \text{H}_2\text{SO}_4(1.0\text{cm}^3)$

Etching time : 30sec
- 3) Chemical etching of Nb1%Zr alloy

Etching solution : $\text{H}_2\text{SO}_4(10\text{cm}^3) + \text{H}_2\text{O}(10\text{cm}^3) + \text{HF}(5.0\text{cm}^3) + \text{H}_2\text{O}_2(10\text{cm}^3)$

Etching time : 30sec SWAB

Metallographic photographs are shown in Fig.29 ~ Fig.32. Points photographed are the cone tip(Point A) and the points apart from the tip by 2mm and 4mm (Point B and Point C) as indicated in Fig.29. As shown in Fig.30 ~ Fig.32, the strain of friction welding occurred at the side of Nb1%Zr alloy.

e) XMA observation

Qualitative analysis using XMA was performed to examine elemental distribution in the vicinity of Nb1%Zr/SS304 joint.

XMA photographs of Nb1%Zr/SS304 joints are shown in Fig.33(Point A) and Fig.34(point B). The contents of Nb, C, Fe, Ni and Cr were measured at the cone tip and the tapered part apart from the tip by 5mm. From Fig.33 and Fig.34, each element was changed at the joint. Very narrow intermetallic compound layer was generated at the joint.

2.3 Conclusion

The friction welding technique for jointing different materials have been developed, and joint performance of friction welded Nb1%Zr/SS304 have been investigated under neutron-un-irradiated condition.

A suitable fabricating condition has been obtained from experiments for friction welding of Nb1%Zr/SS304. As the optimum friction conditions, a rotational speed is 2000 rpm and a friction pressure is 1.5~2.0 MPa.

Un-irradiated data on Nb1%Zr/SS304 joints have been obtained, i.e., tensile strength, torsion fatigue strength and burst strength, hardness, metallography and XMA analysis. From the results of tensile tests, tensile strength of Nb1%Zr/SS304 joints is equal to the strength of Nb1%Zr alloy within the error of 10%. The fatigue strength of Nb1%Zr/SS304 joints is similar to that of Nb1%Zr alloy. And the burst positions were base material(Nb1%Zr). From the results of metallographic observation and line scan, it has been found that almost specimens broke at the part of Nb1%Zr alloy, and the joint of Nb1%Zr alloy and SS304 has enough integrity.

3. Characteristics of Nb1%Zr/SS304 Joints under Neutron-irradiated Condition

3.1 Irradiation Capsule

Neutron irradiation on Nb1%Zr alloy and stainless steel joints fabricated by friction welding has been carried out in the JMTR (Japan Materials Testing Reactor). Two capsules named 87M-5J and 87M-20J were fabricated for the irradiation of Nb1%Zr/SS304 joints, being shown in Fig.35 and Fig.38, respectively. They had four inner capsules each. In two inner capsules out of four, the specimens of Nb1%Zr/SS304 joints were directly cooled by coolant water of the reactor. In other two inner capsules, the specimens of Nb1%Zr/SS304 joints were hermetically sealed in the containers. These inner capsules are shown in Fig.36-37 and Fig.39-40. As seen from Fig.36 and Fig.39, specimens were directly cooled by water in 5J-A, 5J-B, 20J-A and 20J-B. On the other hand, the sealed inner capsules (5J-C, 5J-D, 20J-C and 20J-D) were described in Fig.37 and Fig.40. Three neutron fluence and temperature monitors are inserted in the sealed inner capsules.

3.2 Irradiation Temperature

The irradiation conditions of Nb1%Zr/SS304 joints are tabulated in Table 10. The irradiation temperature of Nb1%Zr/SS304 joints were calculated by GENGTC code.

A) 87M-5J capsule

1) 5J-A and 5J-B

The specimens of Nb1%Zr/SS304 joints were directly cooled by water. The surface temperature of Nb1%Zr/SS304 joints were 328K and 331K at SS304 and Nb1%Zr alloy,

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The friction welding technique for jointing different materials have been developed, and joint performance of friction welded Nb1%Zr/SS304 have been investigated under neutron-un-irradiated condition.

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Un-irradiated data on Nb1%Zr/SS304 joints have been obtained, i.e., tensile strength, torsion fatigue strength and burst strength, hardness, metallography and XMA analysis. From the results of tensile tests, tensile strength of Nb1%Zr/SS304 joints is equal to the strength of Nb1%Zr alloy within the error of 10%. The fatigue strength of Nb1%Zr/SS304 joints is similar to that of Nb1%Zr alloy. And the burst positions were base material(Nb1%Zr). From the results of metallographic observation and line scan, it has been found that almost specimens broke at the part of Nb1%Zr alloy, and the joint of Nb1%Zr alloy and SS304 has enough integrity.

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1) 5J-A and 5J-B

The specimens of Nb1%Zr/SS304 joints were directly cooled by water. The surface temperature of Nb1%Zr/SS304 joints were 328K and 331K at SS304 and Nb1%Zr alloy,

respectively. The center of Nb1%Zr/SS304 joints were 330K and 332K at SS304 and Nb1%Zr alloy.

2) 5J-C and 5J-D

Capsule structure and dimension of the sealed inner capsules are shown in Fig.41. Calculation conditions are as follows:

- a) Temperature of coolant water : 323K
- b) Heat transfer coefficient of outer pipe : 12200W/m²K
- c) g-calorific value of iron : 10W/g
- d) Reduced coefficient of materials
 - Nb1%Zr alloy : 1.41
 - Al : 0.77

The results of thermal calculation for 5J-C and 5J-D are shown in Fig.42 and Fig.43, respectively. The surface temperatures of Nb1%Zr and SS304 joints are 792K and 845K, respectively. The center temperature of Nb1%Zr/SS304 joints are 808K and 852K at SS304 and Nb1%Zr alloy, respectively.

B) 87M-20J capsule

1) 20J-A and 20J-B

The specimens of Nb1%Zr/SS304 joints were directly cooled by water. The surface temperature of Nb1%Zr/SS304 joints were 328K and 331K at SS304 and Nb1%Zr alloy, respectively. The center of Nb1%Zr/SS304 joints were 330K and 332K at SS304 and Nb1%Zr alloy.

2) 20J-C and 20J-D

Capsule structure and dimension of the sealed inner capsules are shown in Fig.44. Calculation conditions are as follows:

- a) Temperature of coolant water : 323K
- b) Heat transfer coefficient of outer pipe : 11500W/m²K
- c) g-calorific value of iron : 4.0W/g
- d) Reduced coefficient of materials
 - Nb1%Zr alloy : 1.34
 - Al : 0.80

The results of thermal calculation for 20J-C and 20J-D are shown in Fig.45 and Fig.46, respectively. The surface temperatures of Nb1%Zr and SS304 joints are 690K and 737K, respectively. The center temperature of Nb1%Zr/SS304 joints are 694K and 739K at SS304 and Nb1%Zr alloy, respectively.

The results of thermal calculation by GENGTC code are tabulated in Table 11.

3.3 Characteristics of Nb1%Zr/SS304 Joints

The irradiation conditions of Nb1%Zr/SS304 joints are tabulated in Table 12. Nb1%Zr/SS304 joints fabricated by friction welding were measured after neutron irradiation. Tensile strength, hardness, metallography and XMA analysis were performed.

a) Tensile strength

The tensile tests of Nb1%Zr/SS304 joints were carried out at room temperature and 773K. The specimens used for the tensile tests are shown in Fig.47. The results of the tensile tests at 295K and 773K are shown in Fig.48 and Fig.49, respectively.

Almost specimens irradiated at 323K have broke at part of base material (Nb1%Zr). The results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K are shown in Table 13 and Table 14 (fast neutron fluence : $2.6\sim3.8\times10^{19}\text{n/cm}^2$). The tensile strength of Nb1%Zr/SS304 joints tested at 295K was 489MPa. The strengths of Nb1%Zr/SS304 joints and base material (Nb1%Zr) at 773K were 377MPa and 351MPa, respectively. From these results, the tensile strength of Nb1%Zr/SS304 joints at 773K were higher than that of the base material. The elongation of Nb1%Zr/SS304 joints tested at 295K and 773K were 4.6% and 4.7%, respectively. The elongation of base materials (Nb1%Zr) was 4.0% at 773K, therefore the elongation of Nb1%Zr/SS304 joints at 295K was equal to that at 773K.

Almost specimens irradiated at 323K broke at the part of base material (Nb1%Zr). The results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K are shown in Table 15 and Table 16 (fast neutron fluence : $2.8\sim3.3\times10^{20}\text{n/cm}^2$). The tensile strength of Nb1%Zr/SS304 joints tested at 295K was 515MPa. The strengths of Nb1%Zr/SS304 joints and the base material (Nb1%Zr) at 773K were 355MPa and 325MPa, respectively. From these results, the tensile strength of Nb1%Zr/SS304 joints at 773K were higher than that of base material. The elongation of Nb1%Zr/SS304 joints tested at 295K and 773K were 3.7% and 3.0%, respectively. The elongation of the base materials (Nb1%Zr) was 4.2% at 773K.

Almost specimens irradiated at 743K broke at the part of base material (Nb1%Zr). The results of tensile tests of Nb1%Zr/SS304 joints irradiated at 743K are shown in Table 17 and Table 18 (fast neutron fluence : $3.5\times10^{20}\text{n/cm}^2$), respectively. Tensile strength of Nb1%Zr/SS304 joints tested at 295K was 500MPa. The strength of Nb1%Zr/SS304 joints and the base material (Nb1%Zr) at 773K were 350MPa and 378MPa, respectively. From these results, the tensile strength of Nb1%Zr/SS304 joints at 773K is equal to that of the base material within the error of 10%. The elongation of Nb1%Zr/SS304 joints tested at 295K and 773K were 2.5% and 3.4%, respectively. The elongation of base materials was 6.8% and elongation of the base material was small comparing to that of Nb1%Zr/SS304 joint.

Almost specimens irradiated at 848K also broke at the part of base material (Nb1%Zr). The results of tensile tests of Nb1%Zr/SS304 joints irradiated at 848K are shown in Table 19 and Table 20 (fast neutron fluence : $2.8\sim5.3\times10^{19}\text{n/cm}^2$), respectively. The tensile strength of Nb1%Zr/SS304 joints tested at 295K was 474MPa. The strength of Nb1%Zr/SS304 joints and

base material (Nb1%Zr) at 773K are 362MPa and 503MPa, respectively. From these results, the tensile strength of Nb1%Zr/SS304 joints at 773K was lower than that of base material (Nb1%Zr). the elongation of Nb1%Zr/SS304 joints tested at 295K and 773K are 1.2% and 1.6%, respectively. The elongation of base materials was 3.4%, therefore elongation of Nb1%Zr/SS304 joints is lower than half of base material (Nb1%Zr).

The result of tensile tests of Nb1%Zr/SS304 joints as a function of the irradiation temperature is shown in Fig.50. When irradiation temperature is higher than that at 323K, specimen broke at the part of joints sections and elongation is lower than that of specimen irradiated at 323K.

b) Hardness test

The hardness tests of the cross-section of Nb1%Zr/SS304 joints were carried out after tensile tests. Points measured are described in Fig.51. Hardness profile in the vicinity of Nb1%Zr/SS304 joint is shown in Fig.52. The hardness of Nb1%Zr alloy increased with the increase of the irradiation temperature. The hardness was closely connected with the tensile strength and elongation.

c) Metallographical observation

Metallographical observation was carried out for the specimen fabricated by friction welding. Surface treatment of the specimen was as follows:

1) Mechanical polishing

2) Electrical etching of SS304

Etching solution : $\text{HCl}(31\text{cm}^3) + \text{HNO}_3(1.7\text{cm}^3) + \text{H}_2\text{SO}_4(1.0\text{cm}^3)$

Etching time : 30sec

3) Chemical etching of Nb1%Zr alloy

Etching solution : $\text{H}_2\text{SO}_4(10\text{cm}^3) + \text{H}_2\text{O}(10\text{cm}^3) + \text{HF}(5.0\text{cm}^3) + \text{H}_2\text{O}_2(10\text{cm}^3)$

Etching time : 30sec SWAB

Photographs of metallographical observation are shown in Fig.53 ~Fig.56. Figure 53 and 54 show that SS304 at Nb1%Zr/SS304 joints is strained, and Fig.55 and Fig.56 show that Nb1%Zr alloy side also was strained.

d) XMA observation

Qualitative analysis using XMA was performed to examine elemental distribution in the vicinity of Nb1%Zr/SS304 joint. SEM micrographic photographs of Nb1%Zr/SS304 joints are shown in Fig.57 and Fig.58.

Six elements of Ni, Cr, Fe, Nb, Zr and O are observed at the cone tip of Nb1%Zr/SS304 joint and the point apart from the tip by 5mm. Surface and line analyses results for Ni, Cr, Fe, Nb, Zr and O by SEM/XMA are shown in Fig.59. In Fig.59, it is noted that each element was changed at Nb1%Zr/SS304 joint and the layer of an intermetallic compound was very narrow at the Nb1%Zr/SS304 joint.

3.4 Conclusion

The friction welding technique of different materials have been developed, and joint performance of friction welded Nb1%Zr/SS304 have been investigated under neutron-irradiated condition.

Post irradiation data for Nb1%Zr/SS304 joints has been obtained on tensile strength, hardness, metallographical photograph and XMA analysis. All specimens have broken at the part of Nb1%Zr alloy, and the strength of irradiated specimens increased comparing with that of un-irradiated specimens. The hardness of specimens irradiated at high temperature also increased comparing with that of specimens irradiated at low temperature. Metallographical observation and line scan on the joints have been performed to identify qualitative compositional variations. They are almost the same as those of un-irradiated specimens.

4. Summary

Friction welding technique and the performance of Nb1%Zr/SS304 joint were investigated under neutron-un-irradiated and irradiated condition. Nb1%Zr/SS304 joints fabricated by friction welding have been characterized of tensile, torsion fatigue, burst strength and hardness test, metallographical observation and XMA analysis.

A suitable welding condition has been obtained from experiments for friction welding of Nb1%Zr/SS304 resulting in rotational speed of 2000rpm and friction pressure of 15~20 kgf/cm².

Tensile strength of un-irradiated Nb1%Zr/SS304 joints is equal to the strength of Nb1%Zr alloy within the error of 10%. Fatigue strength of un-irradiated Nb1%Zr/SS304 joints is also similar to that of Nb1%Zr alloy. From the results of metallograph observation and line scan, it has been found that all specimens have broken at the part of Nb1%Zr alloy.

Strength of irradiated specimens is higher than that of un-irradiated specimens. Hardness of irradiated specimens also higher than that of un-irradiated specimens. Metallographical observation and line scan on irradiated joints showed the same qualitative compositional variations as those of un-irradiated joints.

Acknowledgments

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References

1. H.Nishi, Y.Muto and T.Araki, NGEAL, 36(1994)432.
2. K.Okuyama, Welding Technique, 31(1983)24.
3. M.Nakamura, Welding Technique, 31(1983)35.
4. A.Kubota, Welding Technique, 31(1983)40
5. O.Ohashi and T.Hashimoto, Journal of Welding Technique, 45(1976)485.
6. S.Noda, Welding Technique, 33(1985)19.
7. A.Kubota, Welding Technique, 33(1985)28.
8. K.Tanaka, H.Ito, Y.Aoyama and K.Futamatsu, JAERI-M 6799(1976).
9. T.Ishii and I.Tanaka, JAERI-M 7152(1977).
10. Y.Nomura, H.Nakata, M.Tanaka and K.Fukaya, JAERI-M 7629(1978).
11. T.Kikuchi and H.Kawamura, JAERI-M 88-150(1988).
12. L.J.Pionke and J.W.Davis, McDonnell Douglas Co., COO-4247-2(1979).
13. R.F.Mattas, B.A.Loomis and D.L.Smith, Journal of The Materials, Metals&Materials Society, 44(1992)26.

Table 1 Chemical compositions of Nb1%Zr alloy and SS304.

[Nb1%Zr alloy]

Element	C	N	O	H	Zr	Fe	Ta	Ti	Si	W
Spec.	<0.01	<0.03	<0.03	<0.002	0.8~1.2	<0.05	<0.1	<0.05	<0.03	<0.05
Results	0.007	0.002	0.009	0.0004	1.02	0.001	0.070	0.001	0.001	0.007
Element	Mo	Ni	Nb	Remarks ASTM B392-64 1,350°C X 90min. (Annealed)						
Spec.	<0.1	<0.02	>98.5							
Results	0.003	0.001	Bal.							

(in wt%)

[SS304]

(in wt%)

Element	C	Si	Mn	P	S	Cr	Ni
Spec.	<0.08	<1.00	<2.00	<0.045	<0.030	18~20	8~10.5
Results	0.068	0.48	1.23	0.023	0.023	18.34	8.28

Table 2 Physical properties of Nb1%Zr alloy and SS304.

Property \ Material	Nb1%Zr alloy	SS304
Tensile Strength (MPa)	261	627
0.2% Yield Strength (MPa)	160	319
Elongation (%)	34.0	62.8
Hardness	Hv 102	Hv 172
Density (g/cm ³)	8.66	7.82
Melting Point (°C)	~2410	~1410
Thermal Conductivity (cal/cm ² /s/°C)	0.10	0.039
Thermal Expansion (/°C)	7.3×10^{-6}	16.7×10^{-6}

Table 3 Results of tensile test of Nb1%Zr/SS304 joints(Type A and B) at 293K.

Specimen No.	Dimensions (mm)		Tensile Strength (MPa)	Fractured Position	Remarks
	dia.	in. dia.			
1.	13.05	—	242	Welded Interface	bar
2.	13.05	—	217	Welded Interface	bar
3.	13.05	—	286	Welded Interface	bar
mean	—	—	248	—	—
4.	13.0	5.17	228	Welded Interface	pipe
5.	13.0	5.12	229	Welded Interface	pipe
6.	13.0	5.17	256	Welded Interface	pipe
mean	—	—	238	—	—

Table 4 Results of tensile test of Nb1%Zr/SS304 joints(Type C and D) at 973K.

Specimen No.	Dimensions (mm)		Tensile Strength (MPa)	Fractured Position	Remarks
	dia.	in. dia.			
7.	10.00	—	147	Welded Interface	bar
8.	10.00	—	157	Welded Interface	bar
9.	10.01	—	118	Welded Interface	bar
mean	—	—	140	—	—
10.	10.02	5.00	225	Nb1%Zr	pipe
11.	10.00	5.00	206	Nb1%Zr	pipe
12.	10.00	5.00	216	Welded Interface	pipe
mean	—	—	216	—	—

Table 5 Results of tensile test of Nb1%Zr/SS304 joints(Type E) at 293K.

Specimen No.	Dimensions (mm)		Tensile Strength (MPa)	Elongation (%)	Fractured Position
	dia.	length			
13.	6.00	40.0	289	17.3	Nb1%Zr
14.	6.00	40.0	307	18.0	Nb1%Zr
15.	6.00	40.0	277	18.0	Nb1%Zr
mean			292		

Table 6 Results of tensile test of Nb1%Zr/SS304 joints(Type E) at 573K.

Specimen No.	Dimensions (mm)		Tensile Strength (MPa)	Elongation (%)	Fractured Position
	dia.	length			
16.	6.00	40.0	206	18.3	Nb1%Zr
17.	6.00	40.0	186	1.8	Welded Interface
18.	6.00	40.0	205	17.3	Nb1%Zr
mean			199		

Table 7 Results of tensile test of Nb1%Zr/SS304 joints(Type E) at 773K.

Specimen No.	Dimensions (mm)		Tensile Strength (MPa)	Elongation (%)	Fractured Position
	dia.	length			
16.	6.00	40.0	208	17.0	Nb1%Zr
17.	6.00	40.0	207	16.8	Nb1%Zr
mean			208		

Table 8 Results of torsion fatigue test of Nb1%Zr/SS304 joints.

Specimen No.	Stress (MPa)	Fracture Cycles	Remarks
1	123	7.19×10^4	Base Material (Nb1%Zr alloy)
2	98	8.88×10^5	
3*	74	1.26×10^7	
4	123	6.68×10^4	Nb1%Zr/SS304 Joints
5	98	8.23×10^5	
6*	74	1.93×10^7	

* : Non Fracture

Table 9 Results of burst test of Nb1%Zr/SS304 joints.

Specimen No.	Dimensions (mm)		Pressure at Burst (Kg/cm ²)	Hoop Stress (MPa)	Burst Position
	I.D.	O.D.			
1.	11.00	13.00	650	350	Base Material Nb1%Zr
2.	11.00	13.00	630	340	
3.	11.00	13.00	670	361	

Table 10 Irradiation conditions of Nb1%Zr/SS304 tensile test specimen.

Capsule Name	87M-5J	87M-20J
Irradiation Hole	H7-1	K-11
Irradiation Cycle No.	#82	#82
Numbers of Inner Capsule	4	4
Inner Capsule Name	5J-A~D	20J-A~D
Numbers of Tensile Specimen	12	12
Thermal Neutron Fluence (n/cm ²)	$\sim 4 \times 10^{20}$	$\sim 4 \times 10^{19}$
Fast Neutron Fluence (n/cm ²)	$2 \sim 4 \times 10^{20}$	$2 \sim 5 \times 10^{19}$

Table 11 Results of thermal calculation by GENG code.

(Unit : °C)

Inner Capsule Name	5J - C		5J - D		20J - C		20J - D	
	SS304	Nb1%Zr	SS304	Nb1%Zr	SS304	Nb1%Zr	SS304	Nb1%Zr
Material of Specimen								
Center of SUS Core	817	848	783	800	665	706	712	752
Outside of SUS Core	816	846	782	799	661	703	708	748
Inside of Thermal Bond	790	821	737	756	—	—	—	—
Outside of Thermal Bond	783	814	732	752	—	—	—	—
Inside of Specimen	533	582	537	576	426	470	416	462
Outside of Specimen	514	574	523	570	422	468	412	460
Inside of Thermal Bond	300	315	354	368	—	—	—	—
Outside of Thermal Bond	290	303	347	360	—	—	—	—
Inside of SUS Core	164	168	150	150	219	227	143	146
Outside of SUS Core	147	149	135	135	212	220	132	135
Inside of Outer Shell	78.3	79.2	74.1	74.0	60.5	61.4	63.7	64.3
Outside of Outer Shell	74.2	74.8	70.6	70.4	58.8	59.3	61.5	62.0

Table 12 Irradiation conditions of Nb1%Zr/SS304 joints.

	Irradiation Temperature (K)	Fast Neutron Fluence (n/cm ²)	Number of Test Specimens
A	323	2.6×10^{19}	3
B	323	3.8×10^{19}	3
C	323	2.8×10^{20}	3
D	323	3.3×10^{20}	3
E	848	5.3×10^{19}	3
F	848	2.8×10^{19}	3
G	743	3.5×10^{20}	3
H	743	3.5×10^{20}	3

Table 13 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
A-W1	295	467.5	475.3	4.8
A-W2	773	324.4	355.7	4.3
A-B1	773	353.8	360.6	4.1

Table 14 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
B-W4	295	464.5	502.7	4.3
B-W5	773	344.0	397.9	5.0
B-B4	773	334.2	341.0	3.8

Table 15 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
C-W13	295	479.2	484.1	3.9
C-W14	773	293.0	336.1	4.8
C-B7	773	316.5	318.5	4.3

Table 16 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 323K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
D-W16	295	——— #1	544.9	3.4
D-W17	773	281.3	374.4	1.1
D-B10	773	——— #1	331.2	4.1

#1 : Broken before 0.2% proof stress.

Table 17 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 743K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
G-W19	295	—— #1	424.3	0.7
G-W20	773	259.7	417.5	6.1
G-B8	773	—— #1	395.9	8.7

#1 : Broken before 0.2% proof stress.

Table 18 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 743K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
H-W22	295	—— #1	576.2	4.3
H-W23	773	—— #1	282.2	0.7
H-W11	773	345.9	359.7	4.8

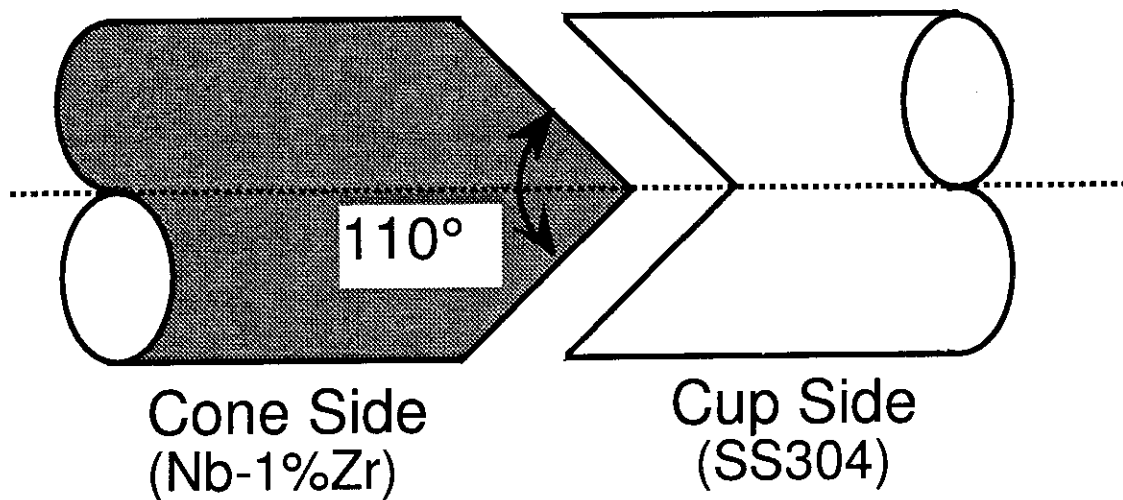
#1 : Broken before 0.2% proof stress.

Table 19 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 848K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
E-W7	295	405.7	493.9	1.2
E-W8	773	262.6	323.4	1.1
E-B2	773	474.3	480.2	3.9

Table 20 Results of tensile tests of Nb1%Zr/SS304 joints irradiated at 848K.

Specimen No.	Test Temp. (K)	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
F-W10	295	411.6	453.7	1.1
F-W11	773	272.4	400.8	2.0
F-B5	773	512.5	526.3	2.9



Conditions

Rotational Speed : 2000 rpm

Friction Pressure : 1.5~2.0MPa

Upset Pressure : 2.5~3.0MPa

Welding Time : 0.1 sec

Fig.1 Conditions of friction welding for Nb1%Zr/SS304 joint.

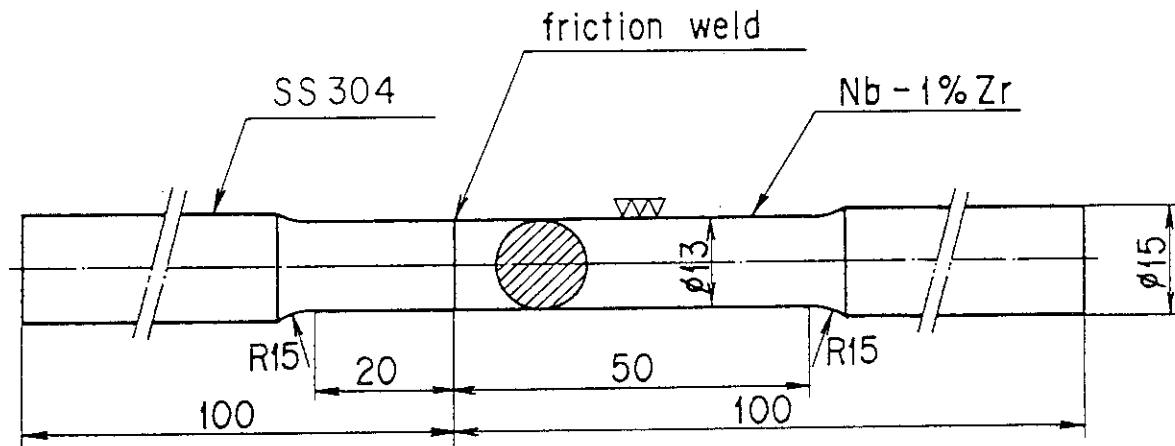


Fig.2 Rodlike specimen of tensile test at 293K(Type A).

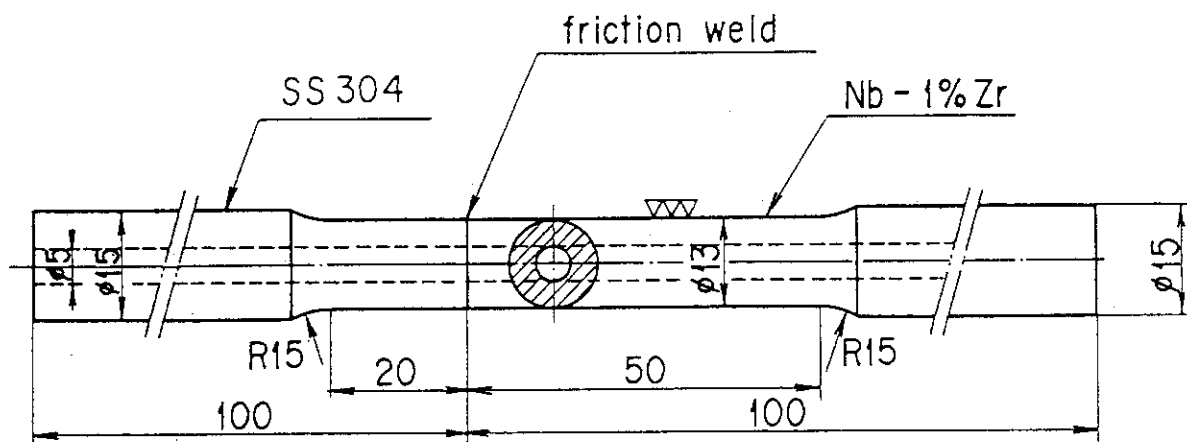


Fig.3 Tubular specimen of tensile test at 293K(Type B).

— 25 —

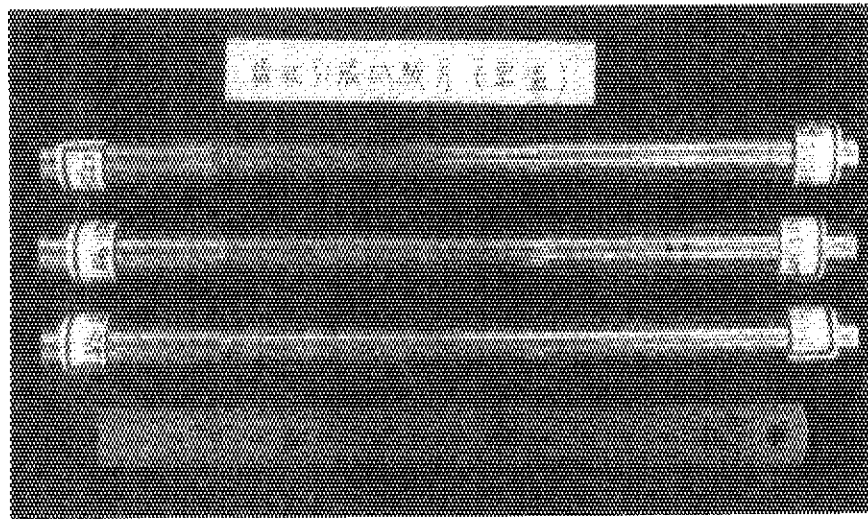


Fig.6 Appearance of type A before tensile test.

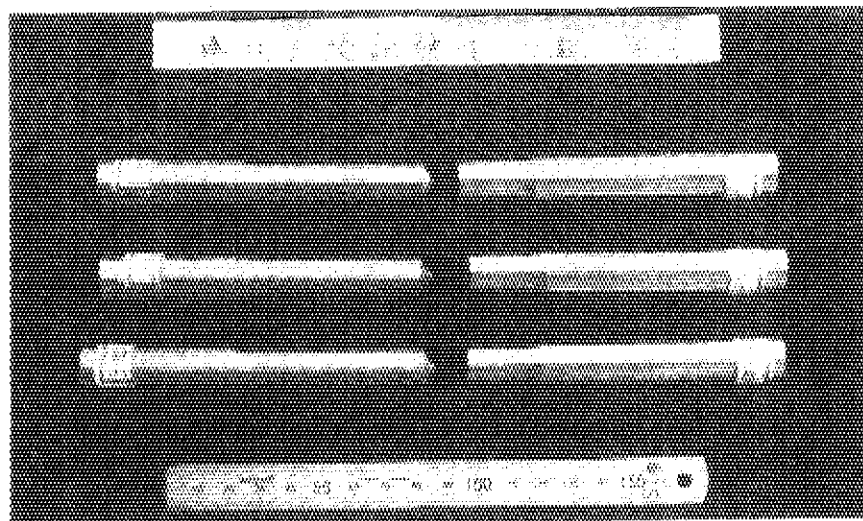


Fig.7 Appearance of type A after tensile test.

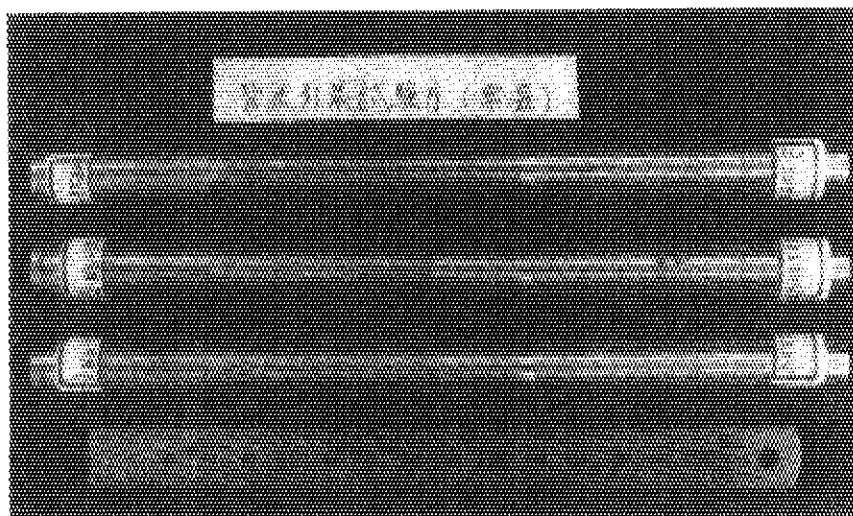


Fig.8 Appearance of type B before tensile test.

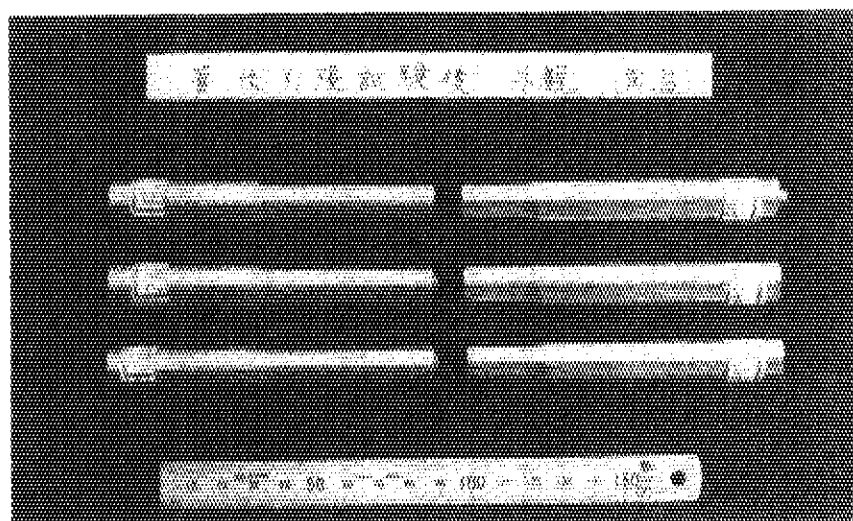


Fig.9 Appearance of type B after tensile test.

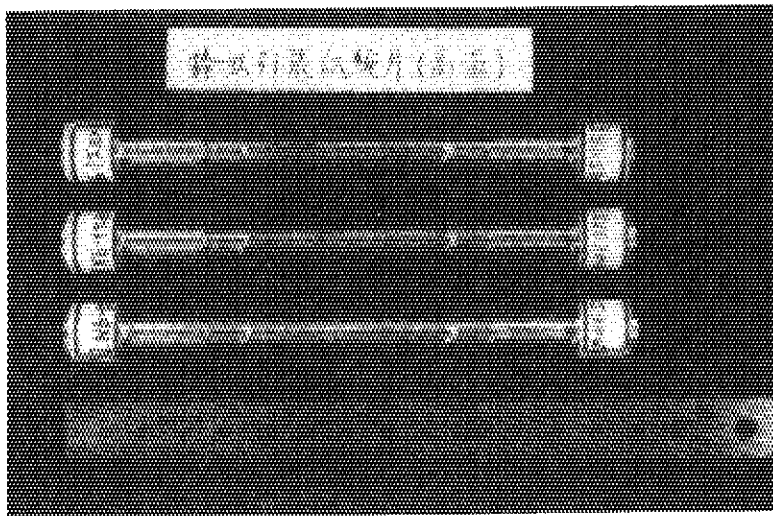


Fig.10 Appearance of type C before tensile test.

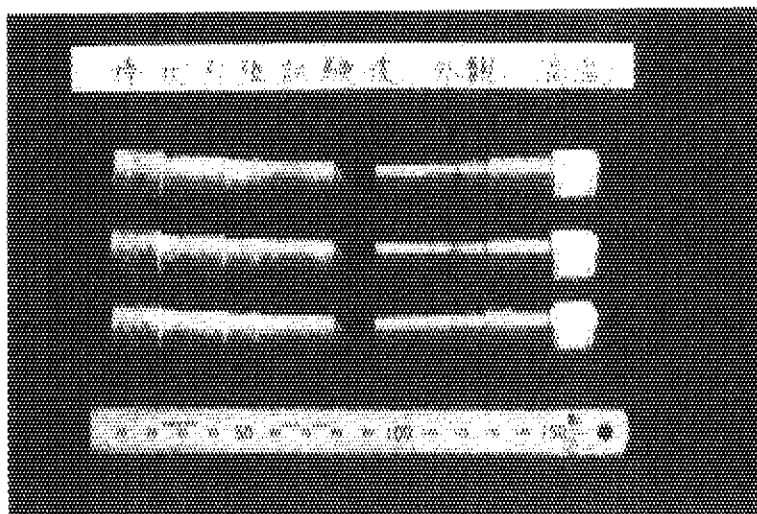


Fig.11 Appearance of type C after tensile test.

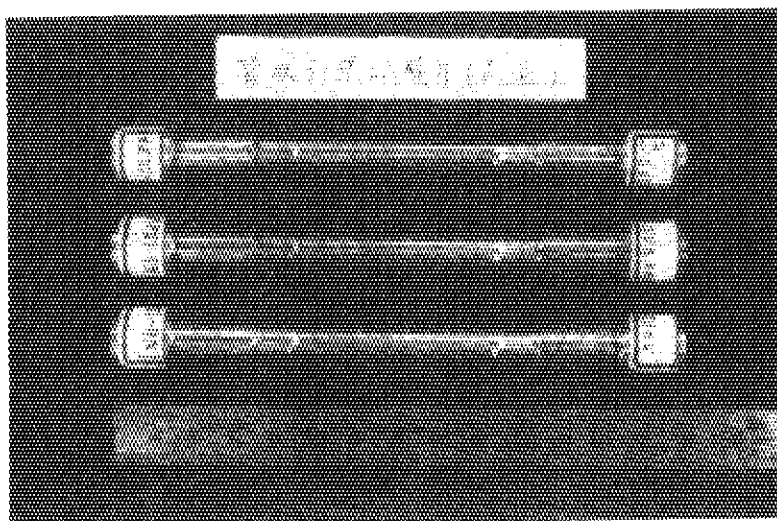


Fig.12 Appearance of type D before tensile test.

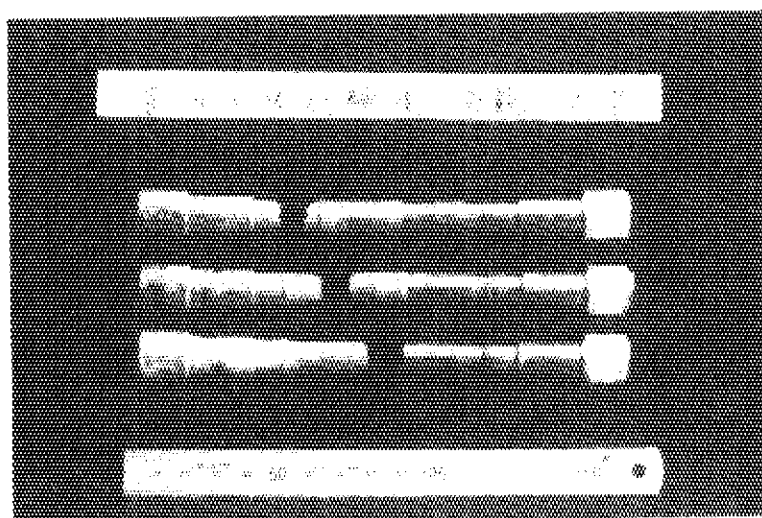


Fig.13 Appearance of type D after tensile test.

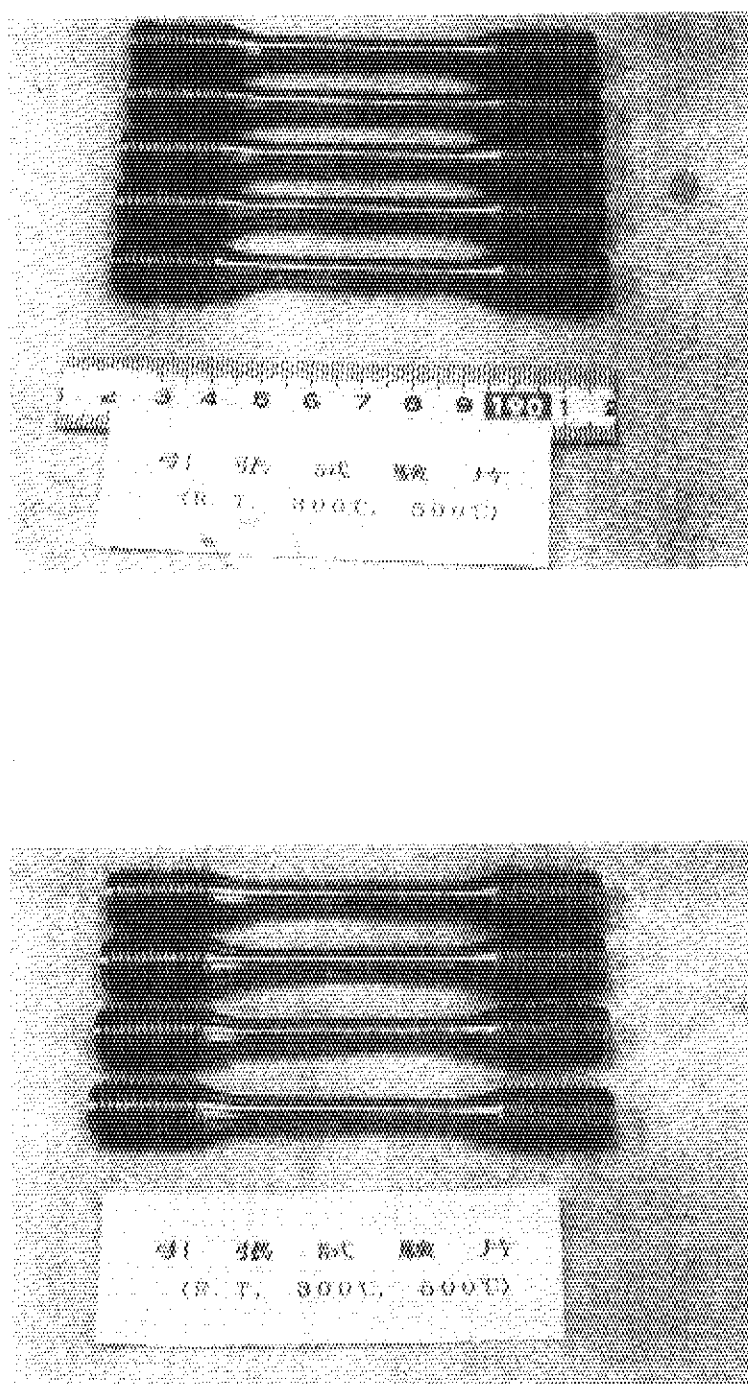


Fig.15 Appearance of type E before tensile test.

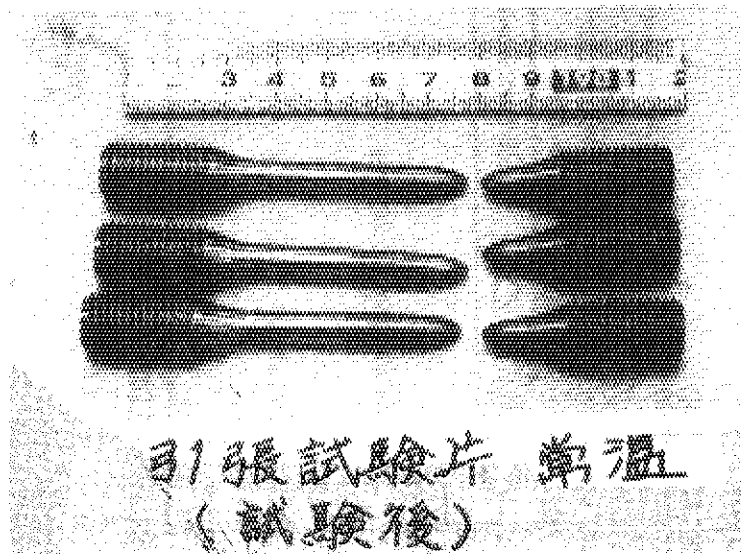


Fig.16 Appearance of type E after tensile test at 293K.

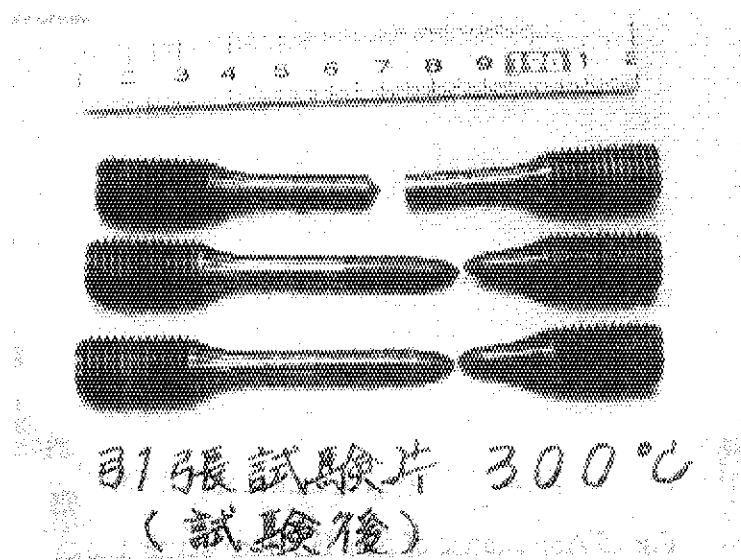


Fig.17 Appearance of type E after tensile test at 573K.

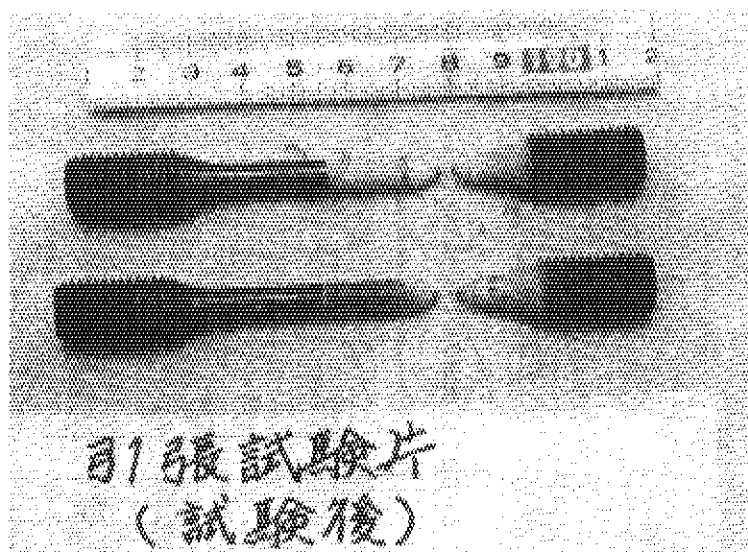


Fig.18 Appearance of type E after tensile test at 773K.

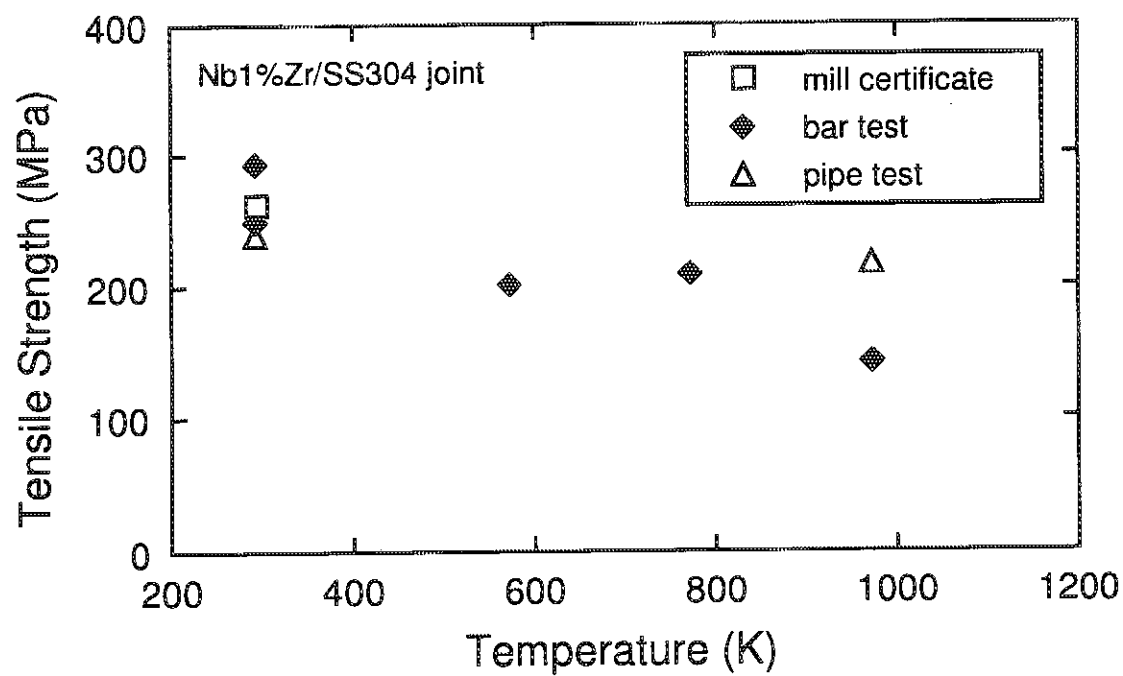


Fig.19 Results of tensile test for Nb1%Zr/SS304 joint.

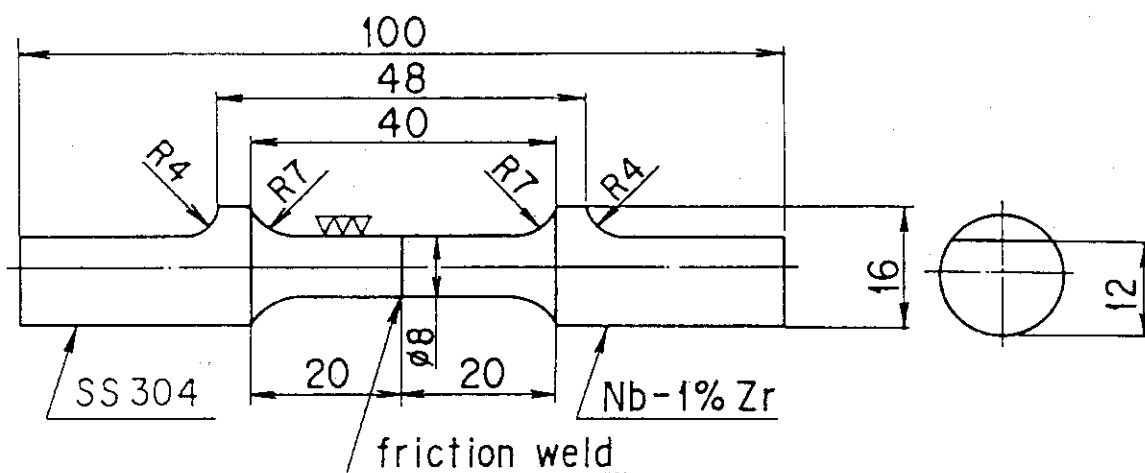


Fig.20 Torsion fatigue test specimen.

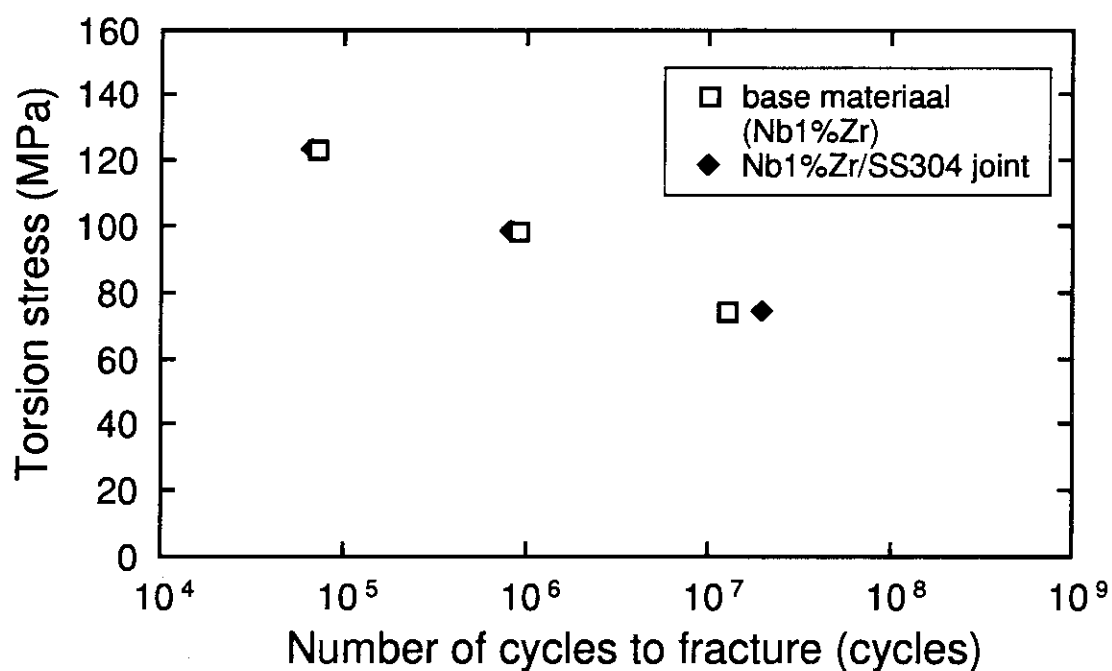


Fig.21 S-N curve of torsion fatigue test.

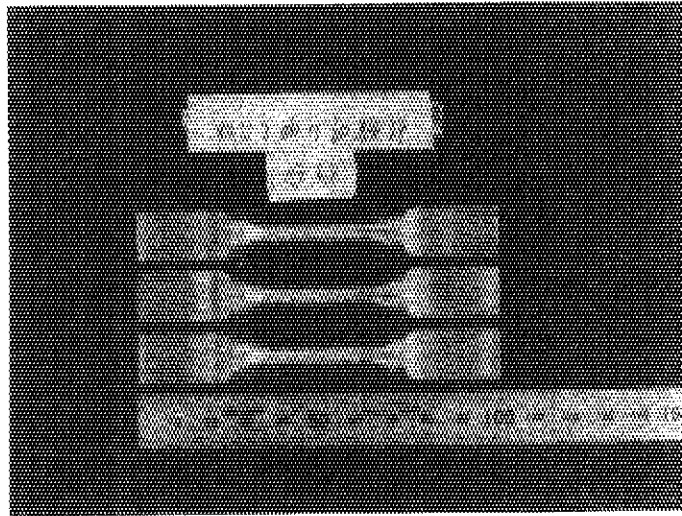


Fig.22 Appearance of specimen before torsion fatigue test(base material).

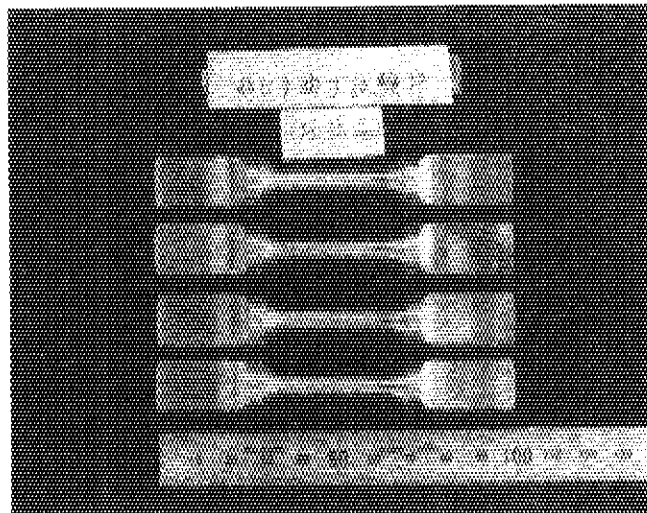


Fig.23 Appearance of specimen before torsion fatigue test(Nb1%Zr/SS304 joint).

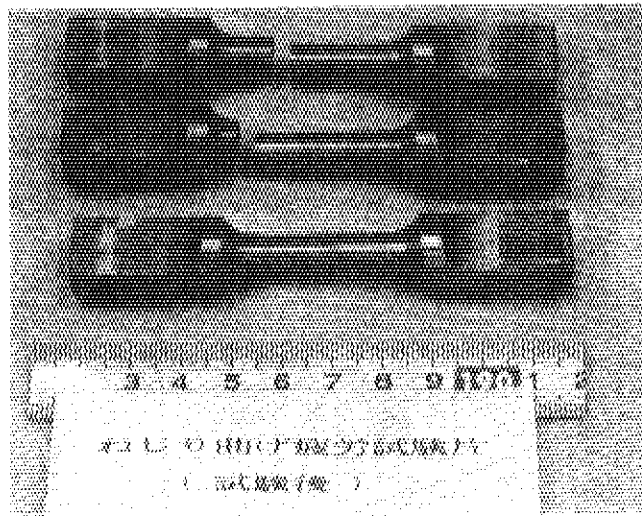


Fig.24 Appearance of specimen after torsion fatigue test(base material).

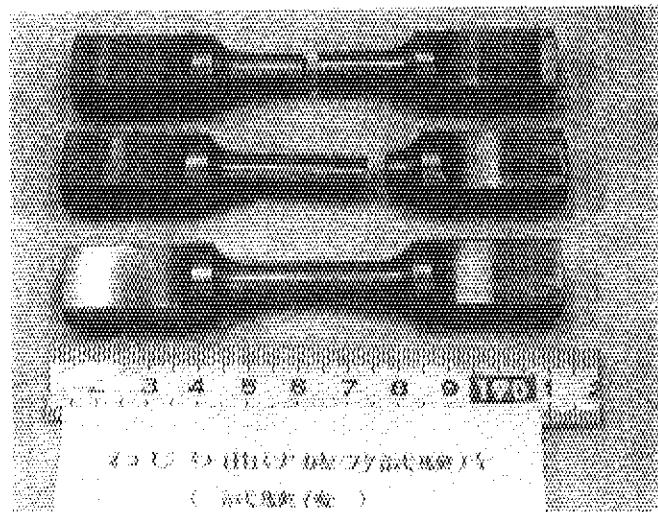


Fig.25 Appearance of specimen after torsion fatigue test(Nb1%Zr/SS304 joint).

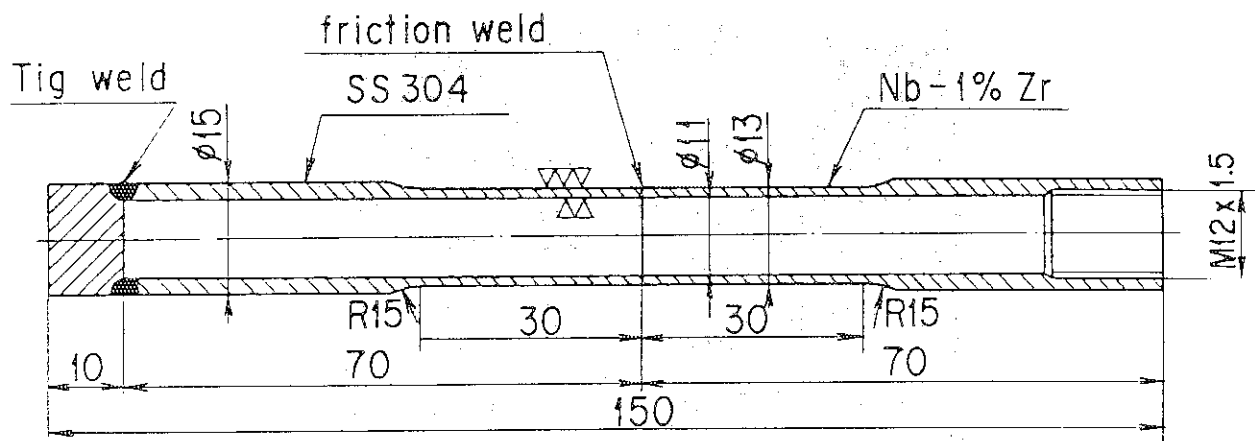


Fig.26 Burst test specimen.

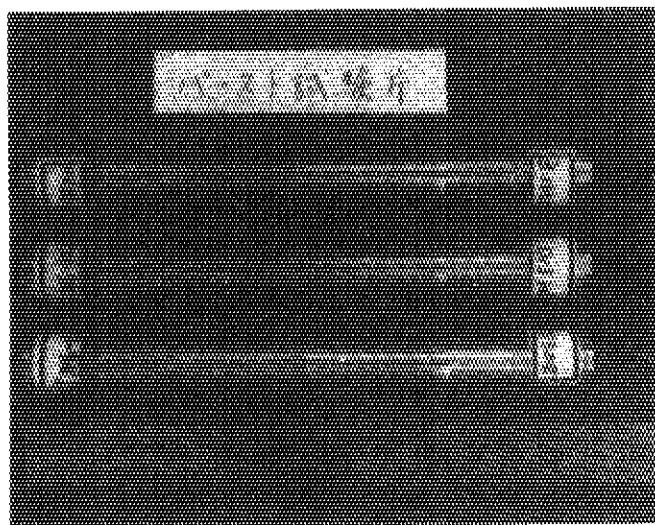


Fig.27 Appearance of specimen before burst test.

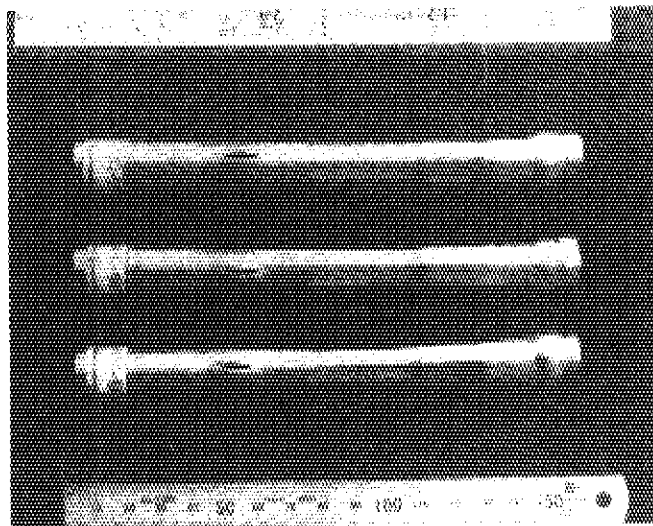


Fig.28 Appearance of specimen after burst test.

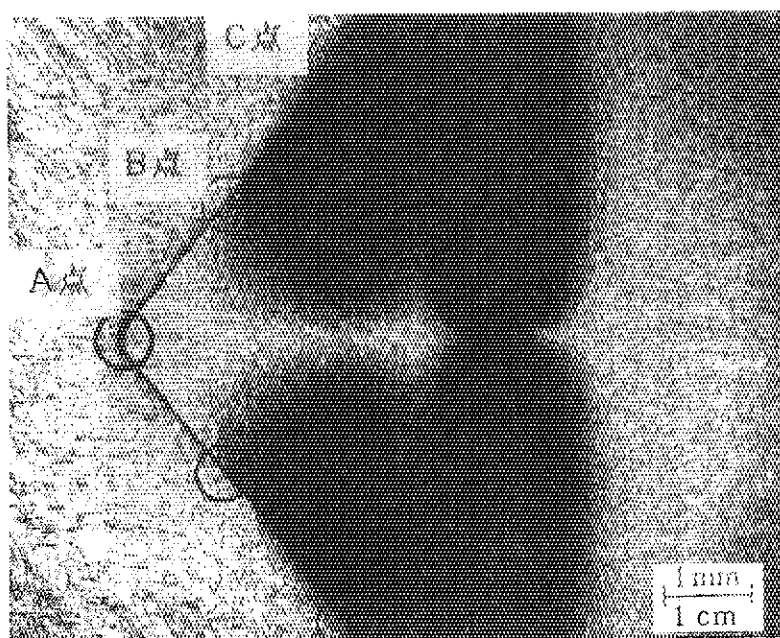


Fig.29 Metallographic photograph of Nb1%Zr/SS304 joint(whole view).

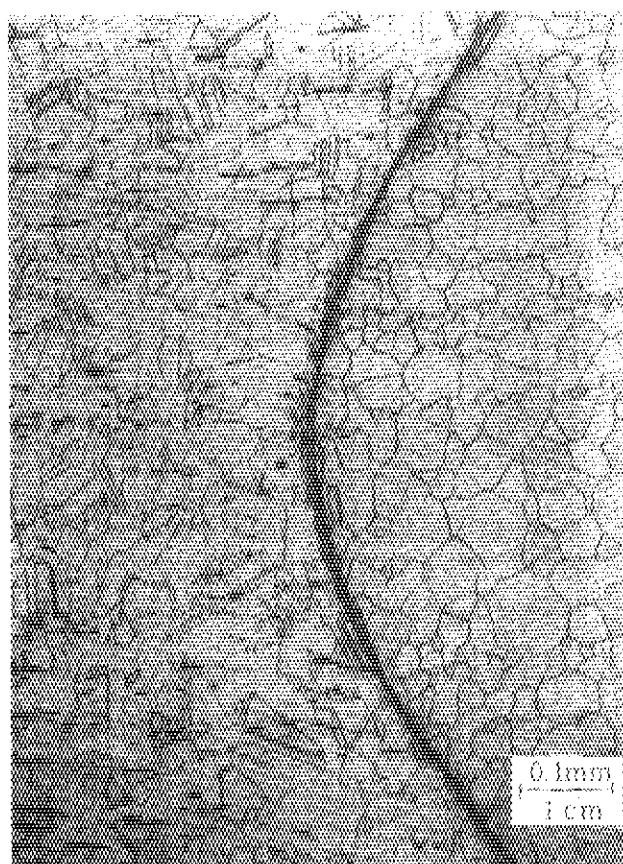


Fig.30 Metallographic photograph of Nb1%Zr/SS304 joint(cone tip : Point A).

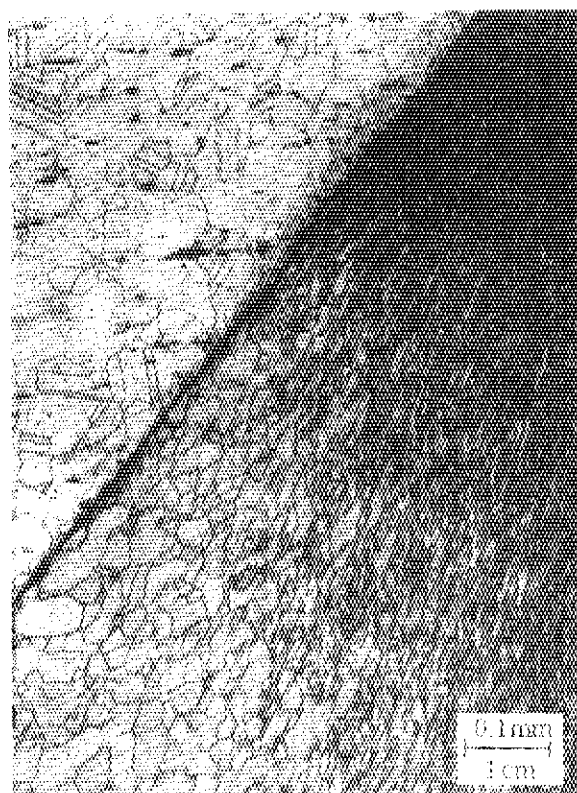


Fig.31 Metallographic photograph of Nb1%Zr/SS304 joint(tapered part : Point B).

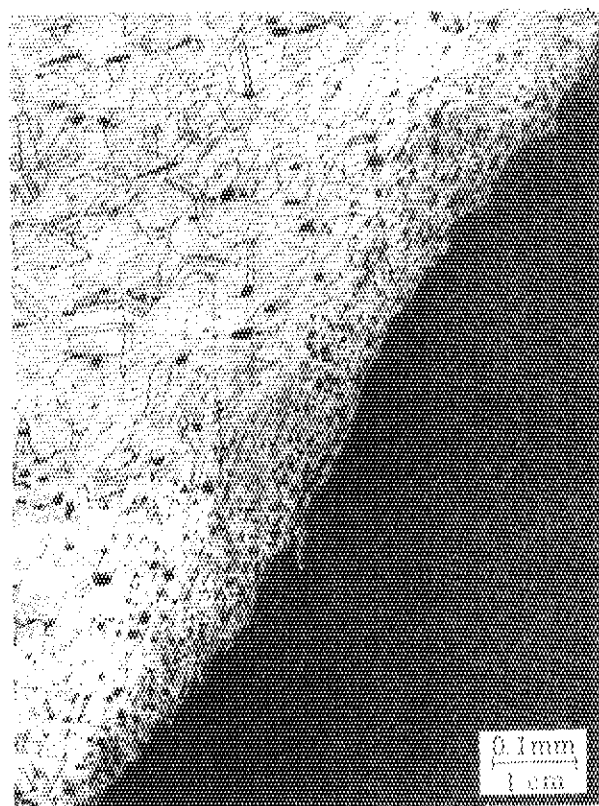


Fig.32 Metallographic photograph of Nb1%Zr/SS304 joint(tapered part : Point C).

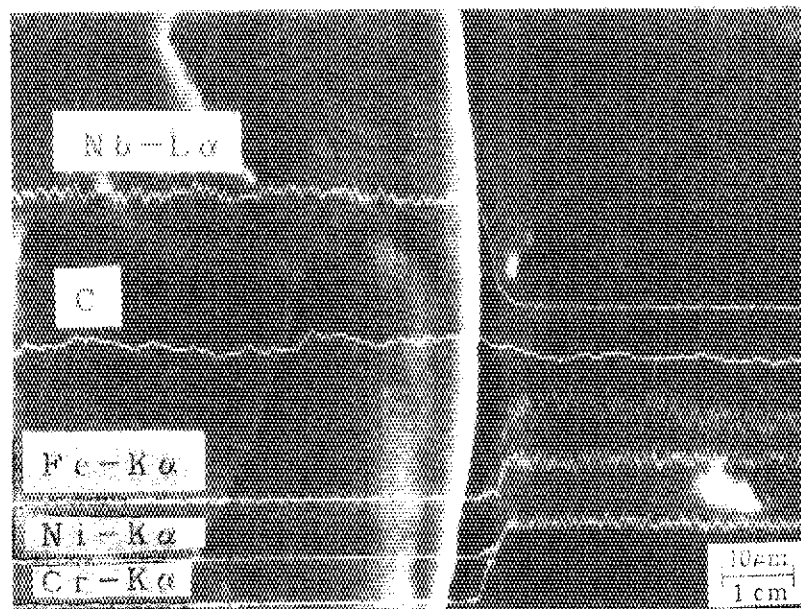


Fig.33 XMA photograph of Nb1%Zr/SS304 joint(cone tip : Point A).

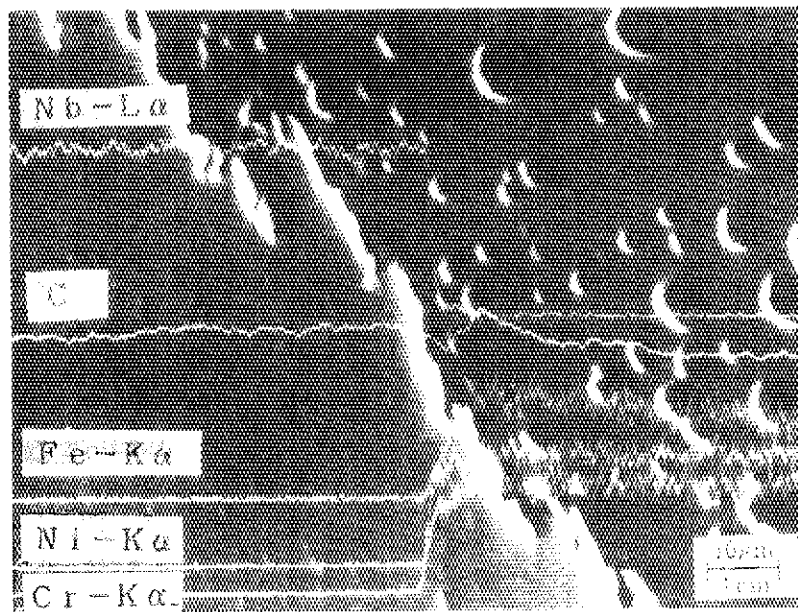


Fig.34 XMA photograph of Nb1%Zr/SS304 joint(tapered part : Point B).

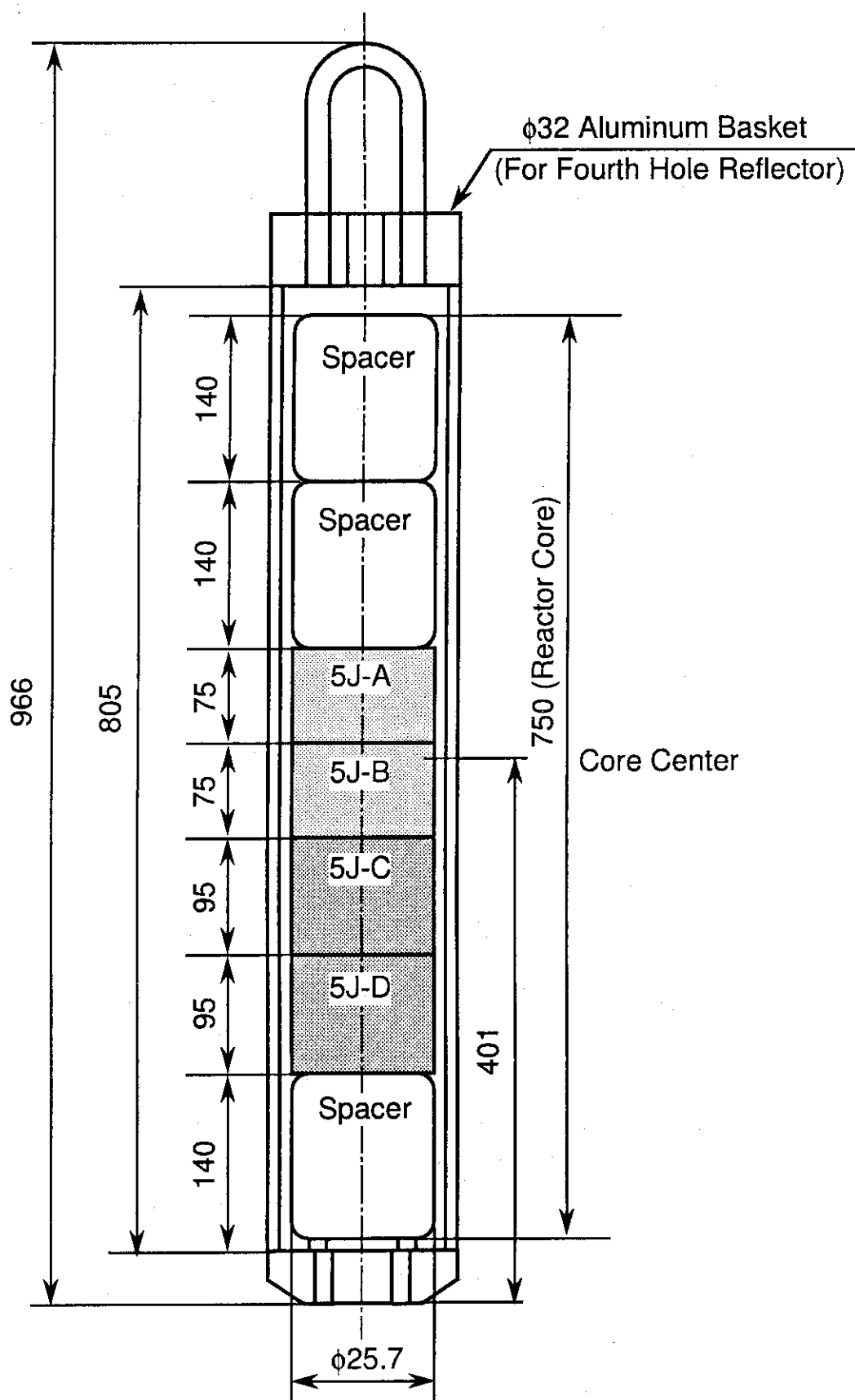


Fig.35 Arrangement of inner capsule (5J-A, 5J-B, 5J-C and 5J-D) in 87M-5J capsule.

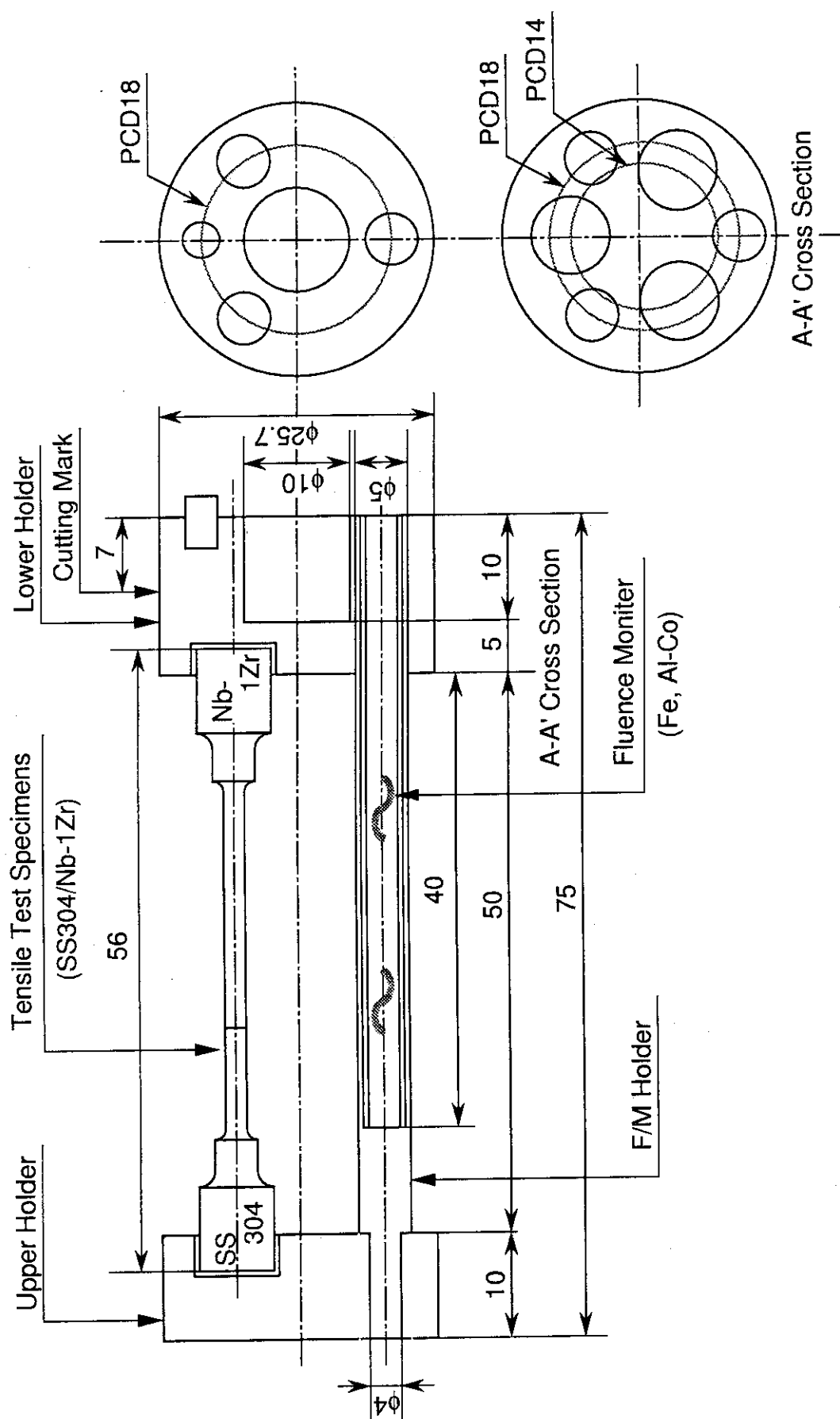


Fig.36 Inner capsule of 5J-A and 5J-B.

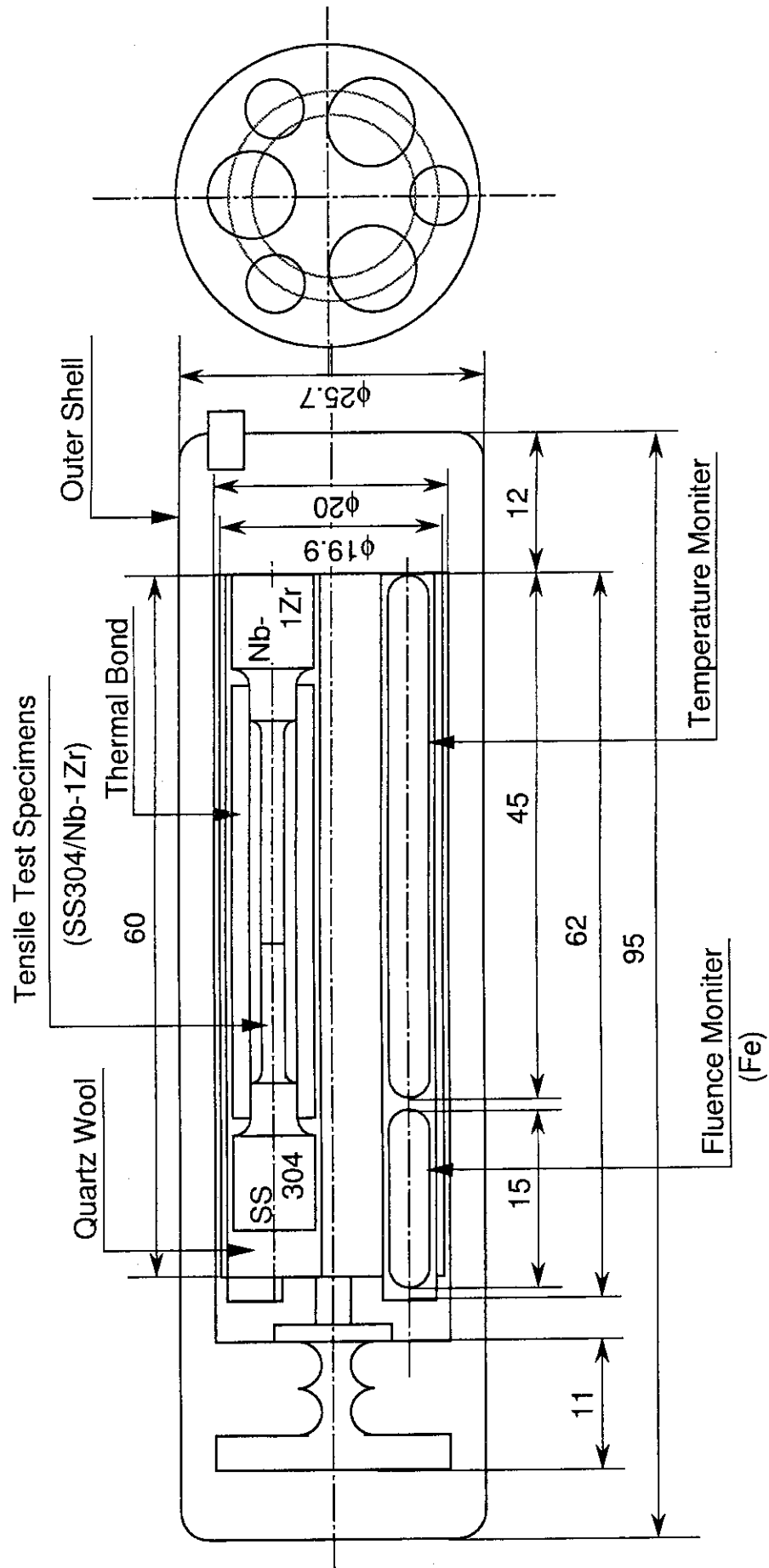


Fig.37 Inner capsule of 5J-C and 5J-D.

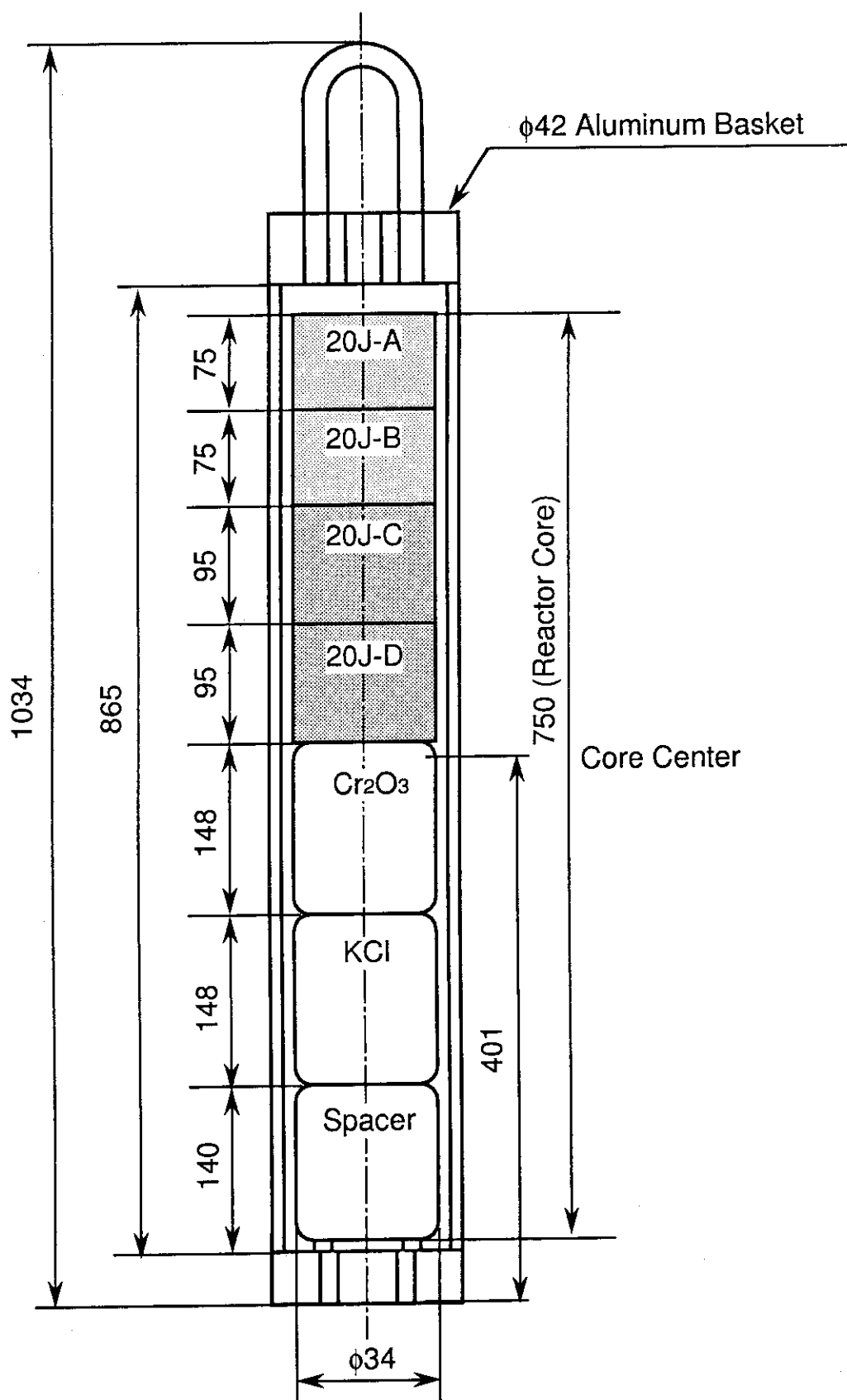


Fig.38 Arrangement of inner capsule (20J-A, 20J-B, 20J-C and 20J-D) in 87M-20J capsule.

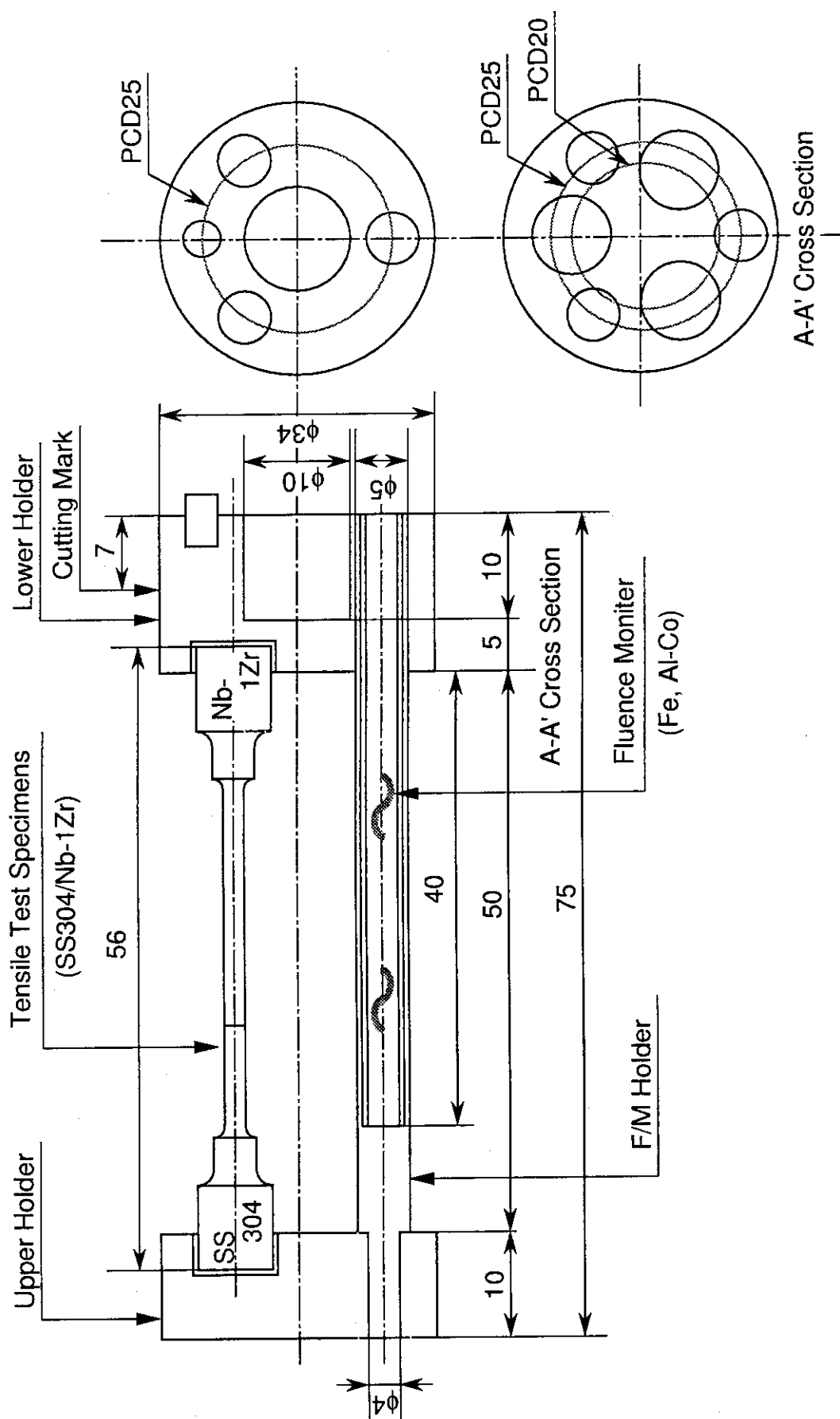


Fig.39 Inner capsule of 20J-A and 20J-B.

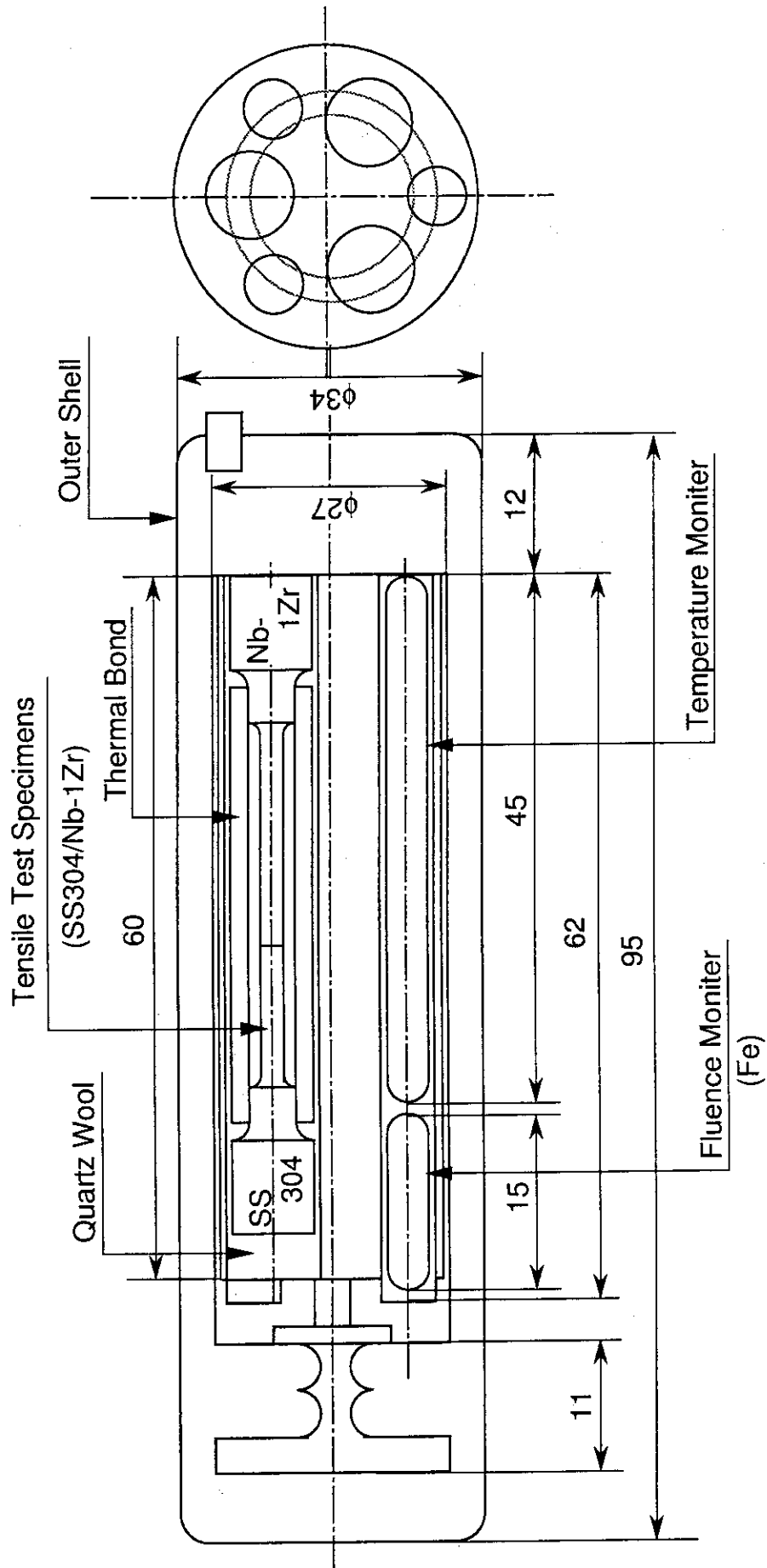


Fig.40 Inner capsule of 20J-C and 20J-D.

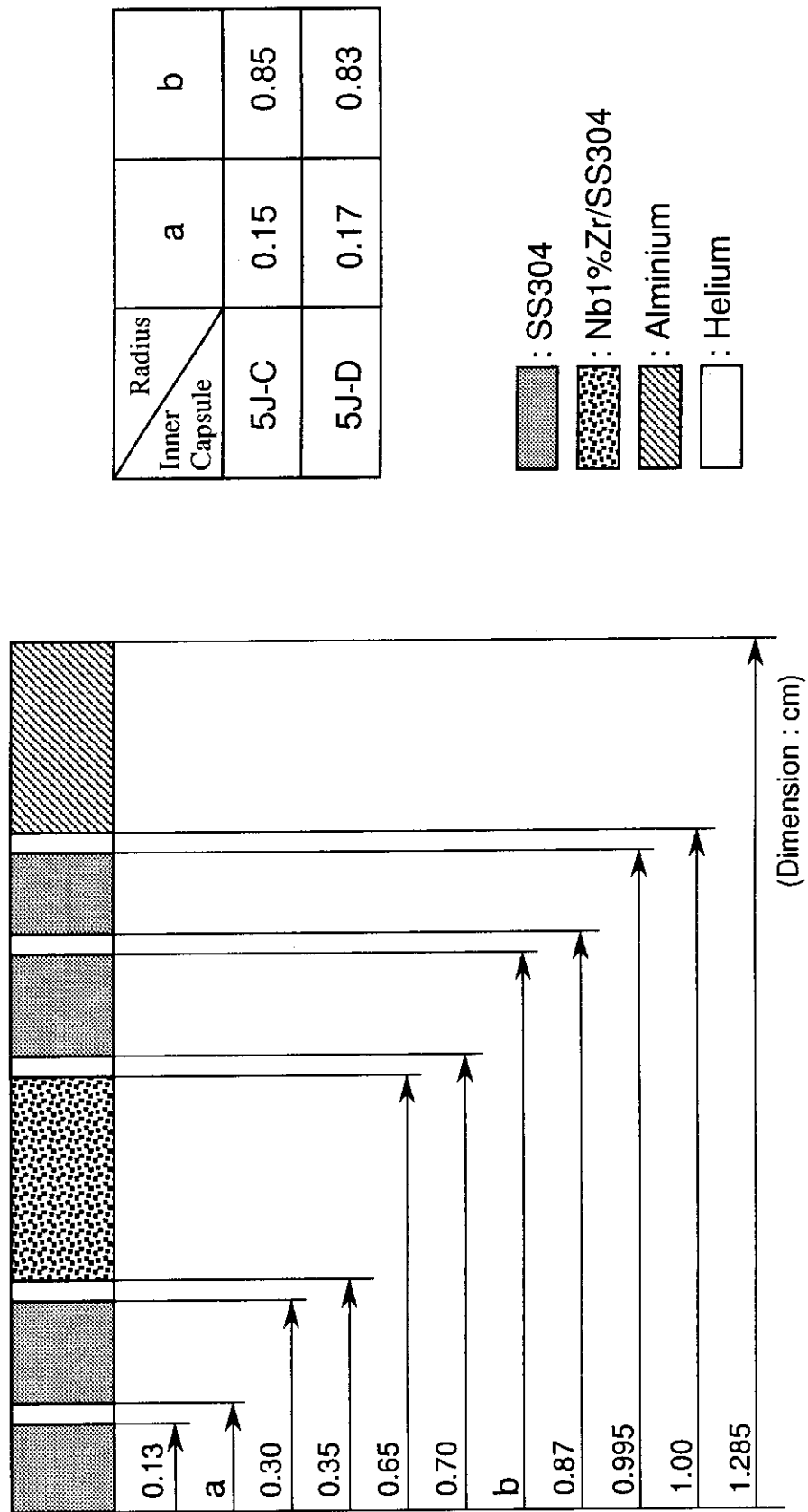


Fig.41 Capsule structure and dimension of inner capsule (5J-C and 5J-D).

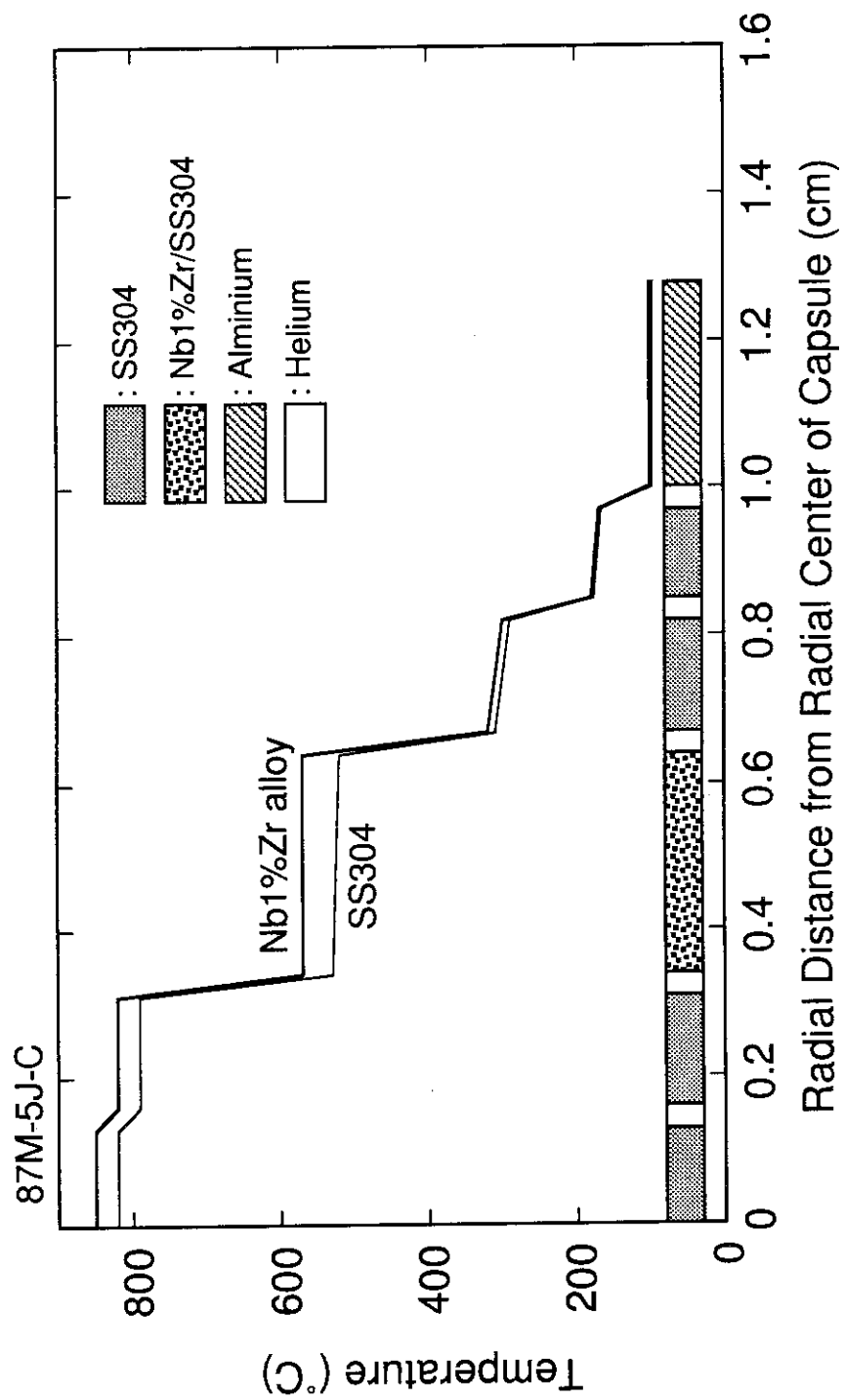


Fig.42 Results of thermal calculation for 5J-C.

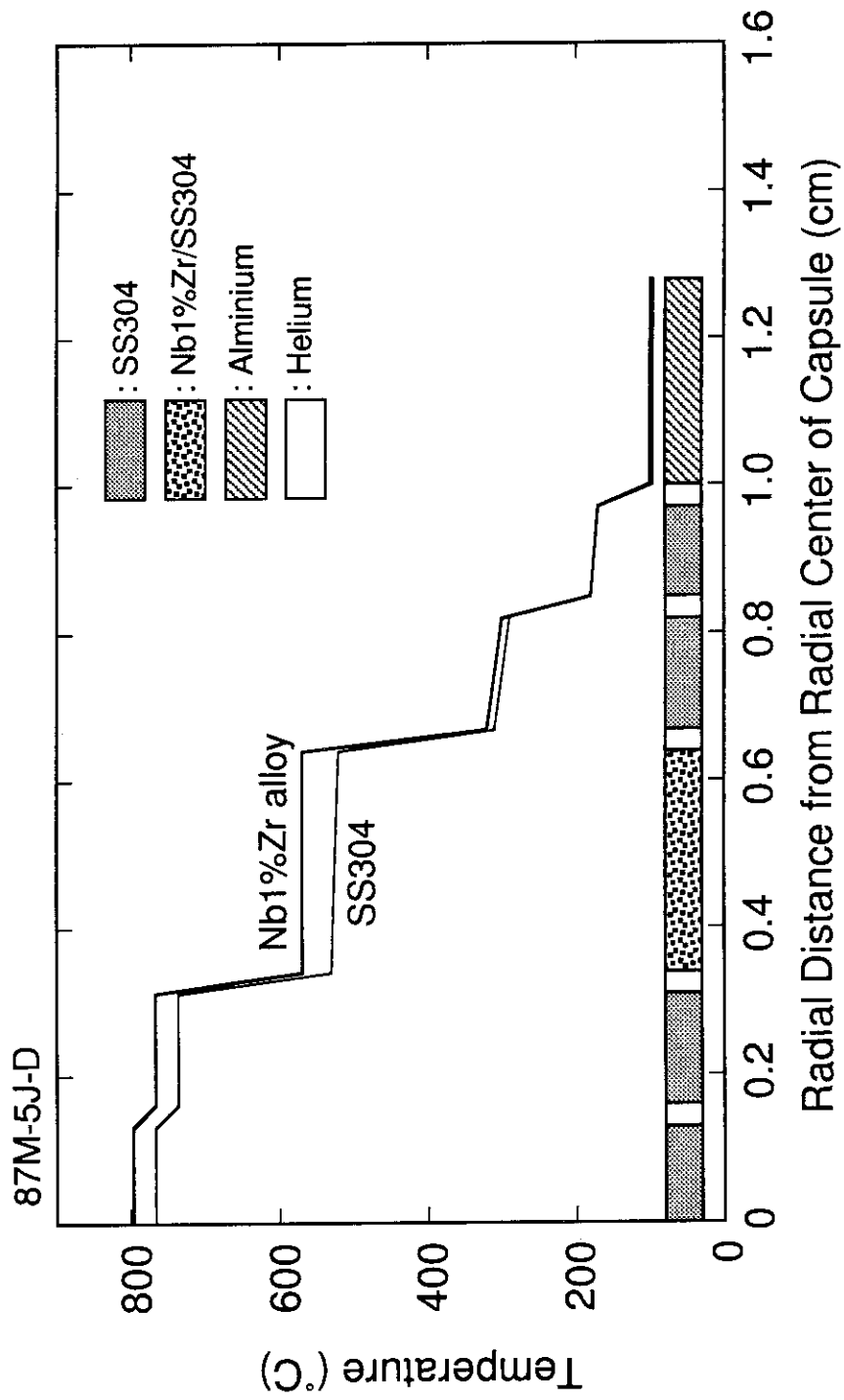


Fig.43 Results of thermal calculation for 5J-D.

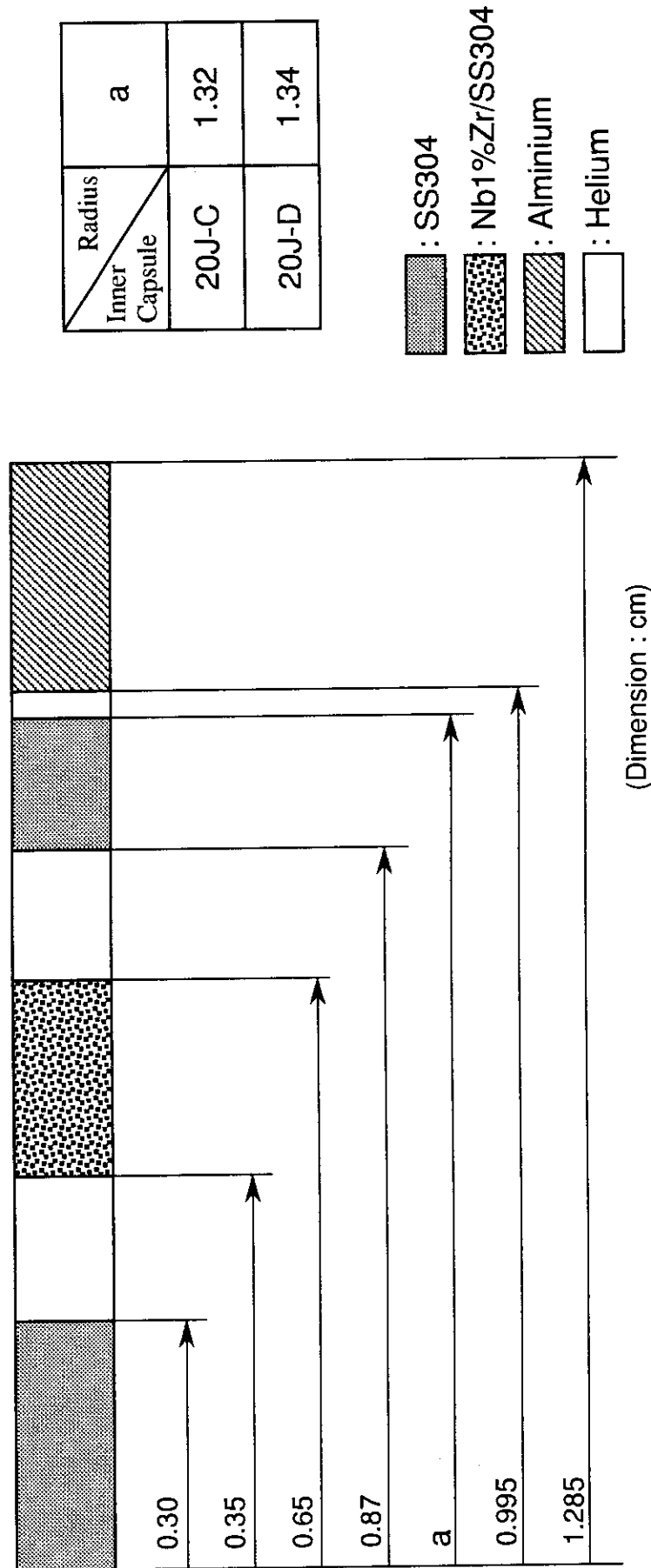


Fig.44 Capsule structure and dimension of inner capsule (20J-C and 20J-D).

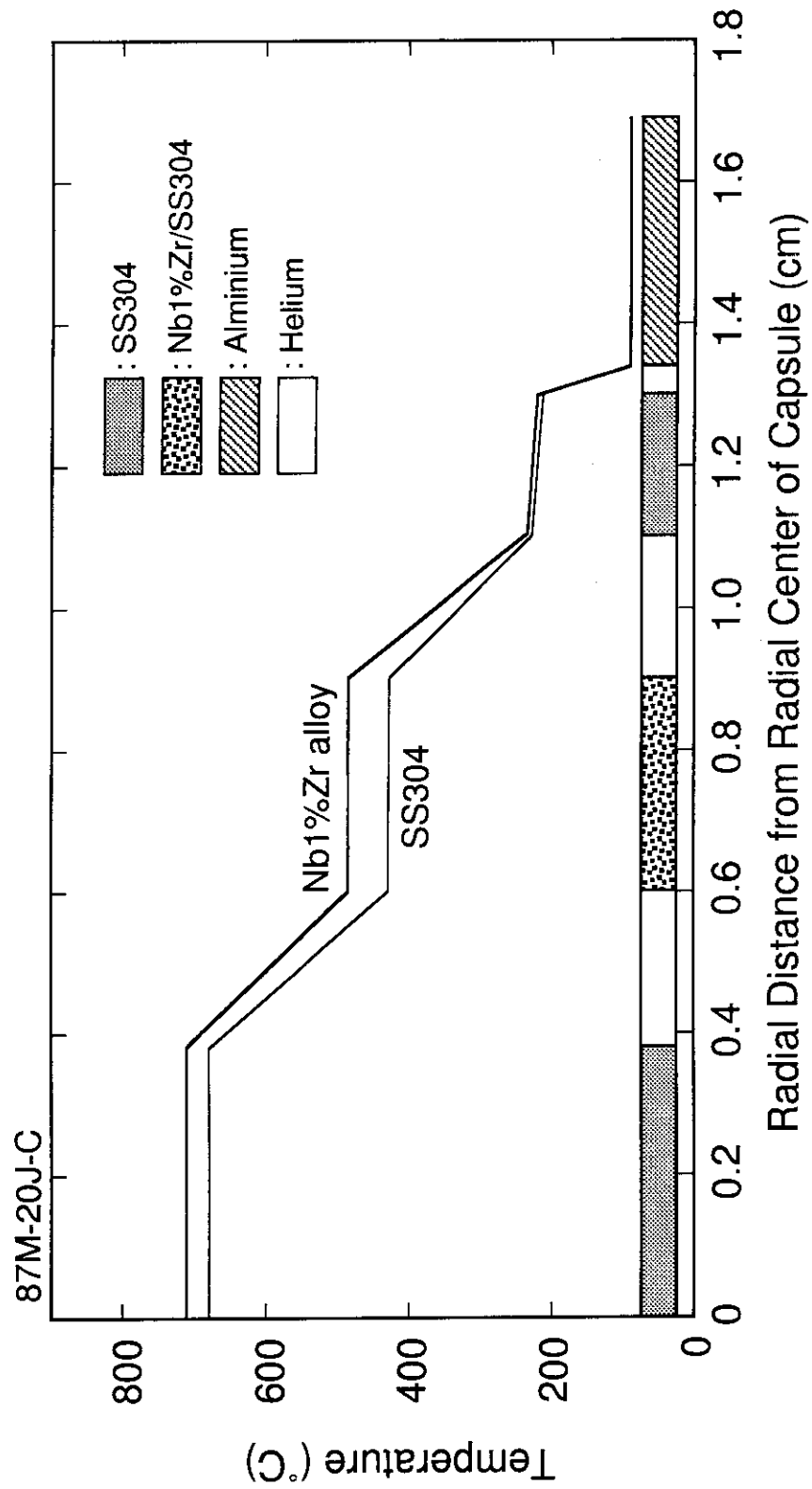


Fig.45 Results of thermal calculation for 20J-C.

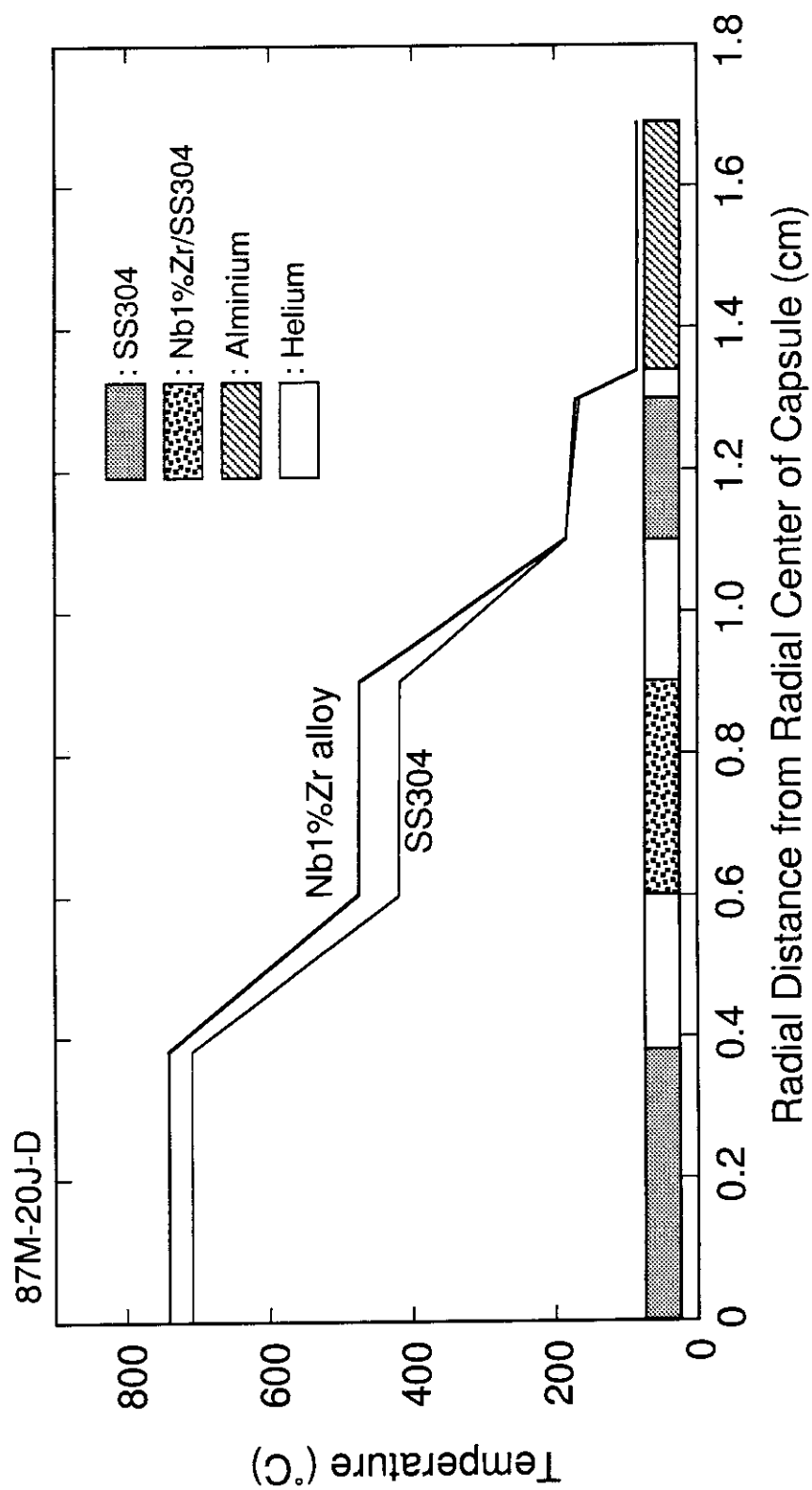
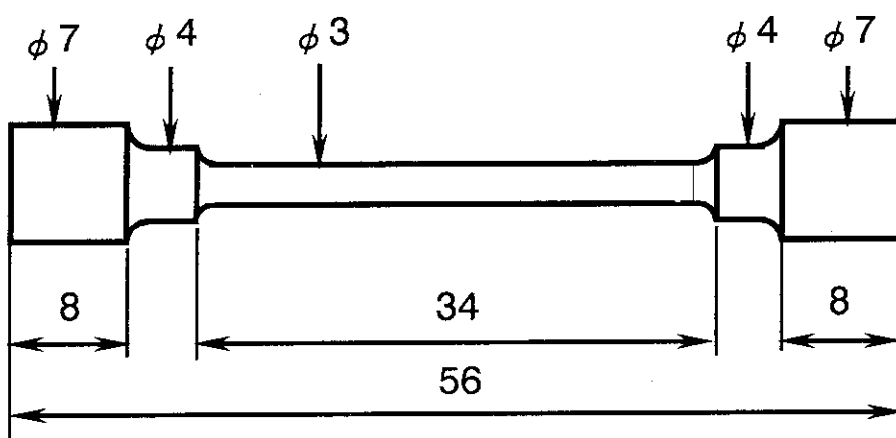
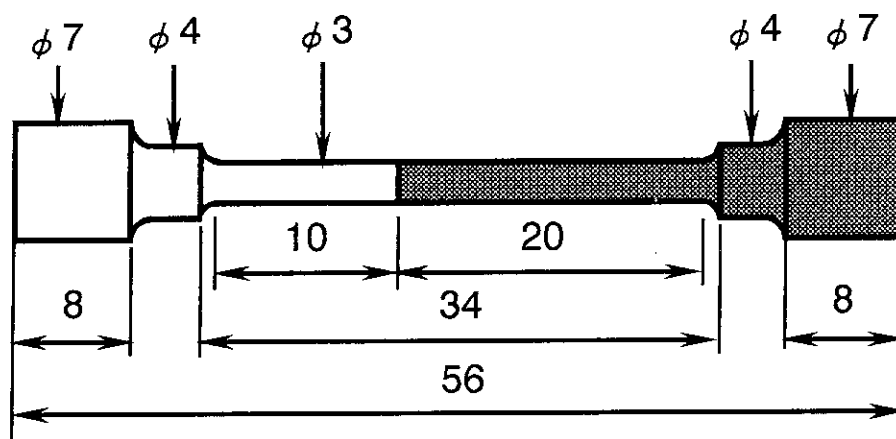


Fig.46 Results of thermal calculation for 20J-D.

Irradiation Sample



Irradiation Condition

Neutron Fluence : 0.1×10^{22} n/cm²
 Irradiation Temp. : 500°C

Fig.47 Irradiation specimens and irradiation conditions.

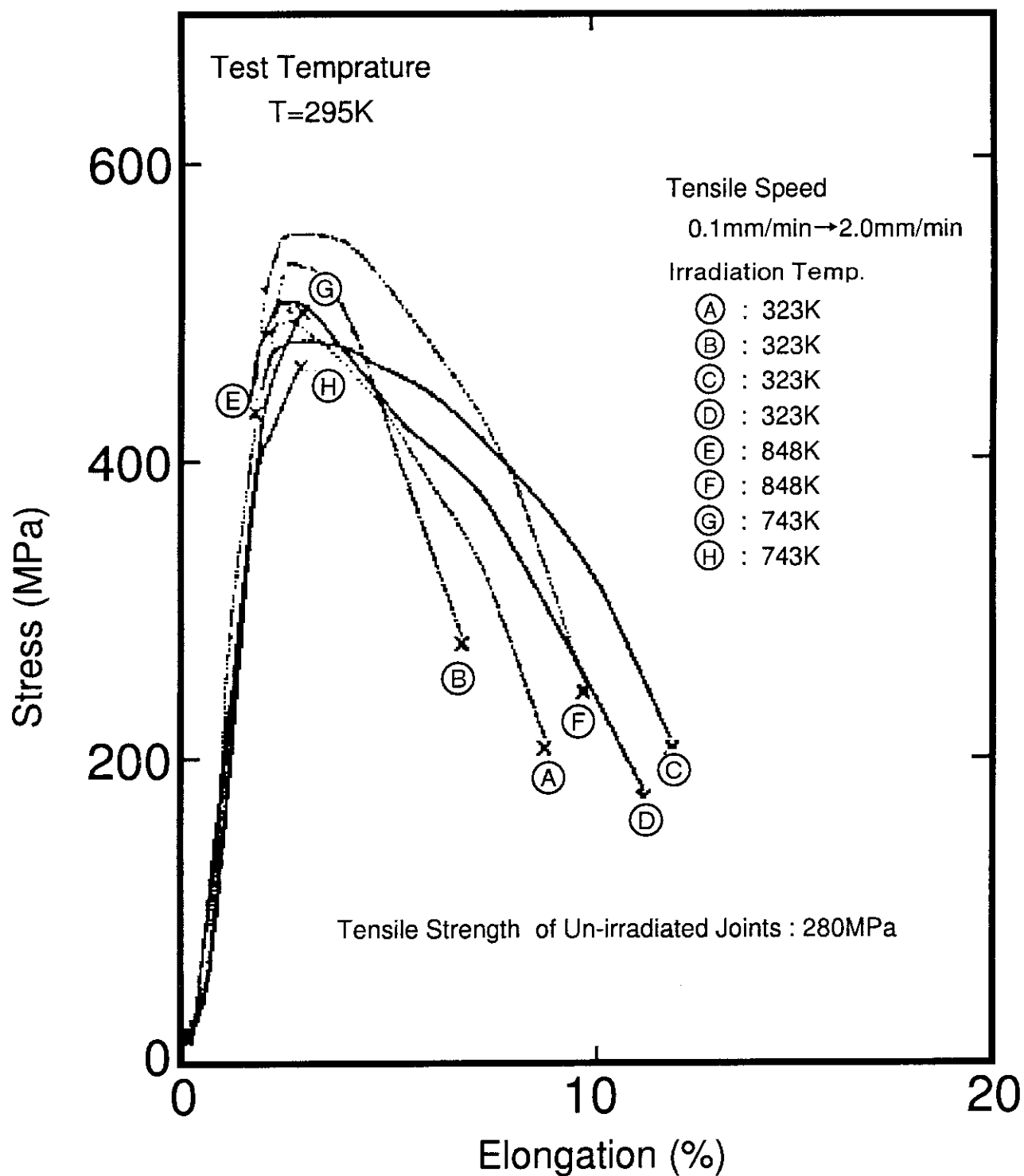


Fig.48 Results of tensile tests at 295K for irradiated Nb1%Zr/SS304 joints.

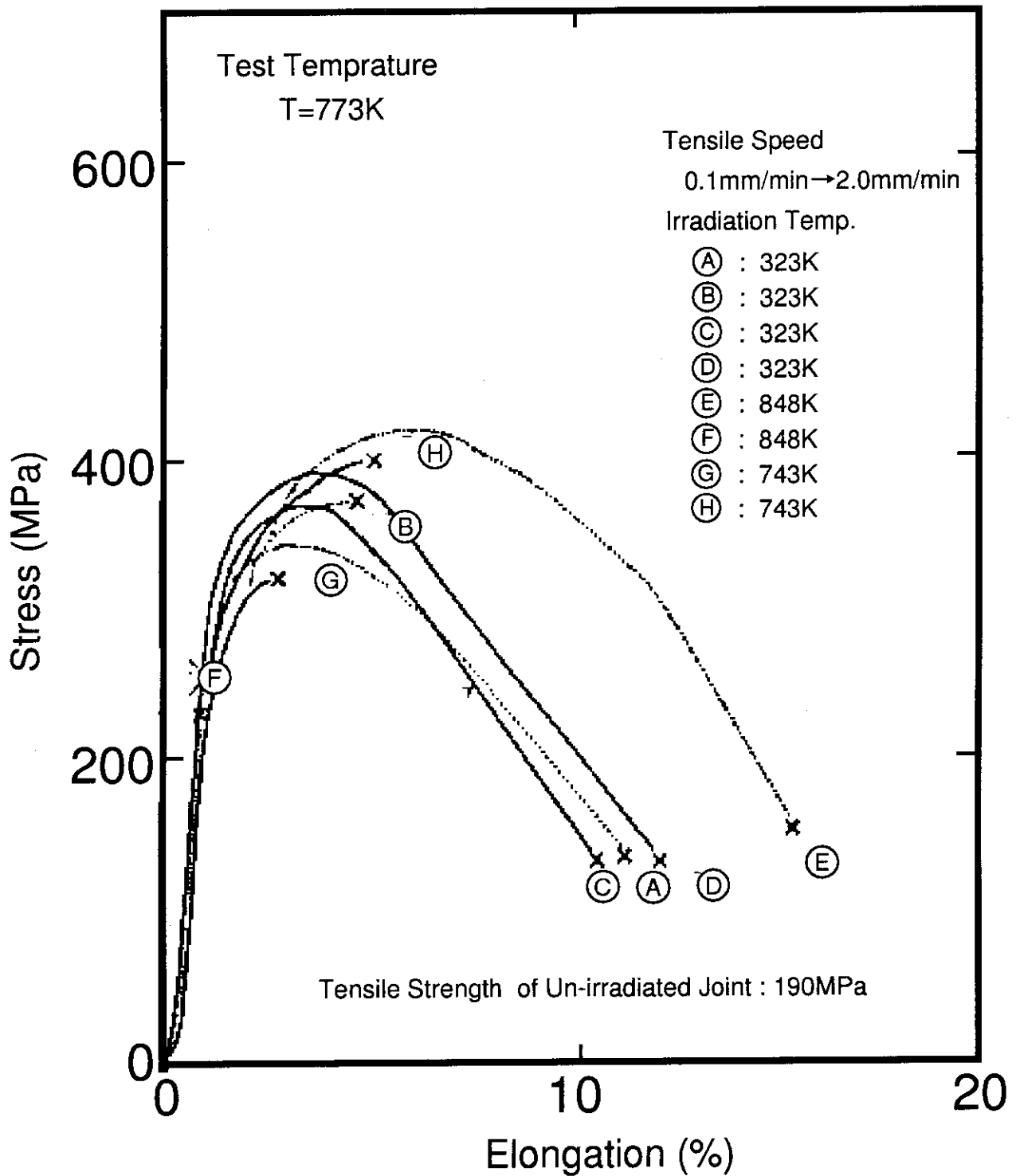


Fig.49 Results of tensile tests at 773K for irradiated Nb1%Zr/SS304 joints.

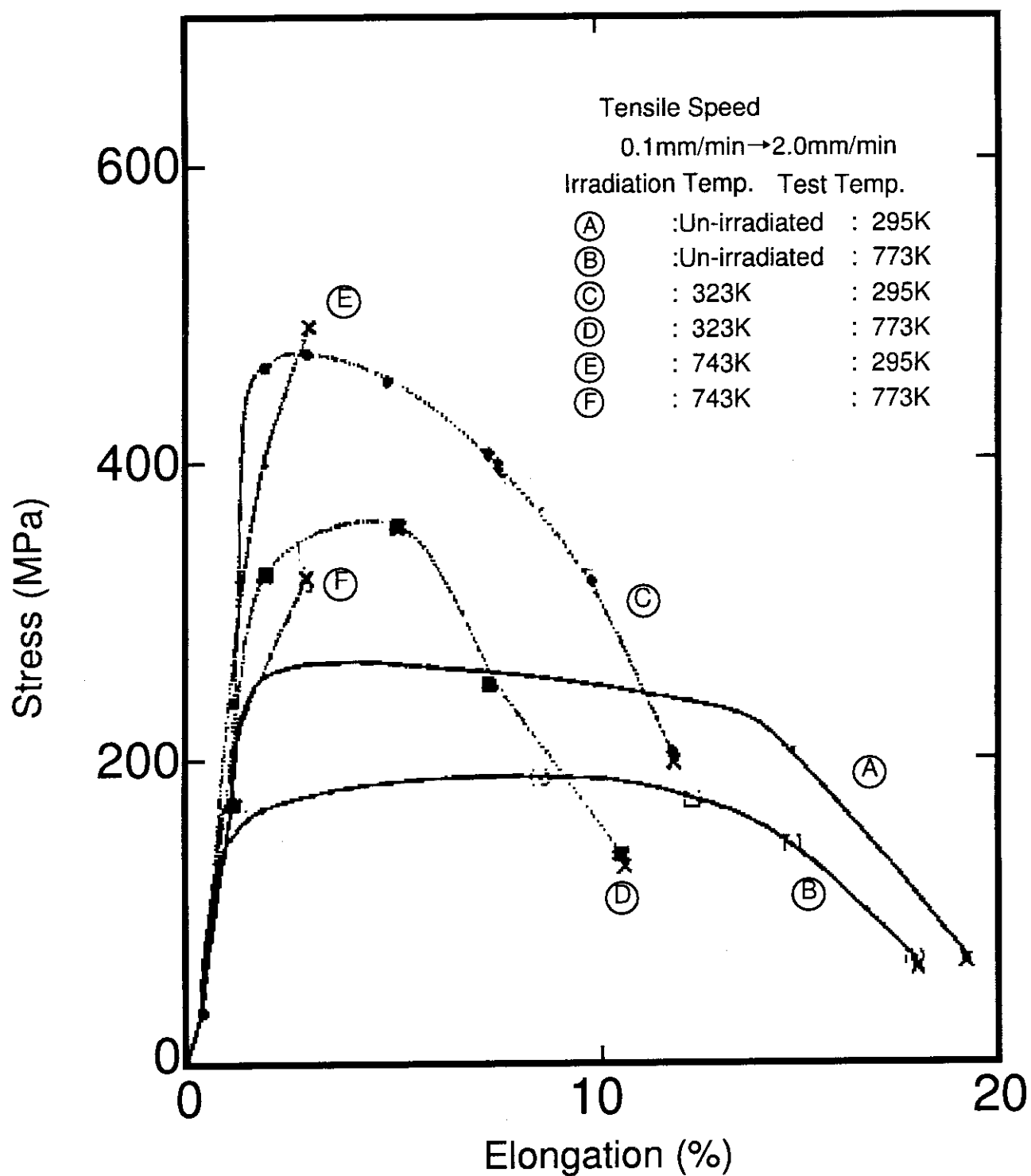


Fig.50 Results of tensile tests of Nb1%Zr/SS304 joints as a function of irradiation temperature.

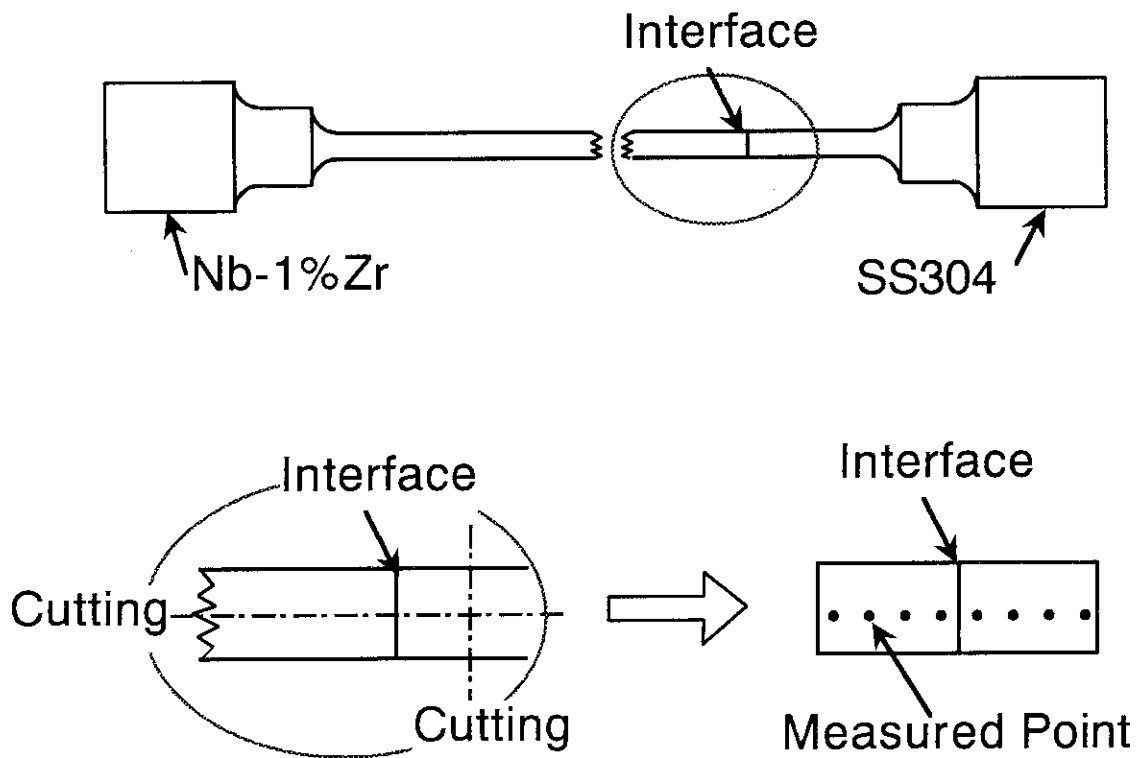


Fig.51 Broken position of tensile tests and hardness measurements.

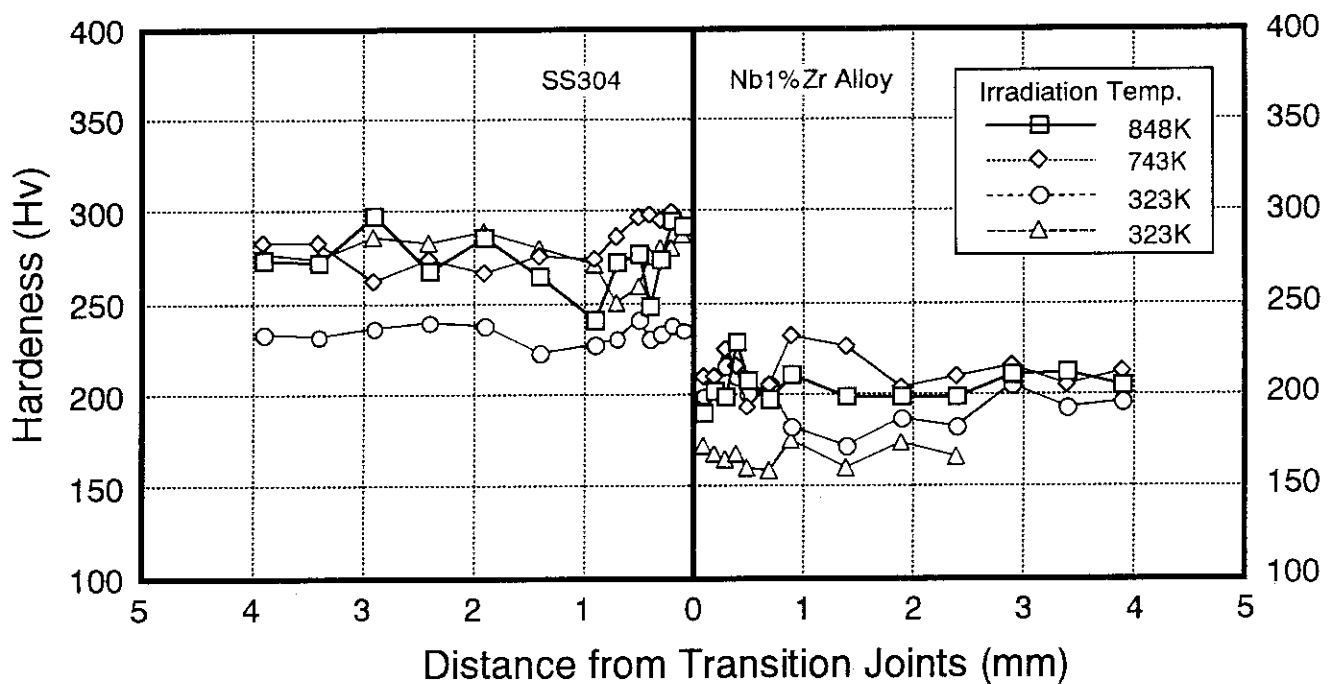


Fig.52 Hardness profile in the vicinity of Nb1%Zr/SS304 joint.



Fig.53 Metallographic photograph of Nb1%Zr/SS304 joints after irradiation(part of weldment).



Fig.54 Metallographic photograph of Nb1%Zr/SS304 joints after irradiation(part of SS304).

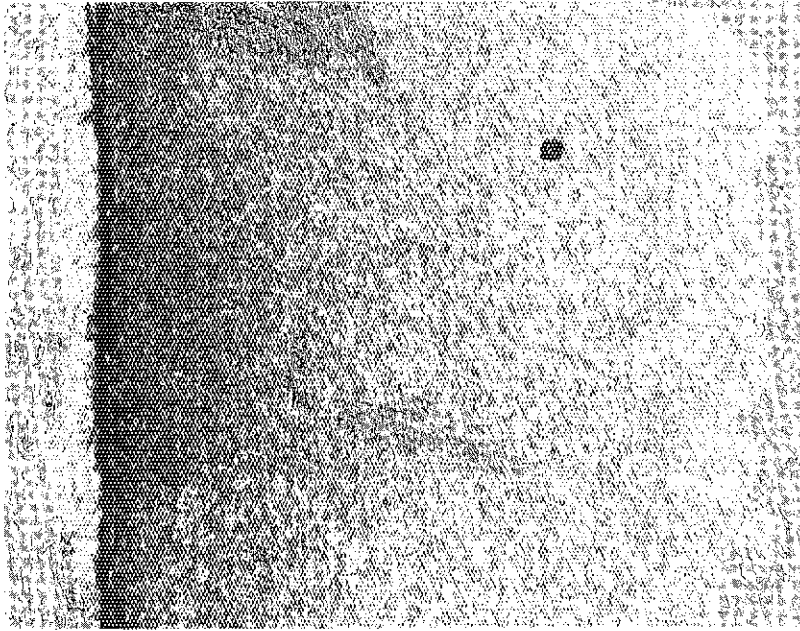


Fig.55 Metallographic photograph of Nb1%Zr/SS304 joints after irradiation(part of weldment).

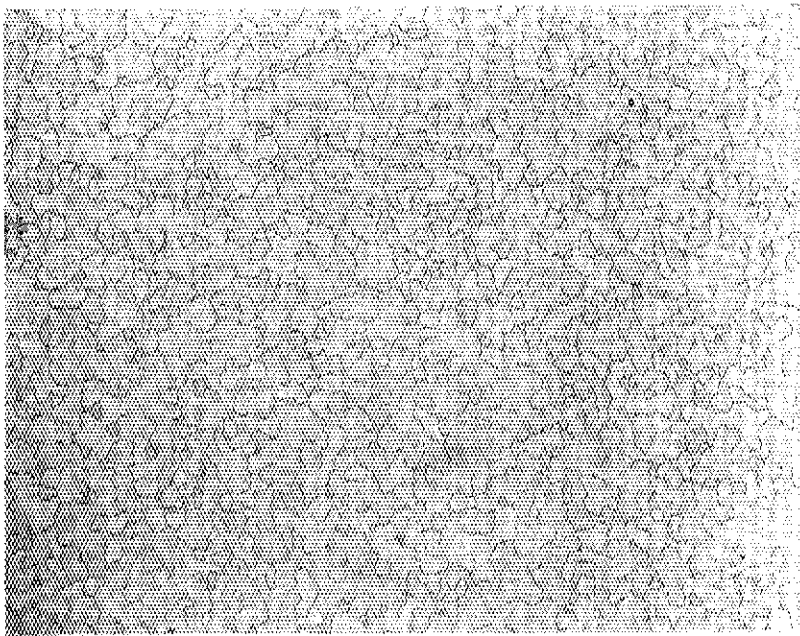
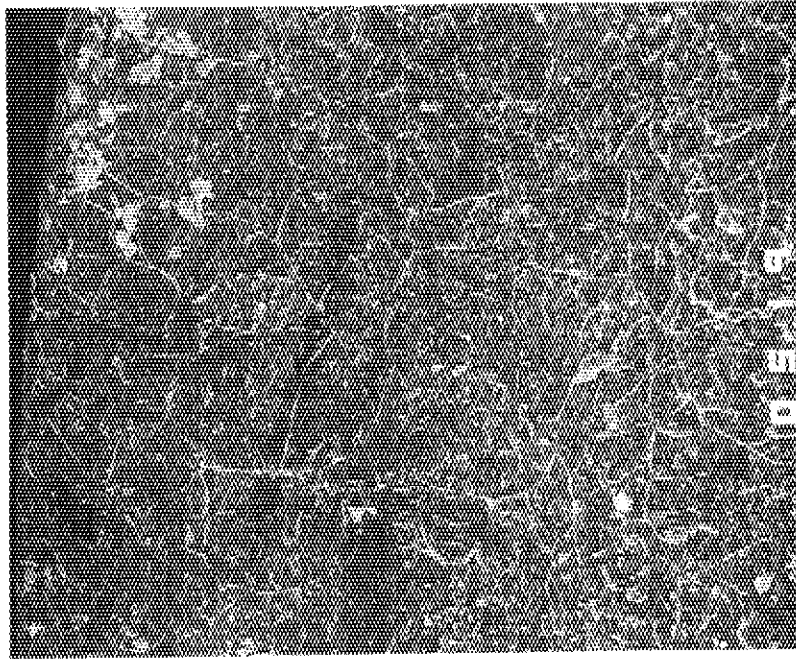
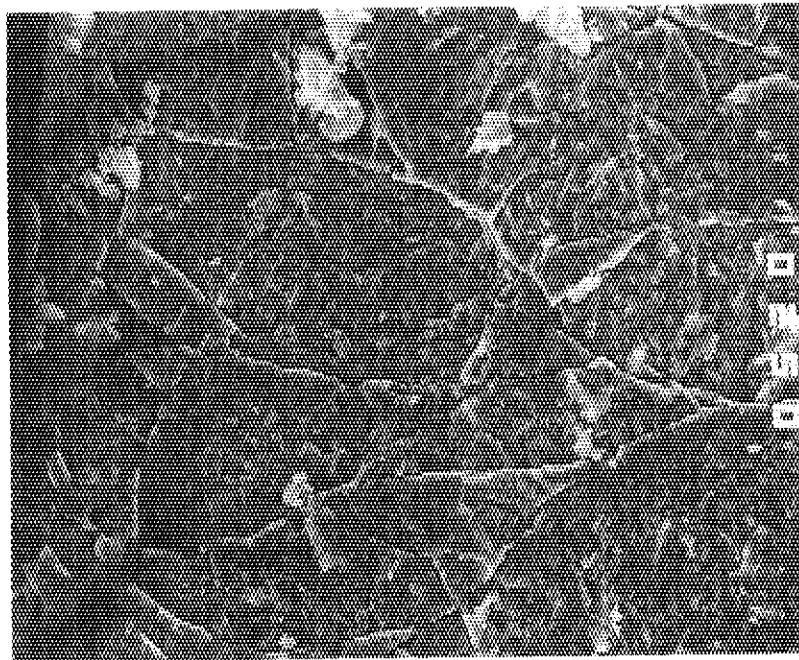


Fig.56 Metallographic photograph of Nb1%Zr/SS304 joints after irradiation(part of Nb1%Zr).

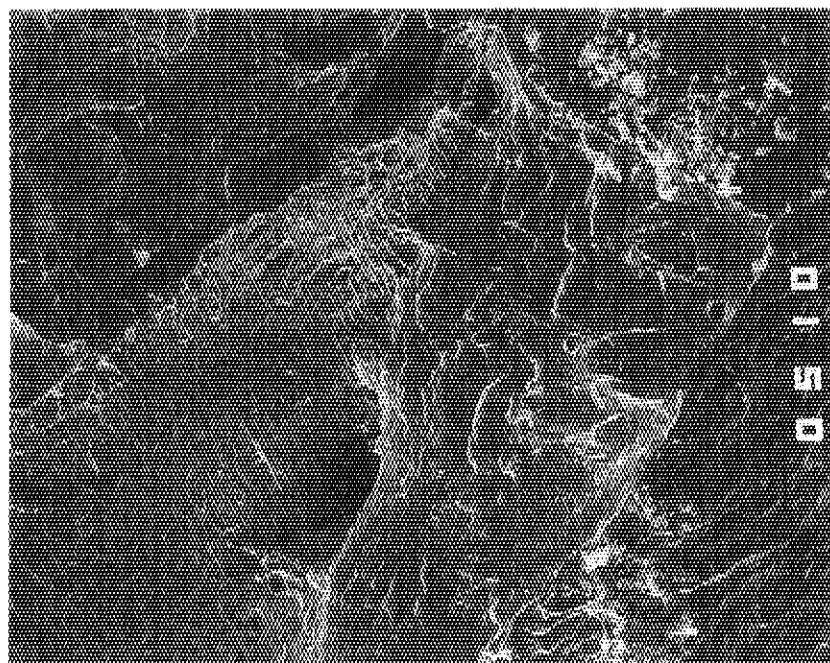


(a) SS304 (×300)

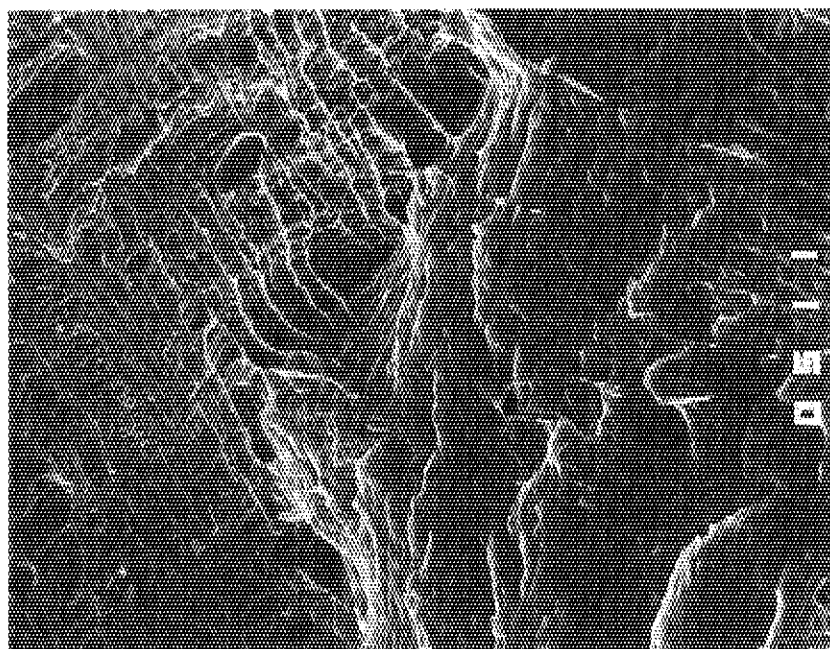


(b) SS304 (×1000)

Fig.57 SEM micrograph of Nb1%Zr/SS304 joints after irradiation.

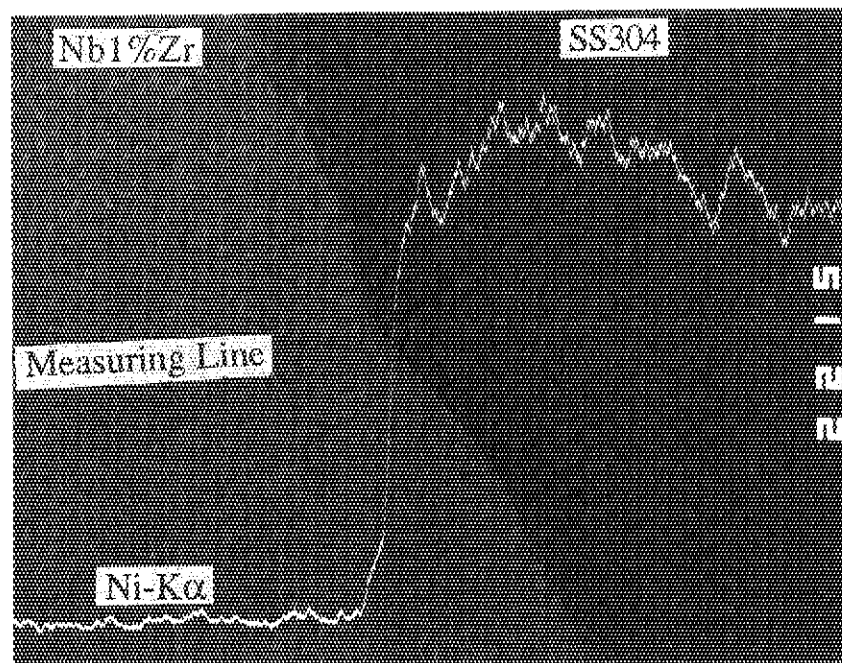
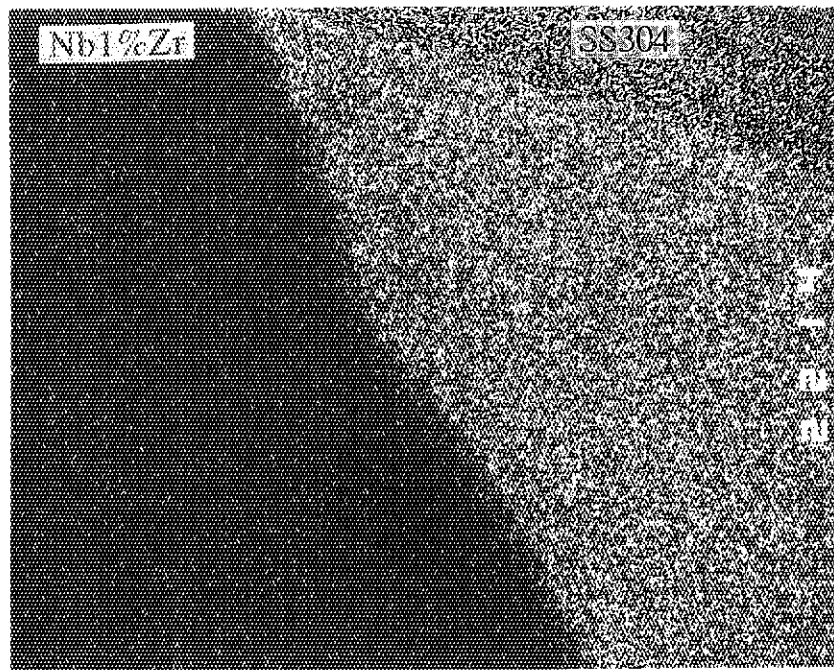


(a) Nb1%Zr alloy ($\times 300$)



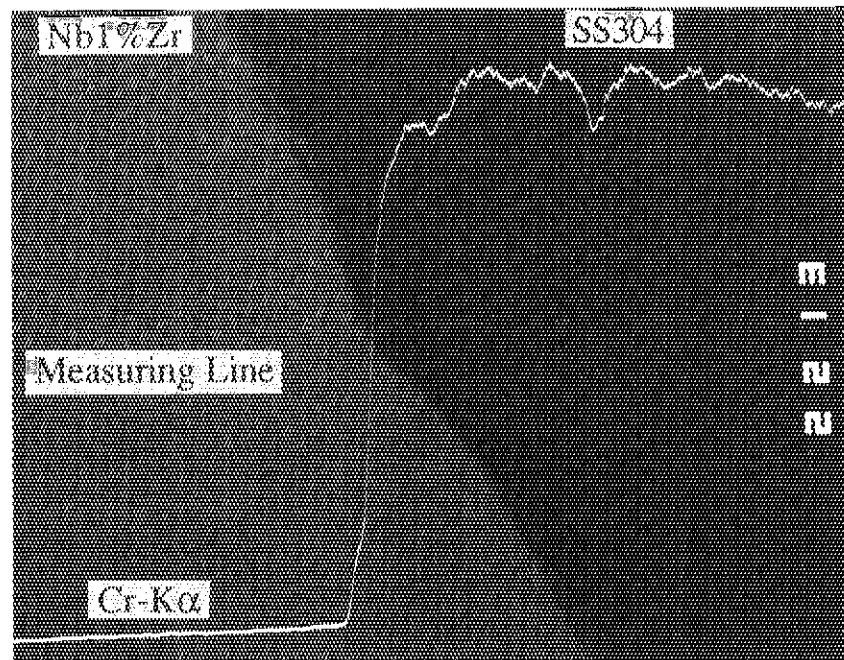
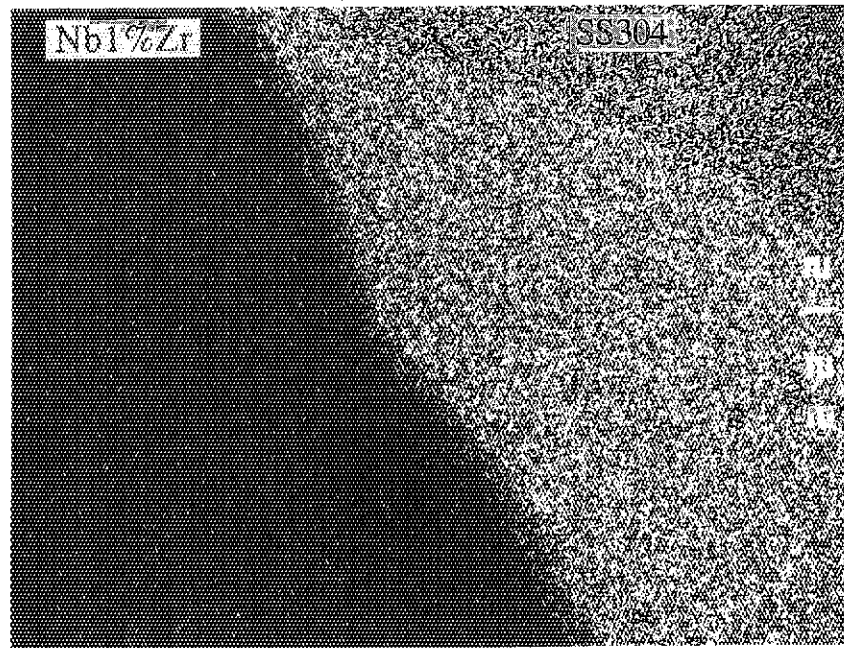
(b) Nb1%Zr alloy ($\times 1000$)

Fig.58 SEM micrograph of Nb1%Zr/SS304 joints after irradiation.



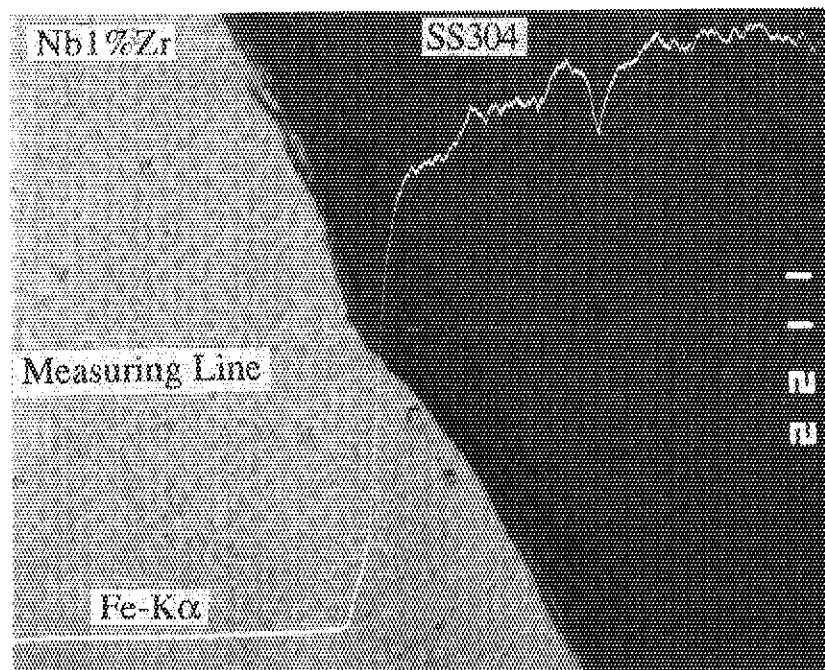
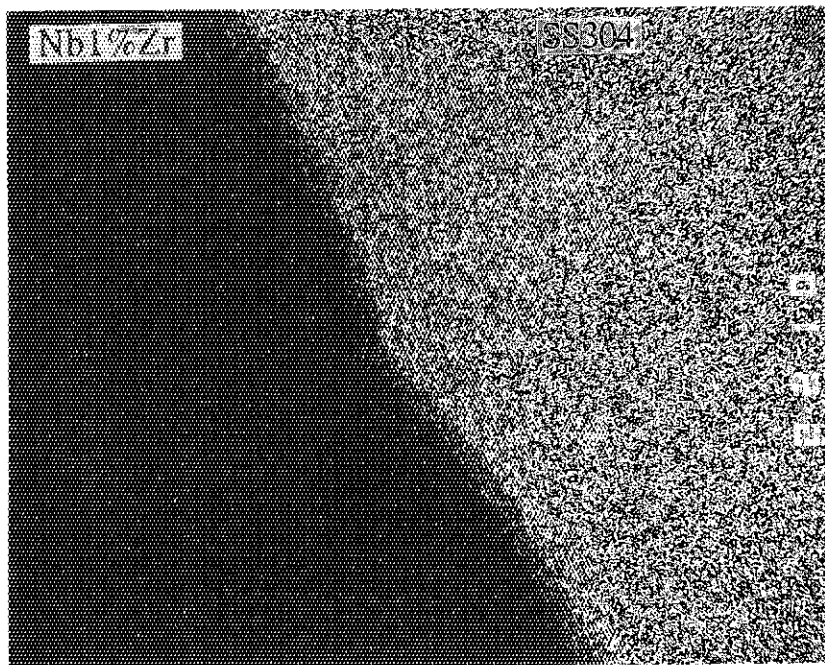
(a) Ni-K α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.



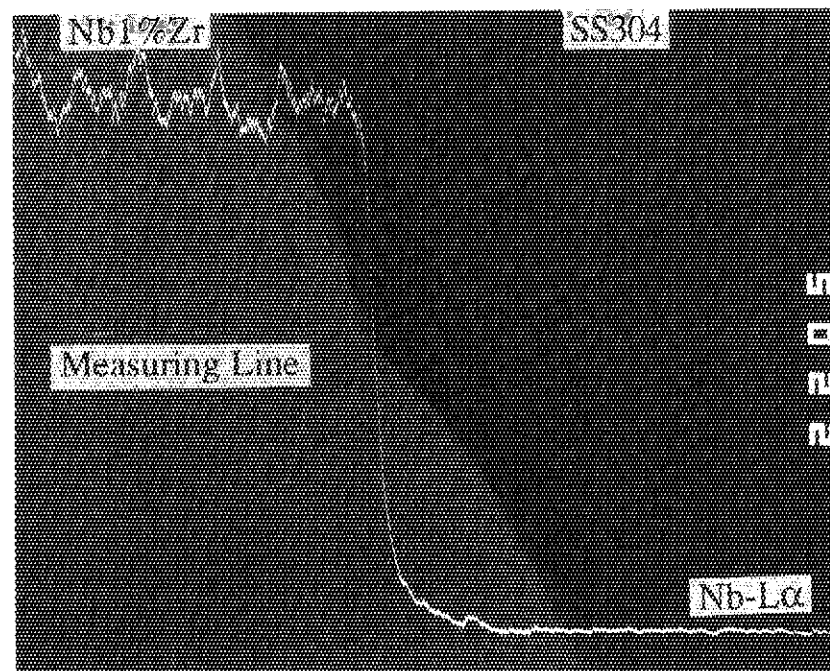
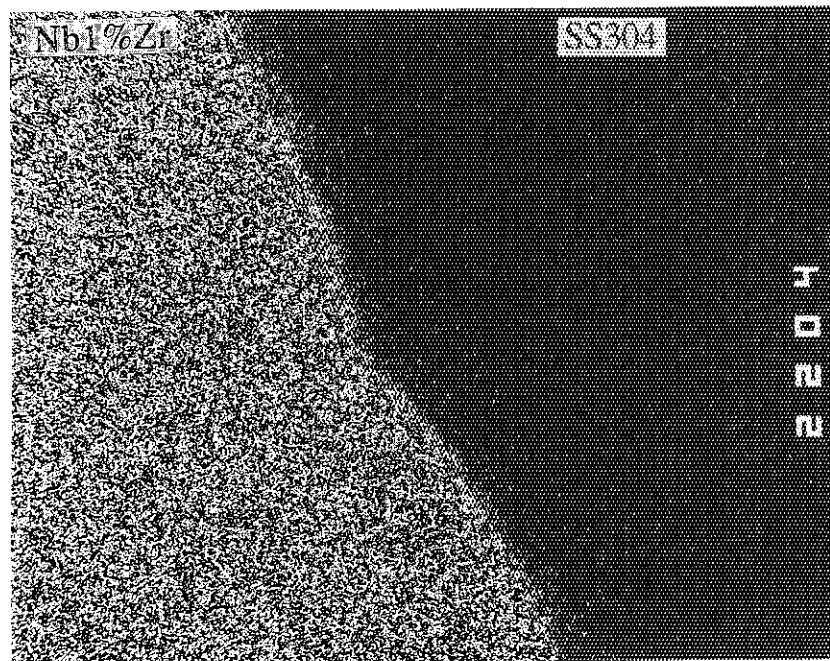
(b) Cr-K α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.



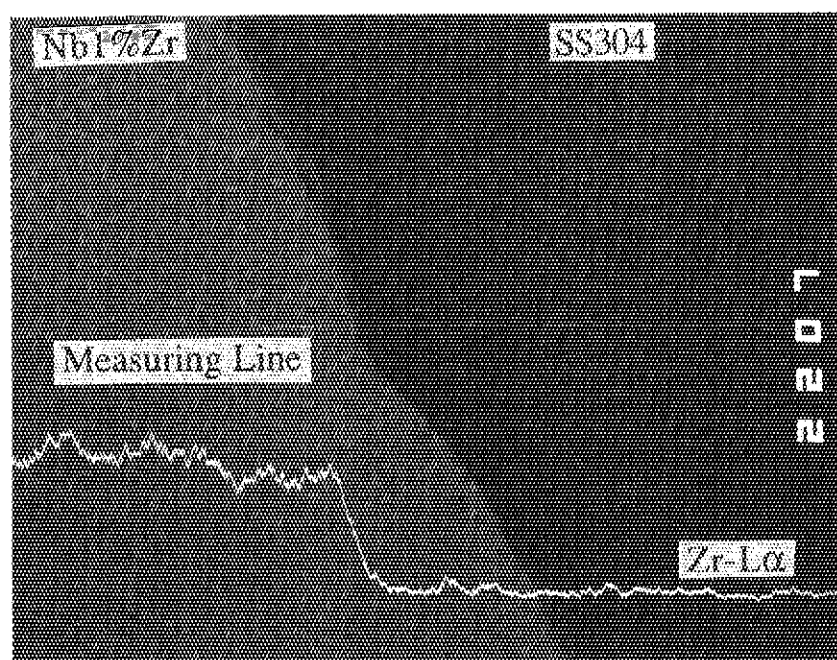
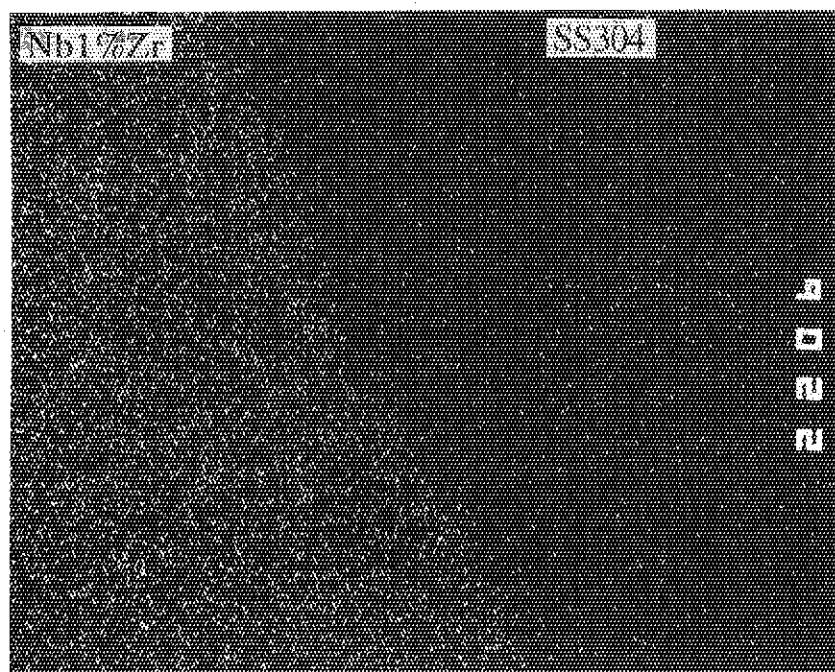
(c) Fe-K α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.



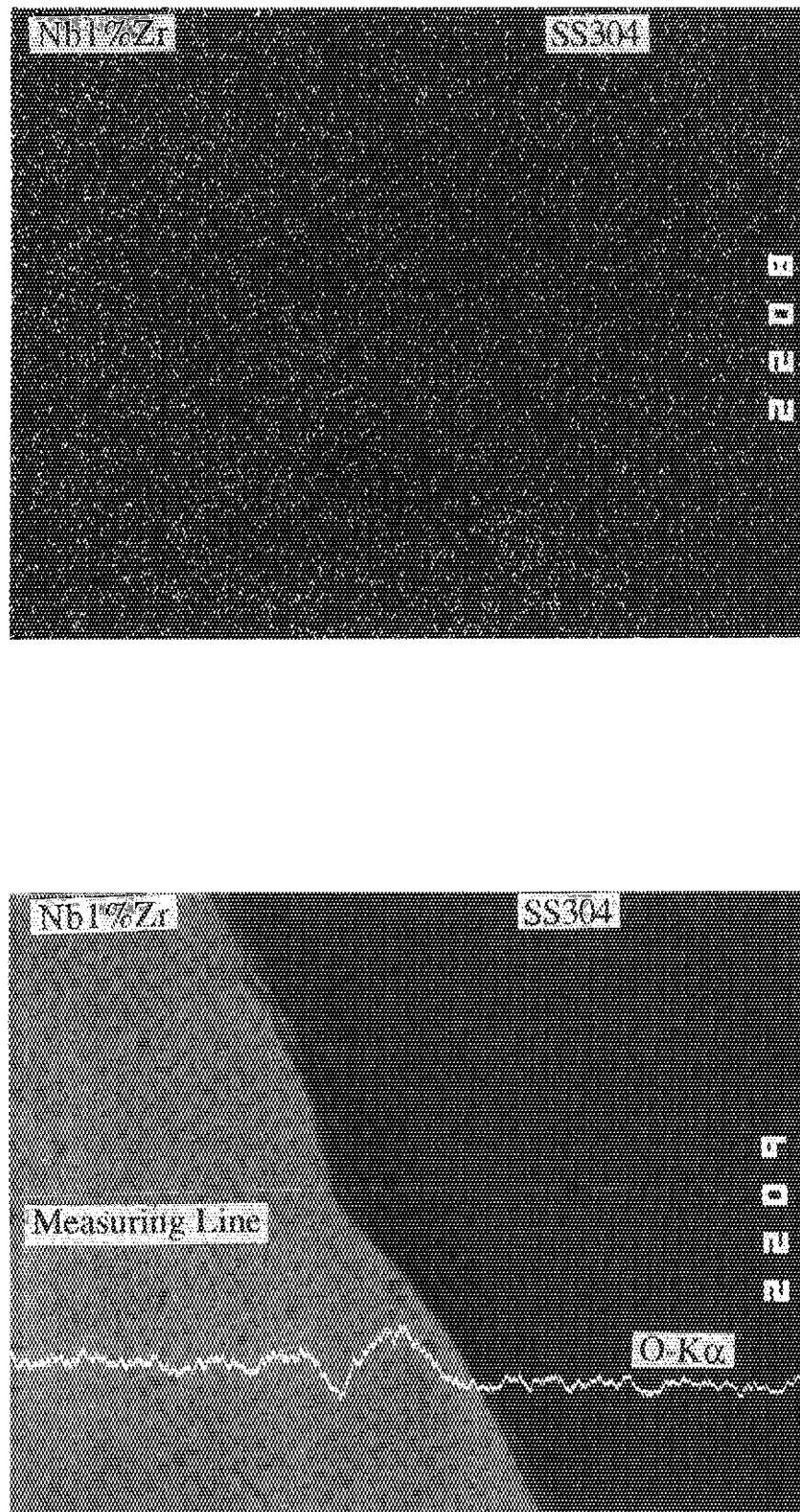
(d) Nb-L α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.



(e) Zr-L α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.



(f) O-K α

Fig.59 SEM/XMA surface and line analysis for Ni, Cr, Fe, Nb, Zr and O in Nb1%Zr/SS304 joints after irradiation.

Appendix. Data on Nb1%Zr alloy

Pure niobium and low alloy forms of niobium have been studied since the early 1930's; however, it was not until the mid 1950's that serious development of niobium as an engineering material began. In this appendix, the data that is presented reflects the properties that are currently commercially achievable.

The unirradiated uniform and elongation are shown in Fig.A-1. Fig.A-2 shows the decrease in uniform elongation after irradiation to 20dpa and 34dpa. Fig.A-3 and Fig.A-4 show the effect of irradiation on both the ultimate and yield strength after irradiation to 20dpa and 34dpa. Swelling of Nb1%Zr alloy is shown in Fig.A-5.

Reference

"ITER BLANKET, SHIELD AND MATERIAL DATA BASE" , ITER DOCUMENTATION SERIES, No.29(1991).

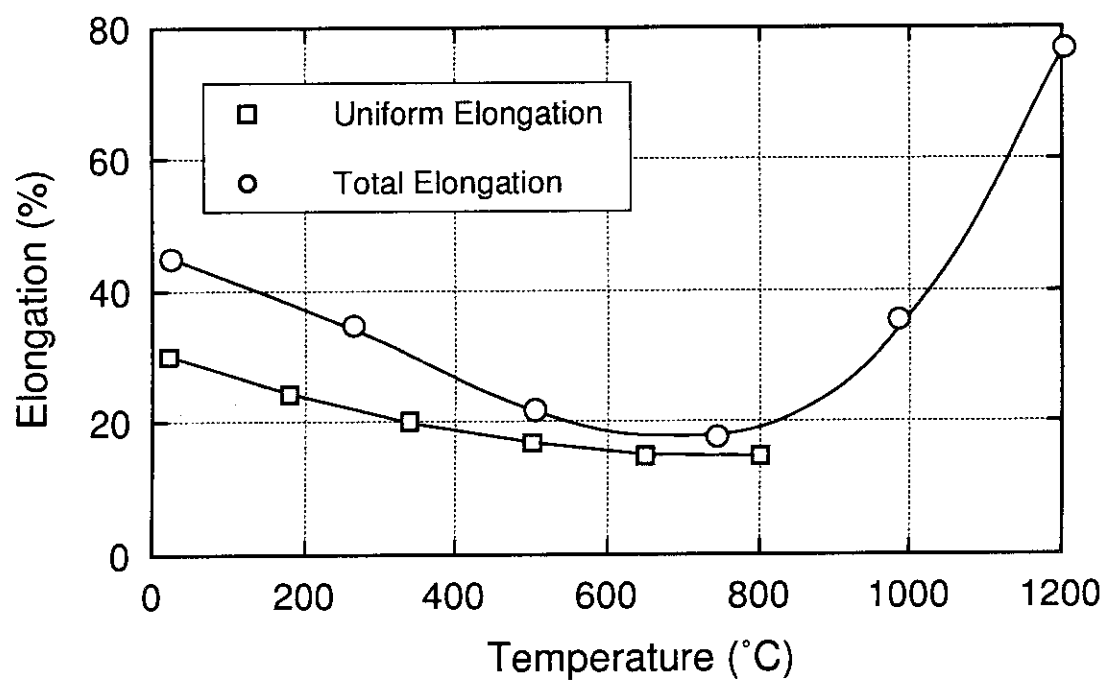


Fig.A-1 Average elongation (dpa=0) of Nb1%Zr, annealed.

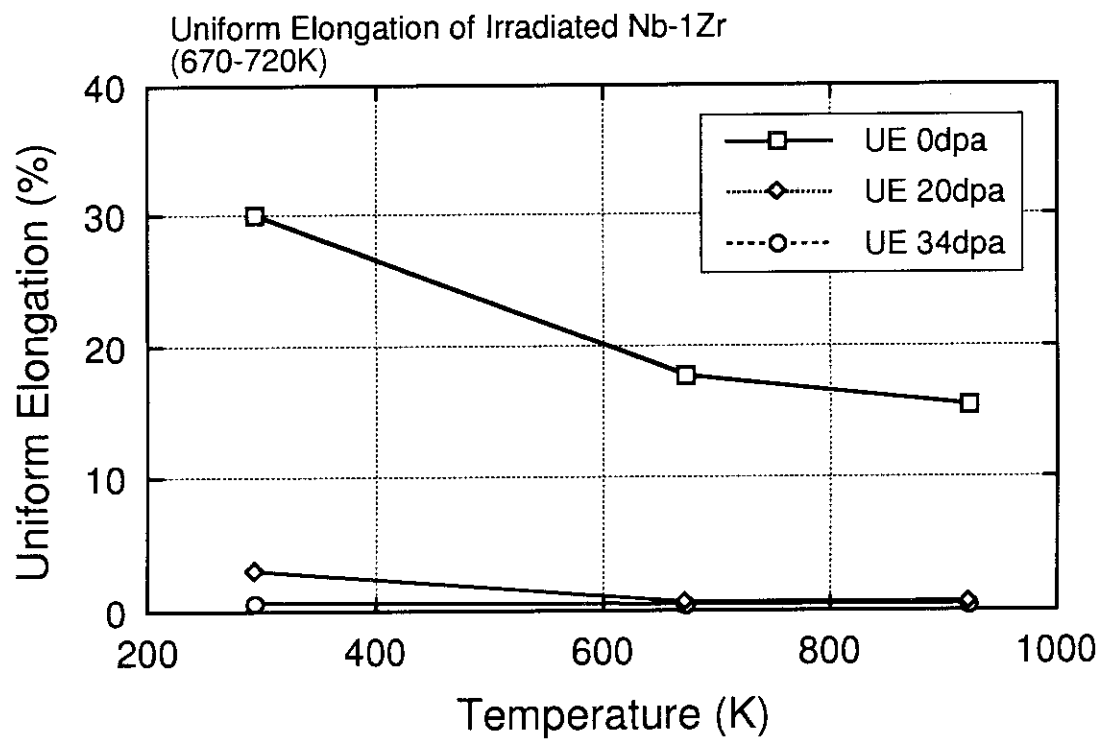


Fig.A-2 Uniform elongation of irradiated Nb1%Zr (670-720K irr. T).

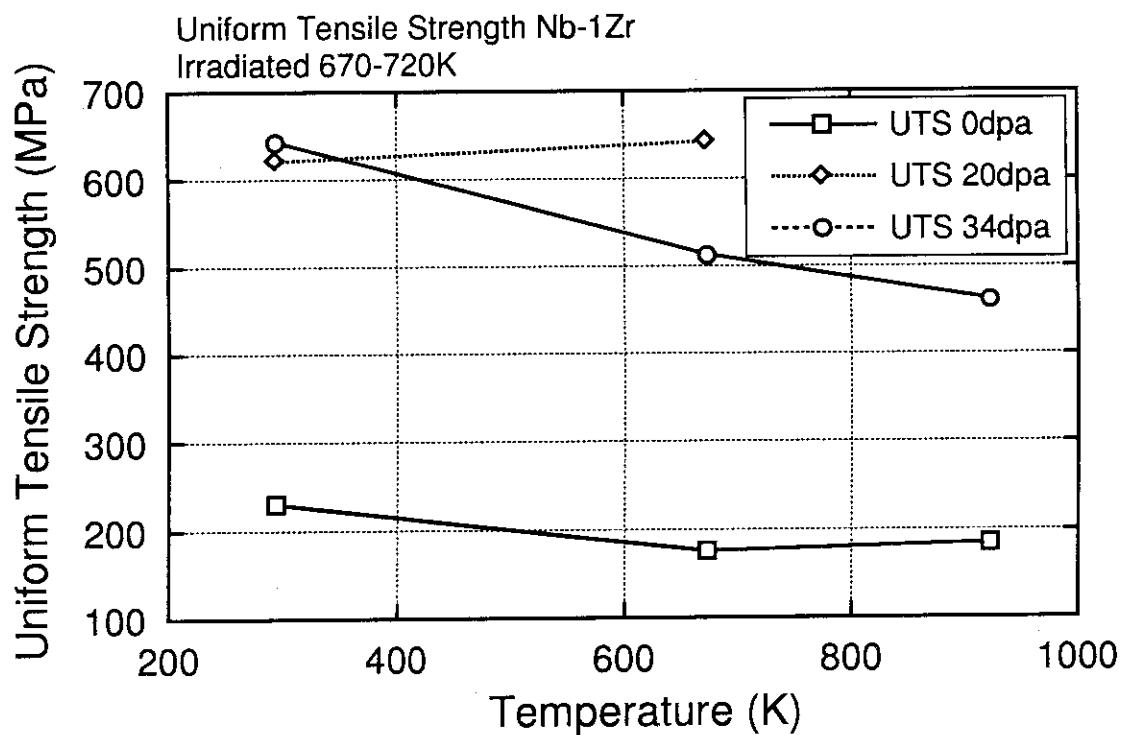


Fig.A-3 Ultimate tensile strength of irradiated Nb1%Zr (670-720K irr. T).

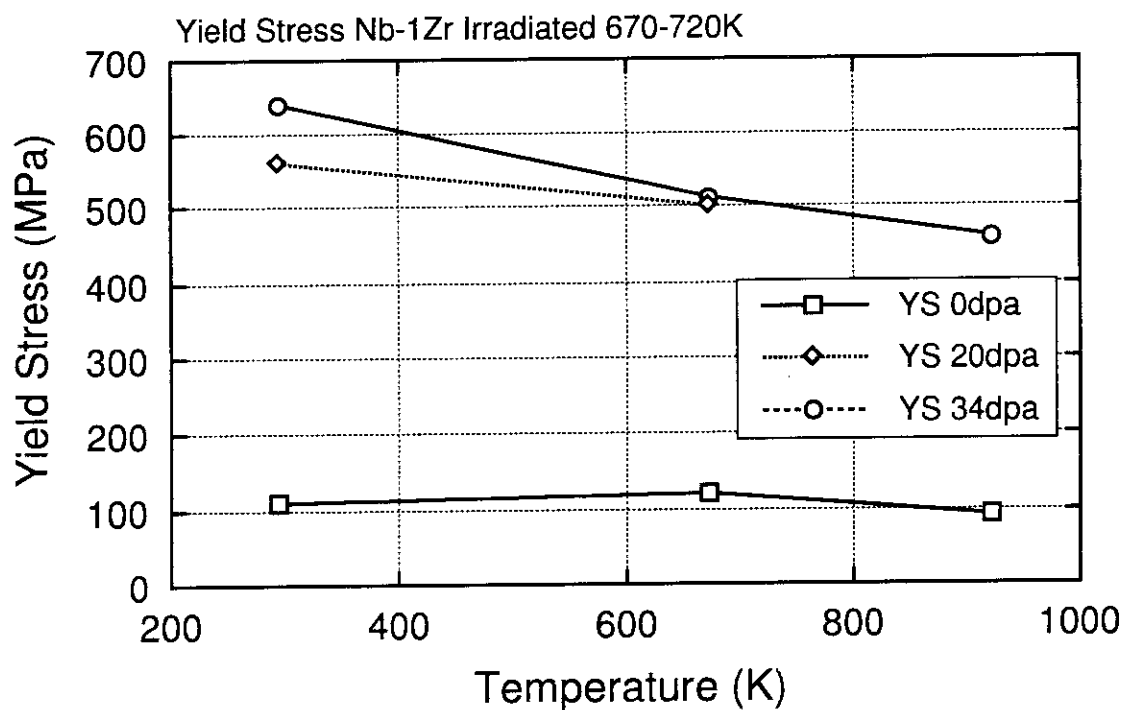


Fig.A-4 Yield stress of irradiated Nb1%Zr (670-720K irr. T).

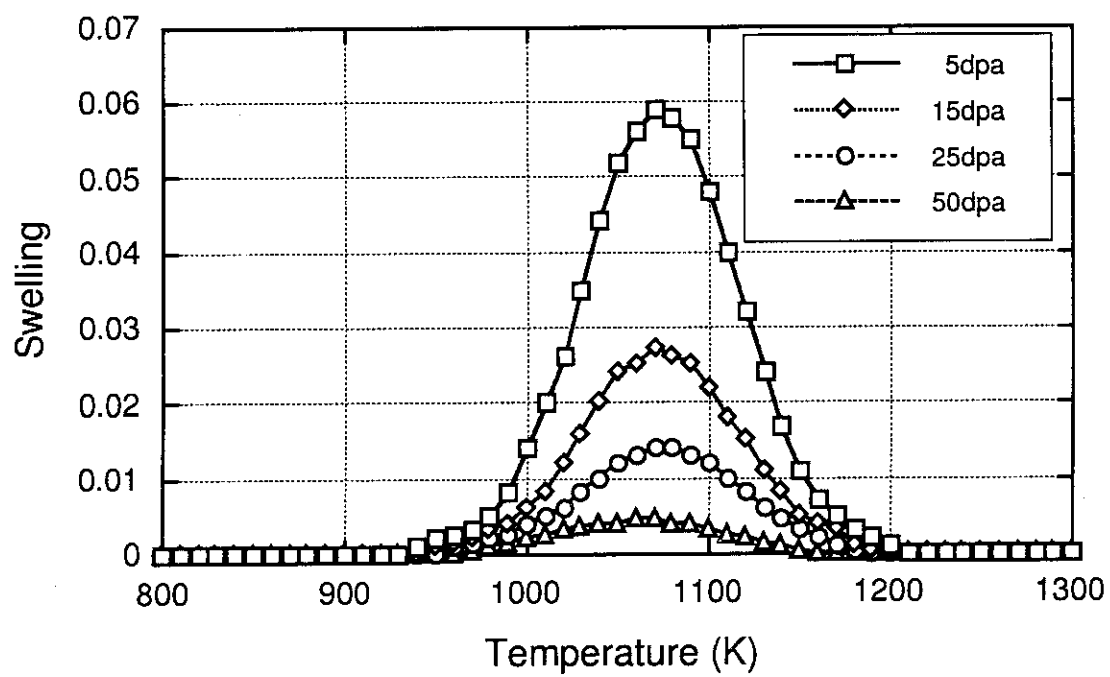


Fig.A-5 Nb1%Zr swelling data.