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Type 316 stainless steel is one of the most promising candidate materials to be used for the structural parts of plasma facing components in the nuclear fusion reactor. The neutron irradiation make the material brittle and reduces its uniform elongation to almost zero at heavy doses. In order to apply such a material of reduced ductility to structural components, the structural integrity should be examined and assured by the fracture mechanics. The procedure requires a formulated stress-strain relationship. However, the available irradiated tensile test data are very limited at present, so that the cold-worked material was used as a simulated material in this study. Property changes of 316 SS, that is, a reduction of uniform elongation and an enhancement of yield stress are seemingly very similar for both the irradiated 316 SS and the cold-worked one. The specimens made of annealed 316 SS, 20% (or 15%) cold worked one and 40% cold worked one were prepared. After the formulation of stress strain behavior, the equation for the cold-worked 316 SS was fitted to the data on irradiated material under the assumption that the yield stress is the same for both materials. In addition, the upper limit for the plastic strain was introduced using the data on the irradiated material.

Keywords : Nuclear Fusion Reactor, Neutron Irradiation, 316 SS, Uniform Elongation, Irradiation Embrittlement, Stress-strain Curve

+ Department of Materials Science and Engineering

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316ステンレス鋼照射材の引張応力ひずみ特性の冷間加工材による模擬

日本原子力研究所東海研究所高温工学部
武藤 康・實川 資朗+・菱沼 章道+

(1995年6月23日受理)

核融合実験炉のプラズマ対向壁の構造材として使用が検討されている316ステンレス鋼は中性子照射により脆化し一様伸びがほとんどゼロになる。この様な特性をもつ材料を構造材として使用するには破壊力学による解析を行い構造健全性を調べる必要がある。この解析には応力ひずみ関係式を必要とする。しかし，現在までに得られている316ステンレス鋼の照射データは極く限られているので，照射材と見かけ上の応力ひずみ特性がほぼ一致している冷間加工材を用いて定式化を試みた。溶体化処理材，20％（または15％）冷間加工材，及び40％冷間加工材に対して応力ひずみ関係式を作成し，降伏応力が等しいという仮定の下に冷間加工度と照射量を結びつけた。また，照射データより塑性ひずみの上限値を定めた。

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In nuclear fusion reactor, structural parts of plasma facing components are planned to be made of Type 316 stainless steel. The components are exposed to neutrons which cause radiation damage of 10 to 30 dpa in the case of ITER CDA design[1]. It is well-known that the neutron irradiation causes both an increase of the yield stress and a decrease of the uniform elongation in 316 SS. Such effects are dependent not only on the irradiation fluence but also on the irradiation temperature.

Though the formulation of the stress-strain relationship is mandatory for the structural design or structural integrity evaluation of such components, strength data of the irradiated 316 SS are limited and insufficient for the purpose of formulation.

Similar changes of tensile properties are observed also in the heavily cold-worked 316 SS. Though the hardening and fracture mechanisms are thought to be quite different between in the irradiated 316 SS and heavily cold-worked one, both behave very similarly from the phenomenological viewpoint, as illustrated in Fig. 1[2] and later in Fig. 12. Therefore, the simulation of stress-strain relationship of irradiated 316 SS by heavily cold-worked one was undertaken. The results are very useful for the study regarding the structural integrity evaluation of fusion-reactor components.

2. Stress-strain Relationship of Cold-worked 316 SS

2.1 Tensile Test Data for the Cold-worked 316 SS

Tensile test data listed in Table 1 were used to formulate the stress-strain relationship. The test temperatures were room temperature, 300°C, 330°C and 400°C. At room temperature, data on the 4, 4 and 8 specimens corresponding to each degree of cold-work of 0, 15 and 40%, respectively were available. Among them, only the data on two specimens having medium values were used for each condition. Figures 2(a) to (k) show the measured load-strain curves. The values of total strain up to several per cent were read on these figures. Such a procedure was not only time-consuming but also inaccurate, though it was inevitable in the state that there was no experimental digital data available. In addition, at higher temperature, the slender test specimens with the cross section of only 1.5 mm × 0.76 mm were used, which made an accurate measurement difficult. Therefore, some uncertainty regarding the accuracy cannot be eliminated.

The values of plastic strain were calculated by deducting elastic strains from the total strains. The values of elastic modulus obtained from

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The values of plastic strain were calculated by deducting elastic strains from the total strains. The values of elastic modulus obtained from the tests at room temperature were almost independent of the degree of cold-work. Then, the constant value of 2.7×10^5 MPa was used in the calculation of elastic strain. On the other hand, the values of elastic modulus varied from case to case for the tests at 300 to 400°C conducted at ORNL. Then, the individual measured values were used for the above purpose.

Figure 3(a) to (d) are stress-plastic strain curves produced in that way. Looking at the corners of the curves at room temperature, their shapes seem to change from a circular shape for the annealed 316 SS to an angular one for the 15% cold worked material and again to a circular shape for the 40% cold worked material. The change of shapes due to the cold-work seems to be somewhat different at 300°C and 400°C. Such complicated diversity of cold-work and temperature dependence of shape makes the formulation very difficult as described later.

2.2 Formulation of Stress-strain Relationship

The plastic strain for the cold-worked 316 SS is plotted against stress on logarithmic diagram as shown in Fig. 4. In this study, an engineering strain instead of a true strain was used for the simplicity, because only the small strain area up to 3 percent was needed to be considered. An engineering strain of 3% corresponds to a true strain of 2.956%. Therefore, the difference between the engineering and the true strains is negligibly small.

If the data points come on a straight line, this means the stress-plastic strain relation can be represented by an equation $\sigma = k\varepsilon^m$ which is usually used in the design codes[3][4]. The results, however, showed various trends. For the annealed 316 SS, the data points showed nearly straight lines (Fig. 4(a),(d),(g) and (j)). For the cold worked material, however, they showed convex lines (Fig. 4(b), (c), (e), (f), (i) and (k)), except for the specimen FL-56 (Fig. 4(h)) which showed the straight one.

In order to fit those experimental stress-strain data points to curves represented by an equation, a more sophisticated one will be required. There are some candidate equations as follows,

Prager's equation: $\sigma = Y\cdot\tanh(E\varepsilon/Y)$, (1)

Voce's equation: $\sigma = a + (b-a)\{1 - \exp(-c\varepsilon)\}$, (2)

where Y, E, a, b and c are material constants.

These equations include exponential parameters and are thought to be more suitable to represent the angular shape observed in the vicinity of yield points.

Here, however, the simple equation $\sigma = k\varepsilon^m$ was employed, because the more sophisticated formulation would require the more reliable experimental data.

Two points shown in Table 2, i.e., the data of ε = 0.2% and 2.0% have been selected for the data fitting. The calculated values of parameters m and k are also shown in Table 2 and plotted against the 0.2% yield stress in Figures 5 and 6, respectively. The latter is also shown in linear scale in Fig. 7. The values of parameter k are represented by the straight line fairly well. On the other hand, the values of parameter m seem to scatter more. Therefore, the value of k was firstly determined as follows.

$$\ell og_e k = \ell og_e 257 + 0.00178\,\sigma_y \qquad (3)$$

Then, the values of m were calculated again using the k values calculated by this equation. The modified values were denoted by m* which showed a regression to a concave line shown in Fig. 8 and were represented by the following equation.

$$m^* = 5.74\times10^{-8}(\sigma_y - 600)^{2.3} + 0.036 \qquad (4)$$

The simulated plastic strain curves are compared with the measured ones in Figs. 9(a) and (b). The difference between the calculated and the experimental data is inevitable, because the data themselves didn't show monotonous or consistent trend of curve-shapes depending on the increase of degree of cold-work. In addition, the form of equation $\sigma = k\varepsilon^m$ was not adequate enough for the cold-worked 316 SS as was mentioned previously.

By adding the elastic strain σ/E to the plastic strain obtained from the equation of $\varepsilon=(\sigma/k)^{1/m}$, the total strain can be obtained as follows for the given stress for the cold-worked 316 SS.

$$\varepsilon = \varepsilon_e + \varepsilon_p = \sigma/E + (\sigma/k)^{1/m}, \qquad (5)$$

where

ε = total strain,

ε_e = elastic strain,

ε_p = plastic strain,
E = Young's modulus.

The next step is to correlate the above equation with the irradiation data. For this purpose, the similarity of hardening characteristics of 316 SS between the irradiation and cold-work is utilized. That is, a stress-strain curve is assumed to be the same both for the irradiated 316 SS and the cold-worked one for the given 0.2% yield stress.

2.3 Yield Stress for the Irradiated 316 SS

The 0.2% yield stress for the irradiated 316 SS is represented as follows[2].

$$\sigma_y = B \log_{10}(p) + \sigma_{y,unirr} , \qquad (6)$$

where
B = constant(538 MPa at 300°C, 215 MPa at room temperature),
p = neutron irradiation damage (dpa),
$\sigma_{y,unirr}$ = 0.2% yield stress of unirradiated 316 SS (MPa).

The temperature dependence of unirradiated 316 SS is given by the next equation based on the experimental data.

$$\sigma_{y,unirr} = 302.3\exp(-0.000477T) , \qquad (7)$$

where
T = temperature (K).

2.4 Simulated Stress-strain Curves

The calculation of the simulated stress-strain curves has been conducted. Firstly, the σ_y-values were determined for a given dpa using Eqs.(6) and (7). Then, parameters m and k were calculated using Eqs.(3) and (4), respectively. Finally, the strains were obtained using Eq.(5). Table 3 gives the calculated values of parameters for the typical cases of temperature and irradiation damage. The resultant stress-strain curves are shown in Figs. 10 and 11. The broken line will be explained at the next paragraph.

3. Strain Limit on the Basis of the Uniform Elongation

In the above derivation of the simulated stress-strain curves for the irradiated 316 SS, the strain limit was not considered. This is discussed and supplemented here.

Uniform elongation data versus the yield stress are plotted in Fig. 12. The data for the unirradiated annealed or cold-worked are originated from the same source used in the above formulation. The irradiated data are from the literature[2]. The multi-linear lines can be drawn as the lower bound for the uniform elongation, which means the upper limit of plastic strain. Those values for the above-mentioned typical cases are also shown in Table 3. The elongation at 300°C with 10dpa is 0.66%. The part of stress-strain curve exceeding this limit is drawn by a broken line in Fig. 11.

4. Summary

The tensile stress-strain characteristics are very similar to each other for the irradiated 316 SS and the cold worked one. Therefore, the formulation of stress-strain relationship has been undertaken by using the data of cold-worked 316 SS. The simple equation of $\sigma = k\varepsilon^m$ was adopted. As for the strain limit, the lower bound of experimental data for the uniform elongation of the irradiated 316 SS were utilized. The derived equation is expected to be useful for the evaluation of structural integrity of irradiated components in the fusion reactor.

To discuss the structural integrity of the components made of irradiated 316 SS more exactly based on such a stress-strain relationship, the more accurate and comprehensive data for the cold worked 316 SS are needed. The accurate data mean those by tensile tests in the digital data recording system. The comprehensive data mean those for cyclic stress-strain curves. This is necessary for the equation to be applied to the fatigue life prediction. The experimental data for the irradiated material are of course required. Such data, however, are limited and should be used to modify or ascertain the equations determined on the basis of the cold-worked material.

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[2] Jitsukawa,S., Grossbeck,M.L. and Hishinuma,A., J. Nuclear Materials 191-194, pp.790-794 (1992).

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[4] RCC-MR, A3.3S.5.9.1 Cyclic curves (June 1985).

Table 1 Results of tensile tests

Degree of cold-work %	Test temperature °C	0.2% yield stress MPa	Tensile strength MPa	Total elongation %	Uniform elongation %	Reduction in area %	Specimen No.
0	R.T.	265	531	65.5	49.7	80.0	PCA0LT1(C)
0	R.T.	260	545	61.0	49.7	75.4	PCA0TL2(C)
15	R.T.	578	638	36.5	17.2	79.7	PCA15LT1(B)
15	R.T.	602	672	36.0	18.6	71.3	PCA15TL1(B)
40	R.T.	772	845	20.5	1.8	58.0	PCA40TL2(A)
40	R.T.	813	898	17.0	1.7	61.6	PCA40TL2(D)
0	300	230	466	44.0	36.0	-	ANC-7
15	330	529	555	4.6	1.8	-	DL-56
20	330	630	668	3.4	1.0	-	FL-56
0	400	227	475	48.0	40.3	-	AND-1
20	400	545	556	11.3	2.0	-	BHA-4

Table 2 Values of parameters m and k determined from stresses corresponding to plastic strains of 0.2% and 2.0%

Degree of cold-work %	Test temperature °C	0.2% yield stress MPa	Stress for 2.0% plastic strain MPa	Parameter m	Parameter k	Specimen No.
0	R.T.	265	320	0.08190	440.9	PCA0LT1(C)
0	R.T.	260	320	0.09018	455.4	PCA0TL2(C)
15	R.T.	578	618	0.02906	692.4	PCA15LT1(B)
15	R.T.	602	655	0.03665	756.0	PCA15TL1(B)
40	R.T.	772	845	0.04486	1020.2	PCA40TL2(A)
40	R.T.	813	898	0.05374	1135.4	PCA40TL2(D)
0	300	230	282	0.08852	398.7	ANC-7
15	330	529	555 (ε=1.72%)	0.02203	606.6	DL-56
20	330	630	668 (ε=0.97%)	0.03710	793.4	FL-56
0	400	227	267	0.07048	351.8	AND-1
20	400	545	581	0.02778	647.7	BHA-4

Table 3 Simulated properties of irradiated 316 SS

Temperature °C	Irradiation damage	Young's modulus MPa	0.2% yield stress MPa	m	k MPa	Uniform elongation %
R.T	Unirradiated	195,200	262.5	0.0735	410.1	47.0
R.T	3 dpa	195,200	365.1	0.0523	492.2	34.2
R.T	10 dpa	195,200	477.5	0.0396	601.3	24.1
300	Unirradiated	176,500	230.0	0.0823	387.0	52.0
300	3 dpa	176,500	486.7	0.0390	611.2	23.4
300	10 dpa	176,500	768.0	0.0435	1008.4	0.66

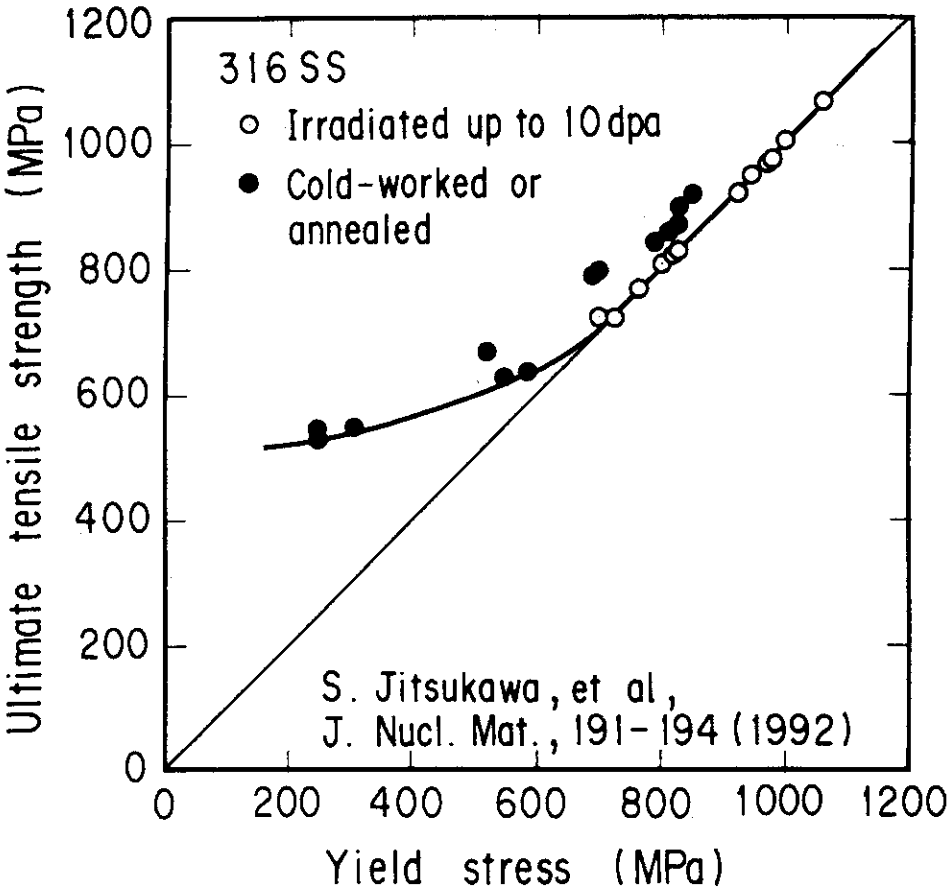


Fig. 1 Relationship between 0.2% yield stress and ultimate tensile strength of the irradiated and cold-worked 316SS

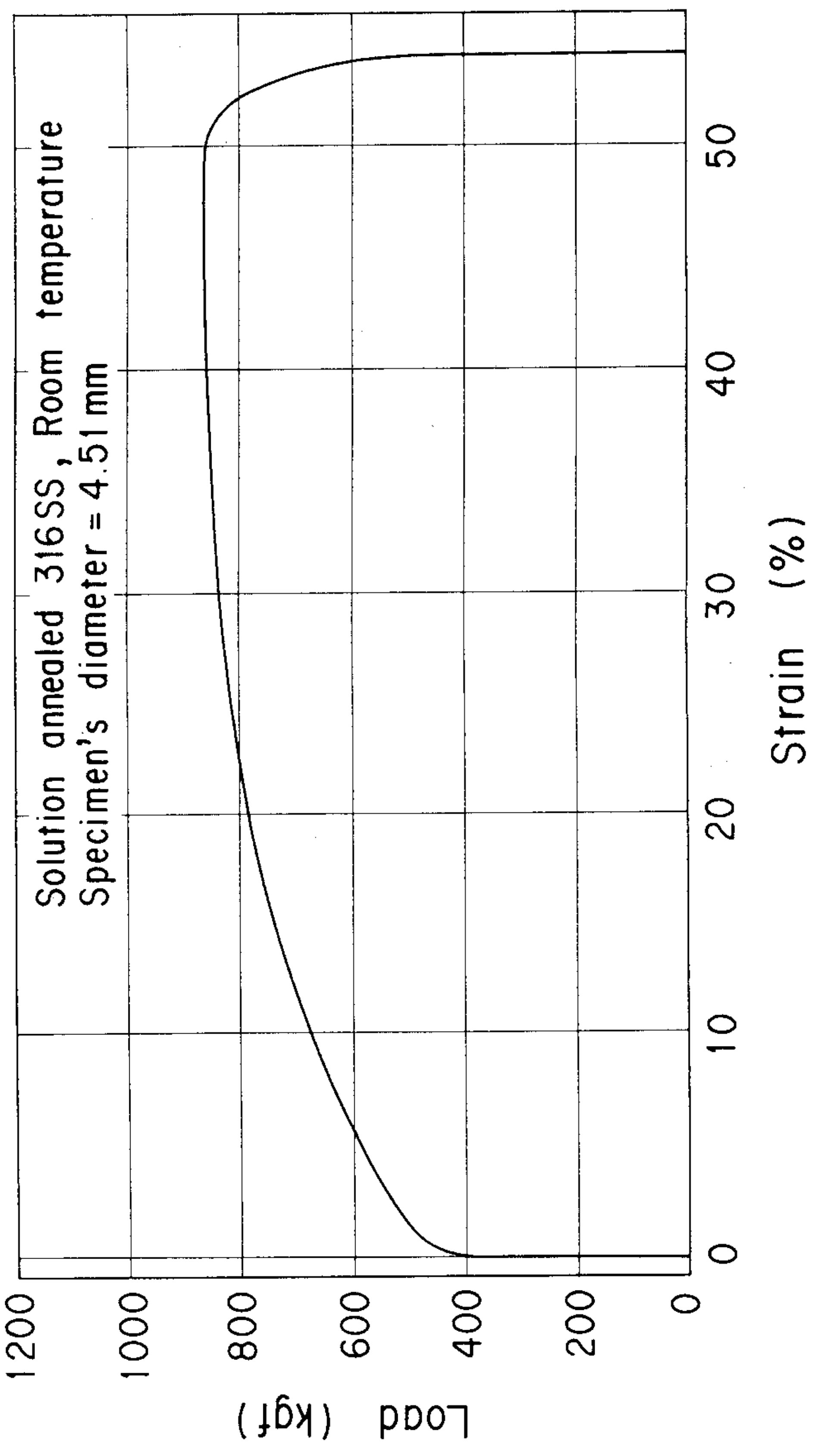


Fig. 2(a) Stress-strain curve
(Solution annealed, R. T., No. PCA0TL1(c))

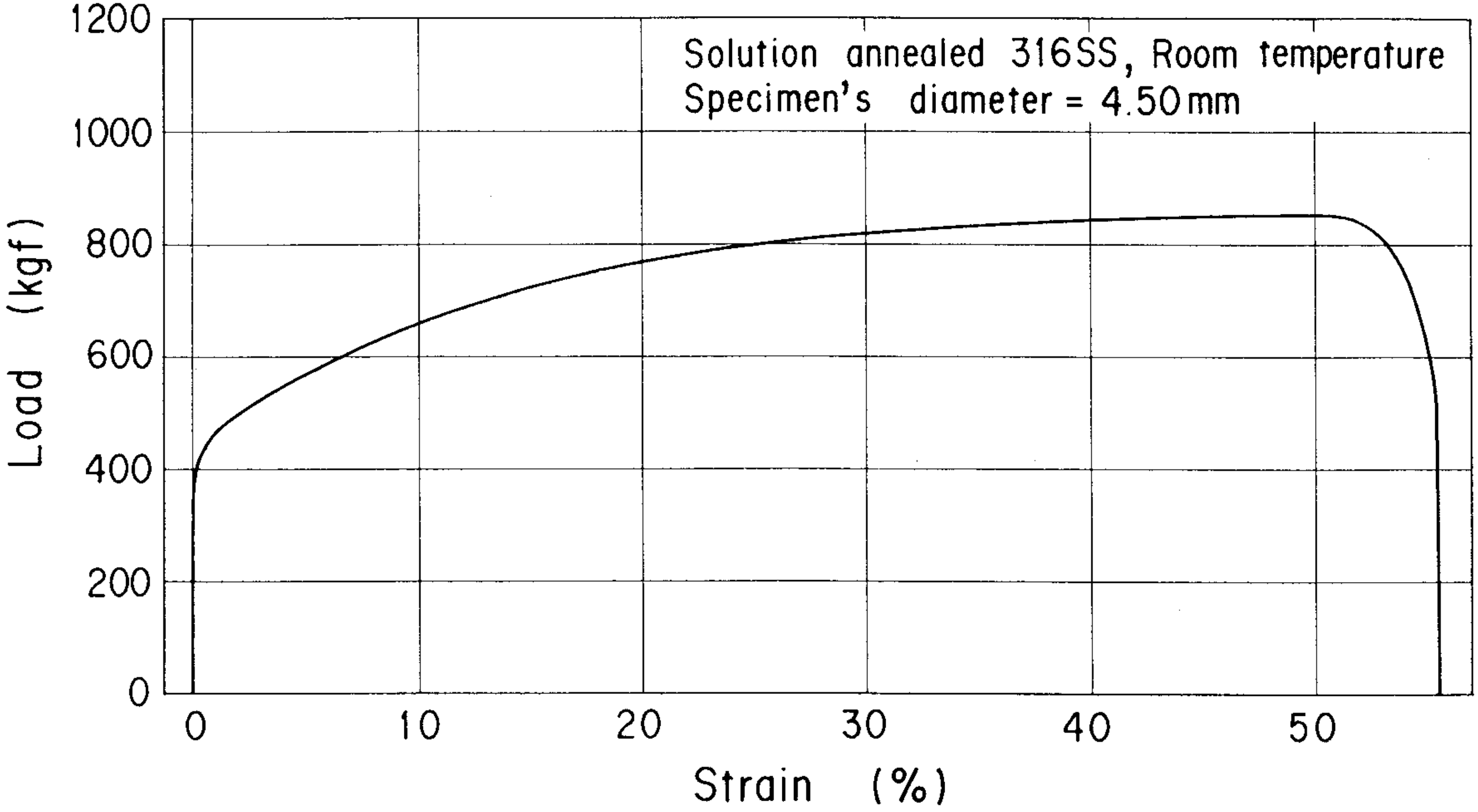


Fig. 2(b) Stress-strain curve
(Solution annealed, R.T., No. PCA0TL2(c))

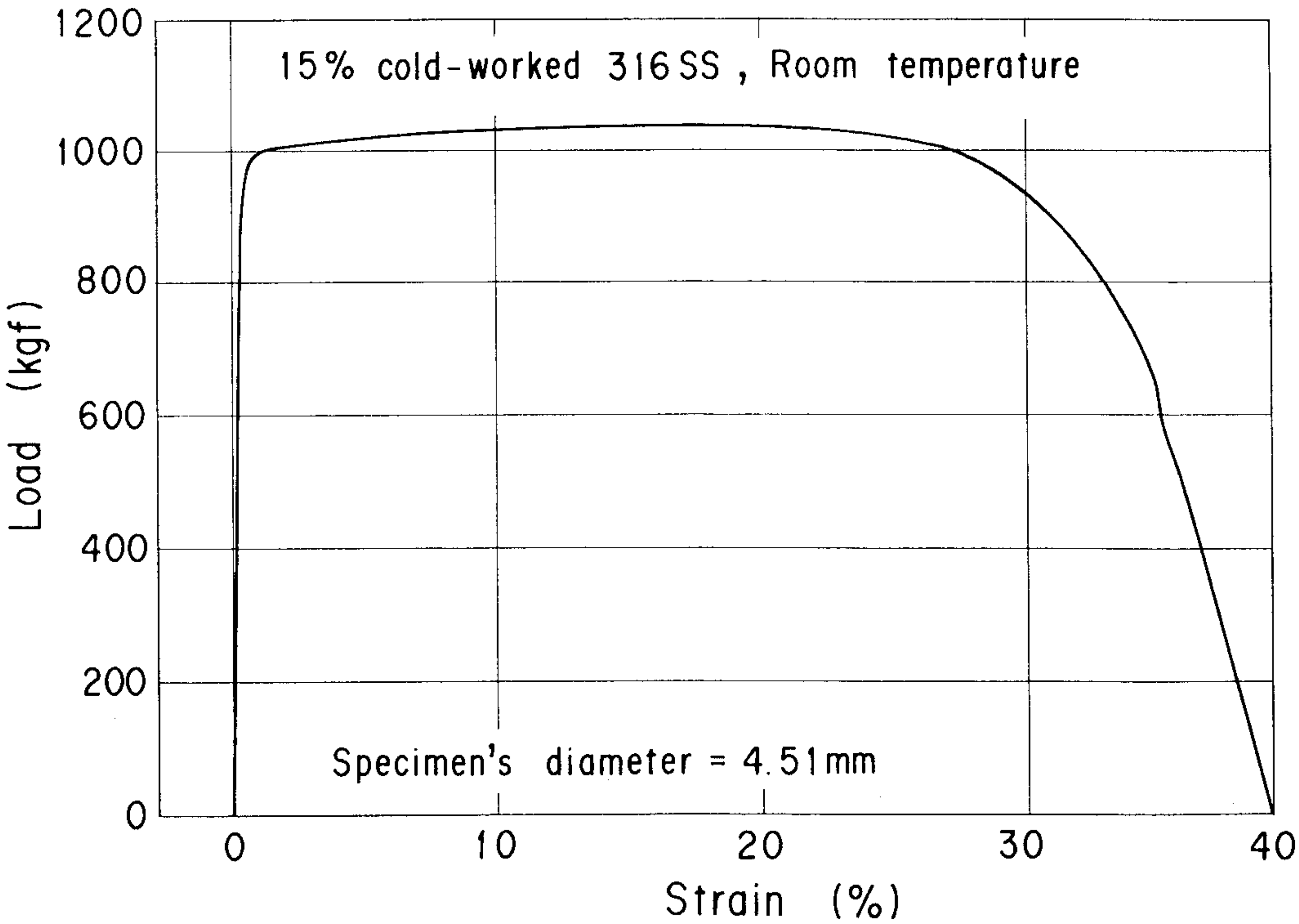


Fig. 2(c) Stress-strain curve
(15% cold-worked, R.T., No. PCA15LT1(B))

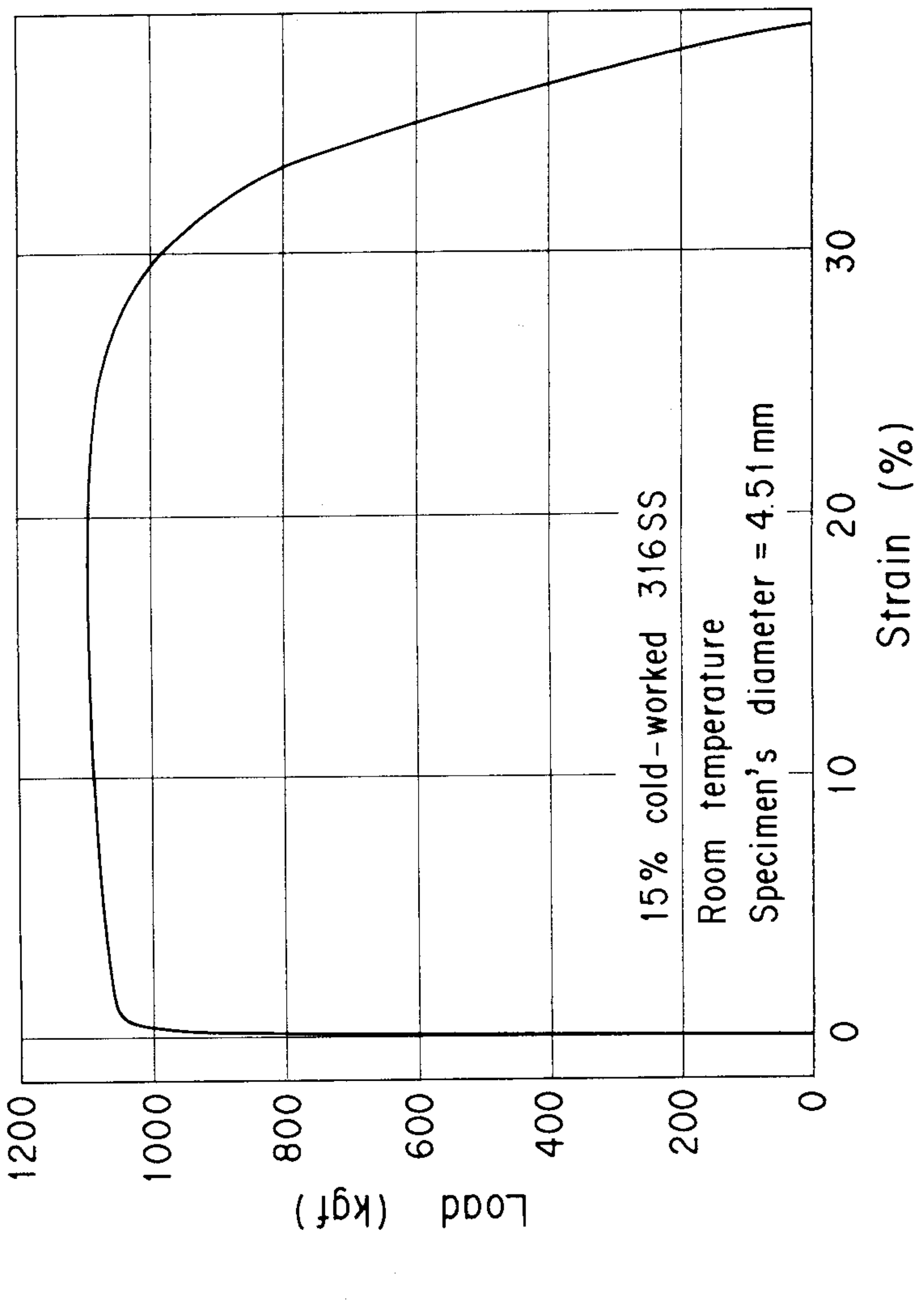


Fig. 2(d) Stress-strain curve
(15% cold-worked, R. T., No. PCA15TL1(B))

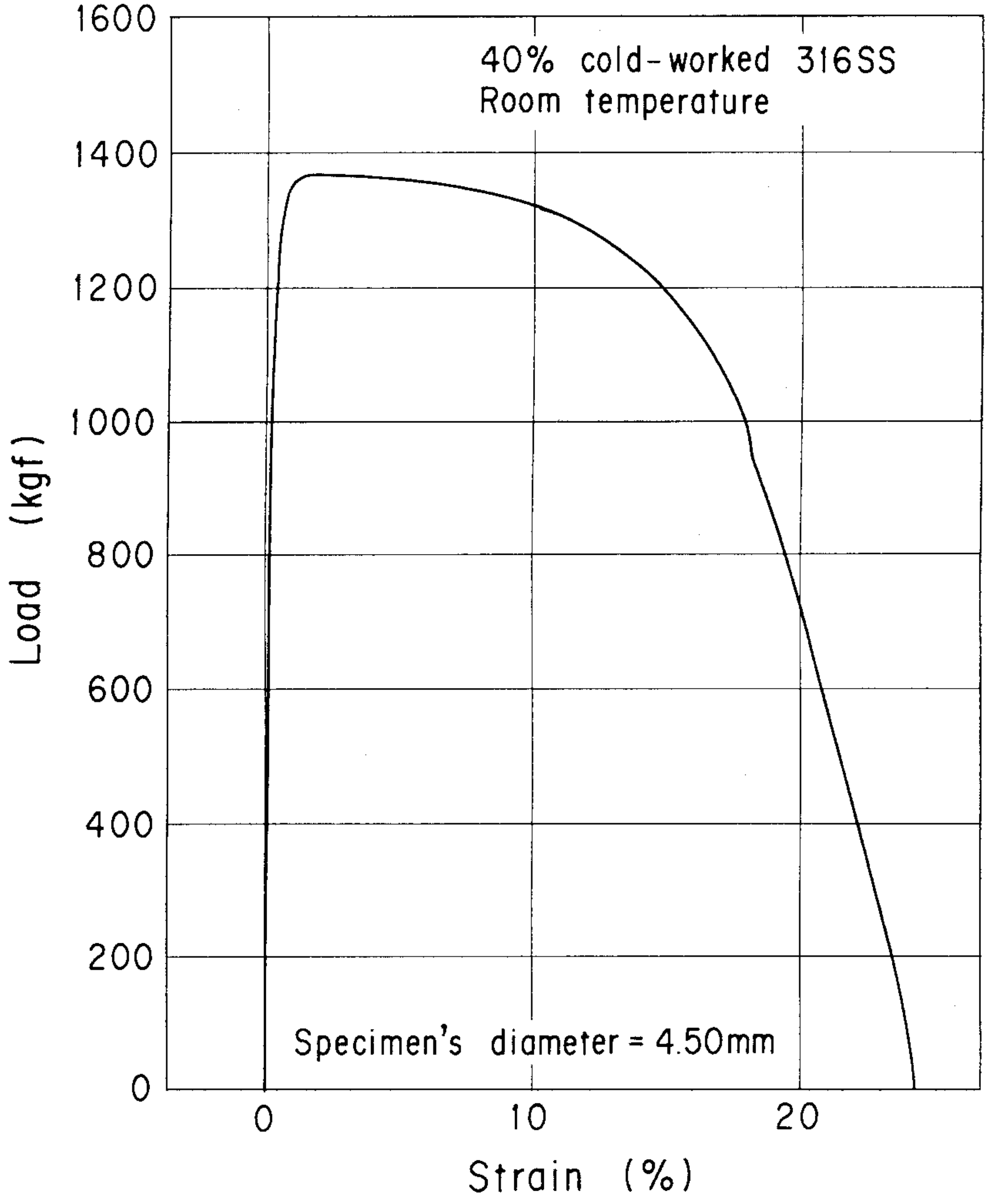


Fig. 2(e) Stress-strain curve
(40% cold-worked, R.T., No. PCA40TL2(A))

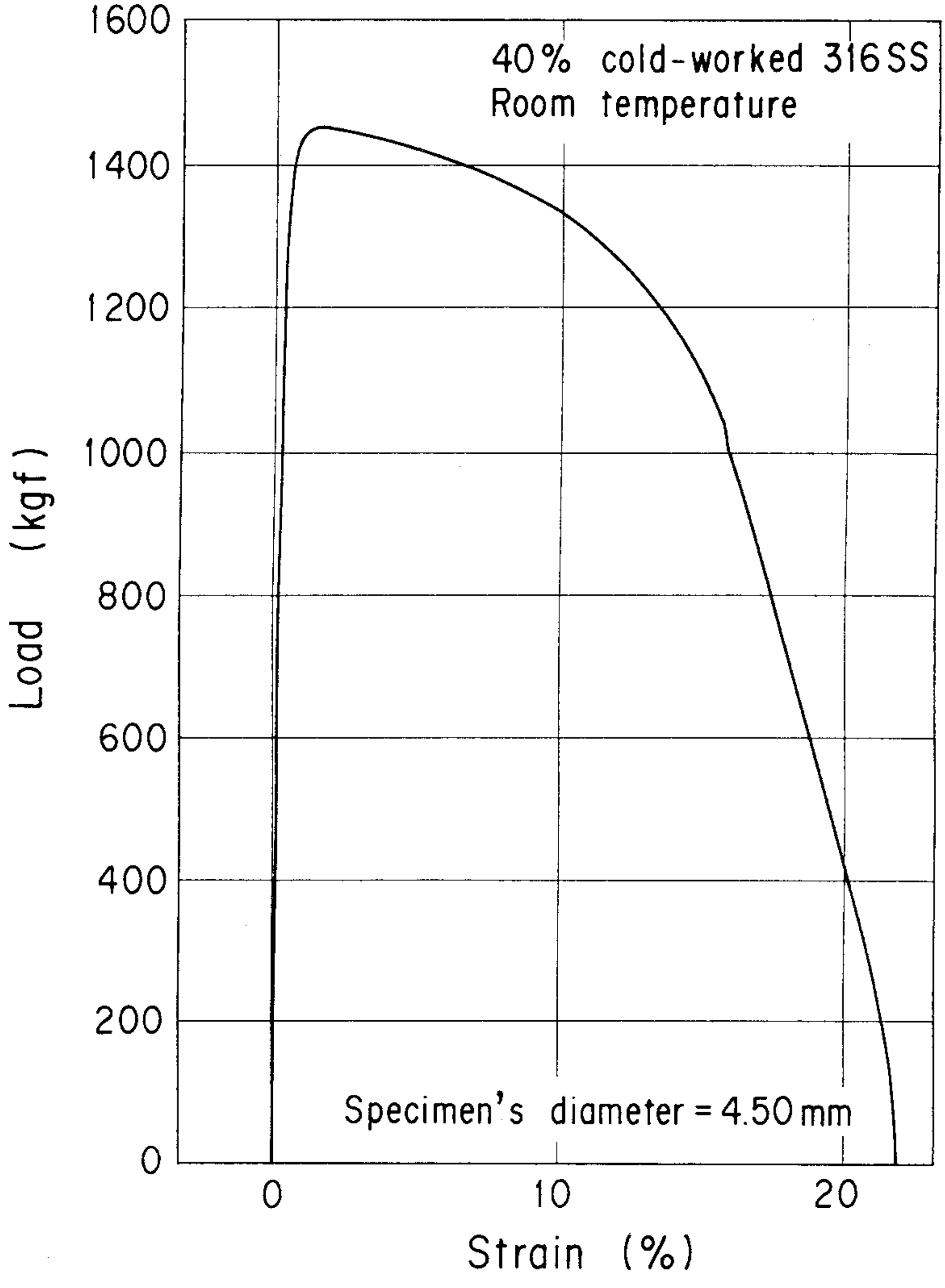


Fig. 2(f) Stress-strain curve
(40% cold-worked, R. T., No. PCA40TL2(D))

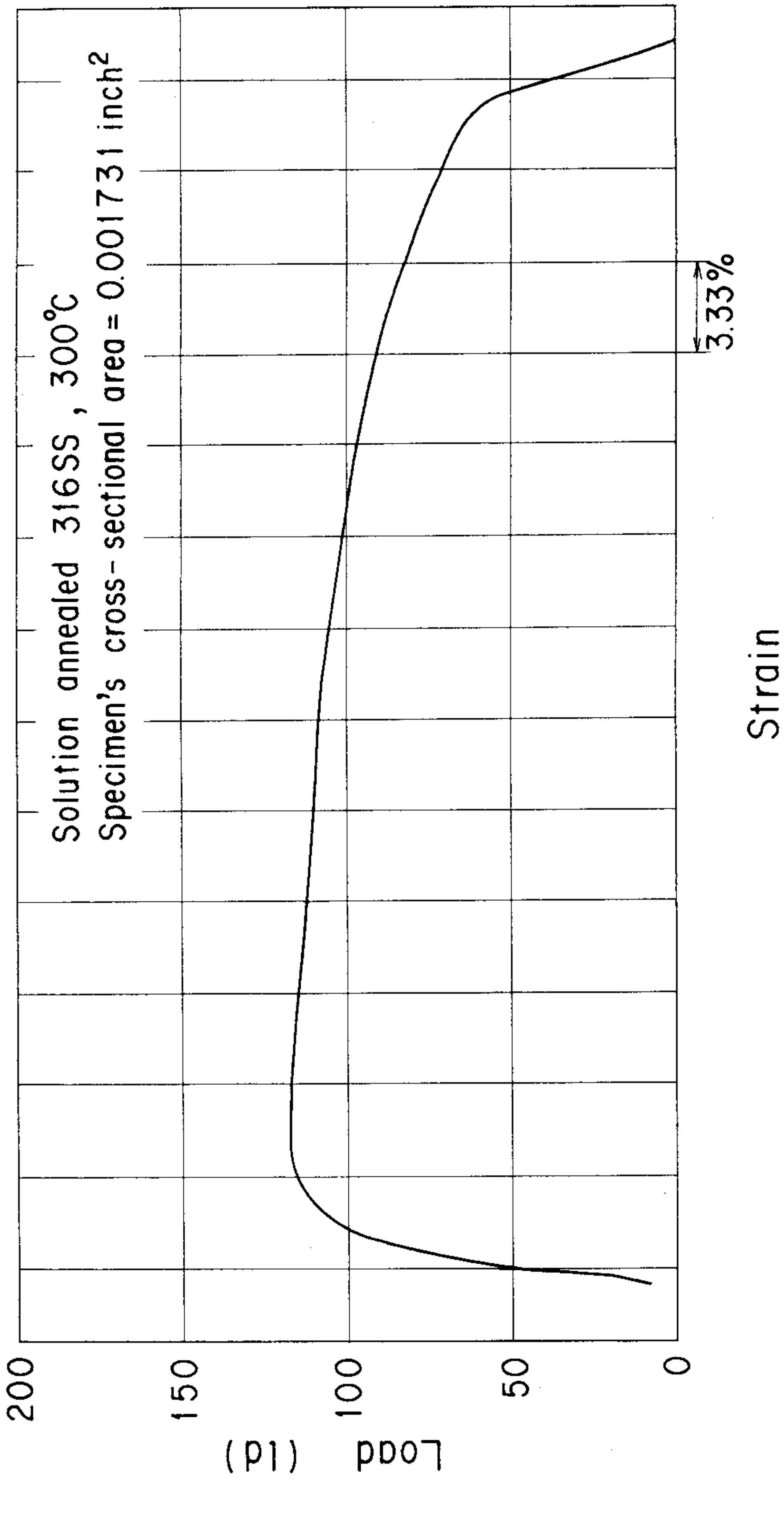


Fig. 2(g) Stress-strain curve
(Solution annealed, 300°C, ANC-7)

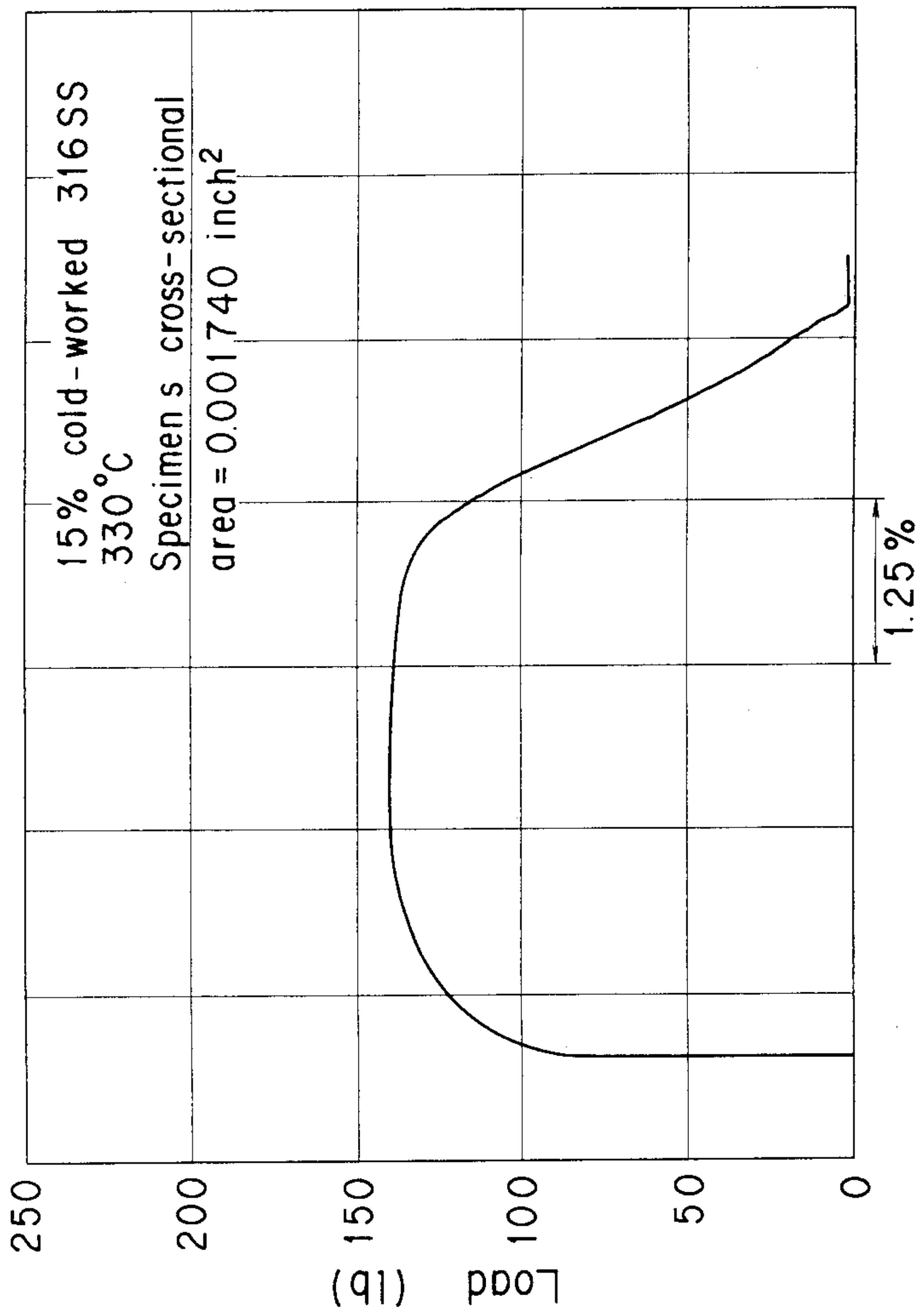


Fig. 2(h) Stress-strain curve
(15% cold-worked, 330℃, DL-56)

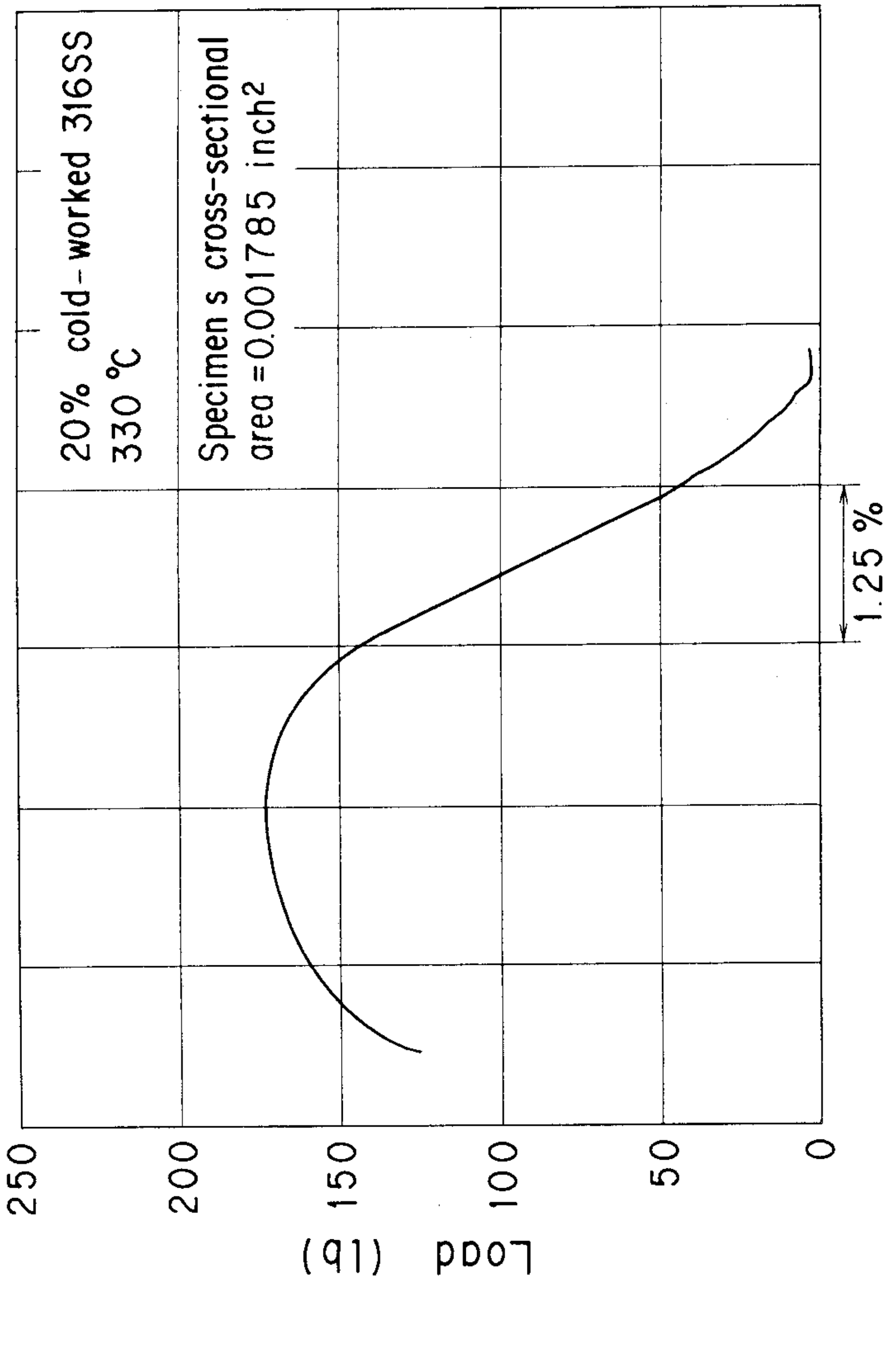


Fig. 2(i) Stress-strain curve
(20% cold-worked, 330℃, FL56)

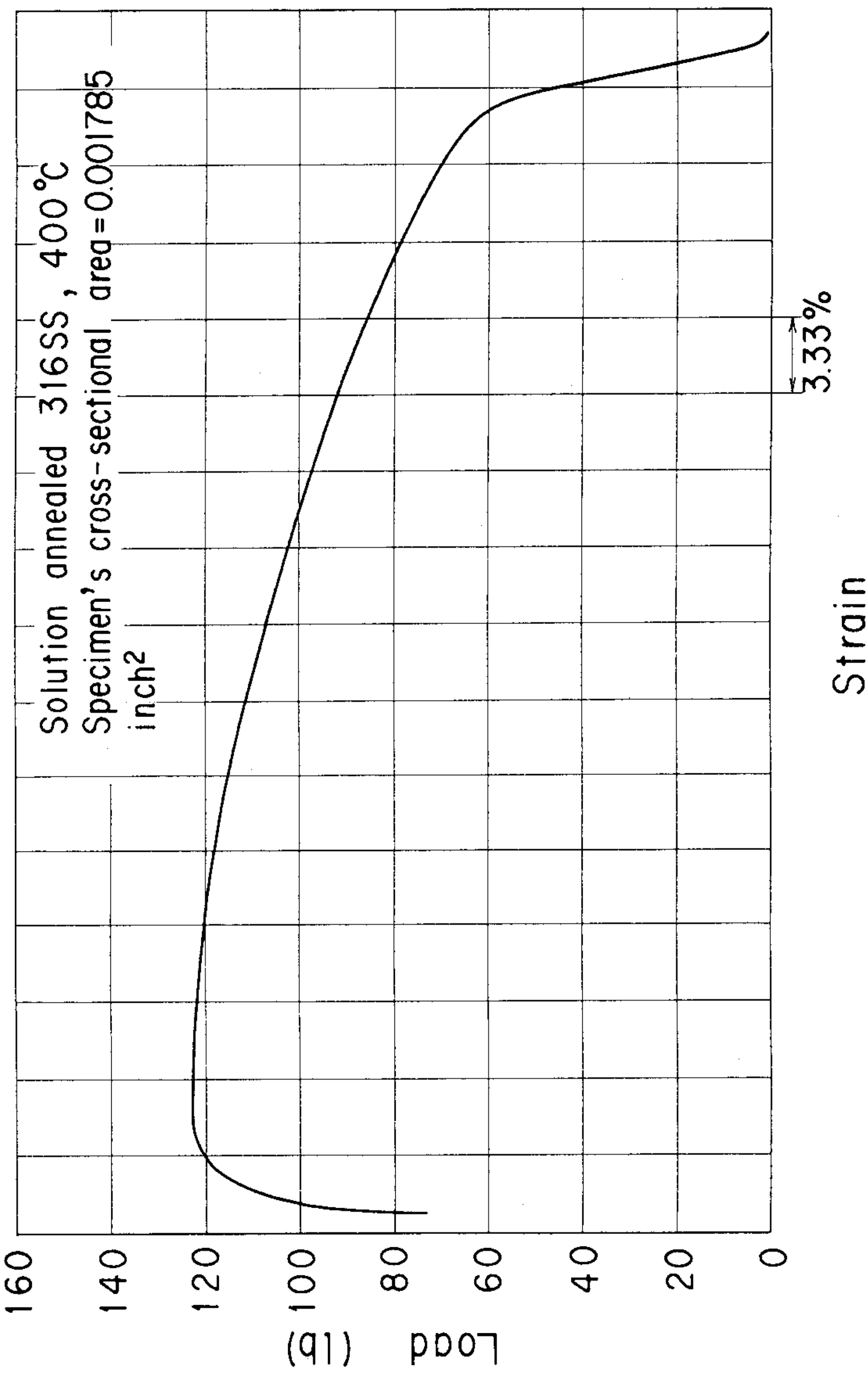


Fig. 2(j) Stress-strain curve
(Solution annealed, 400°C, AND-1)

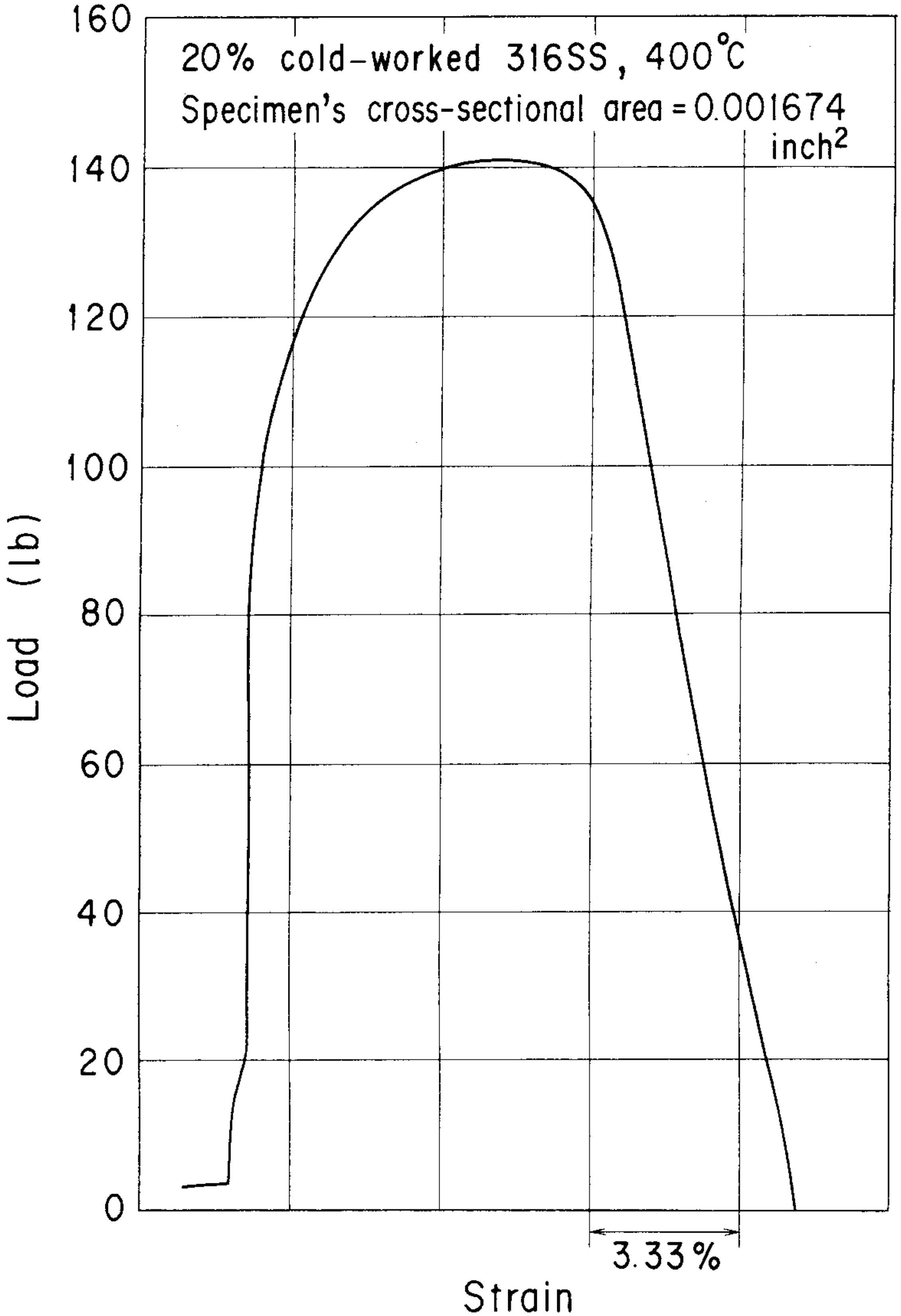


Fig. 2(k) Stress-strain curve
(20% cold-worked, 400℃, BHA-4)

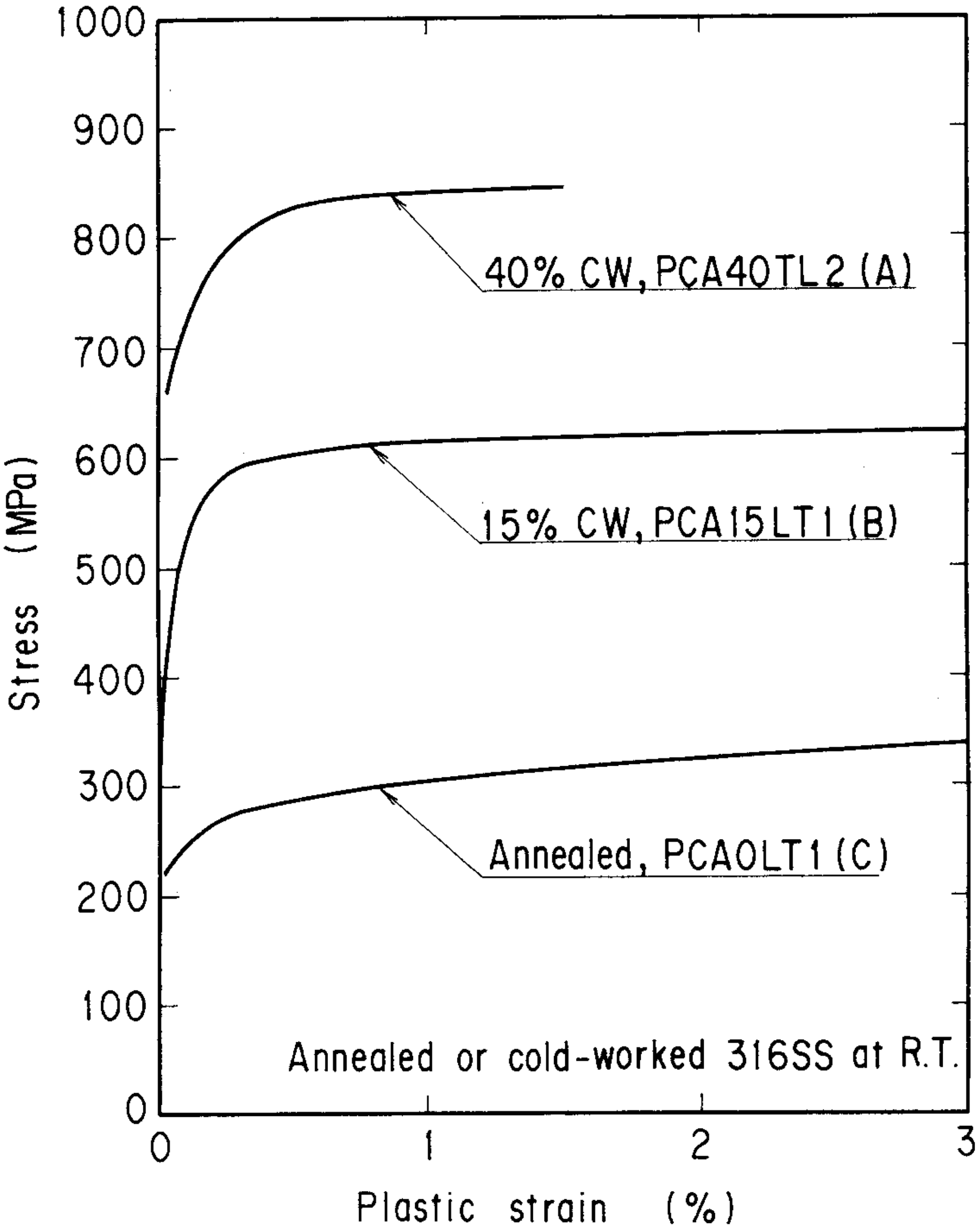


Fig. 3(a) Stress-plastic strain curves at room temperature

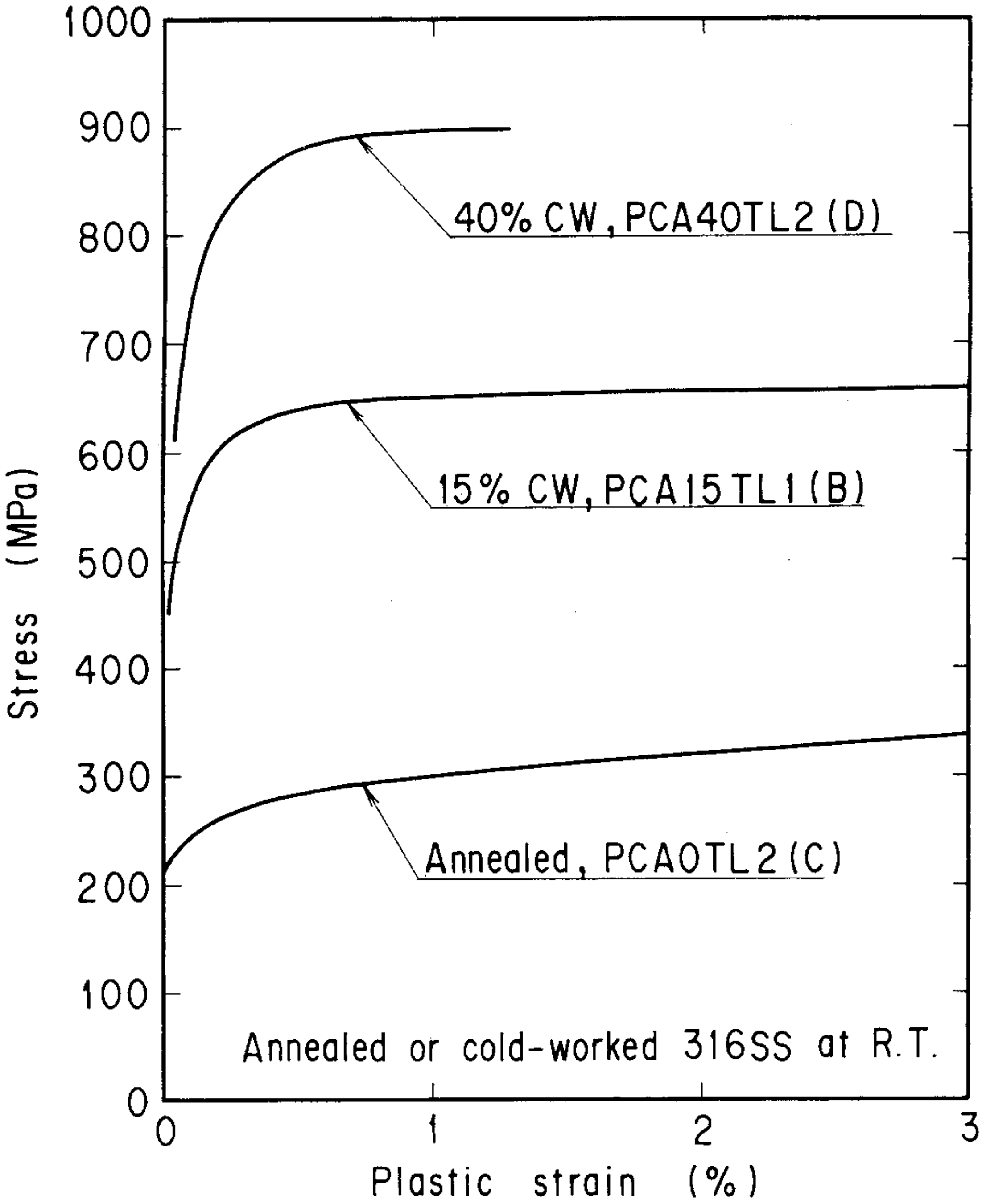


Fig. 3(b) Stress-plastic strain curves at room temperature

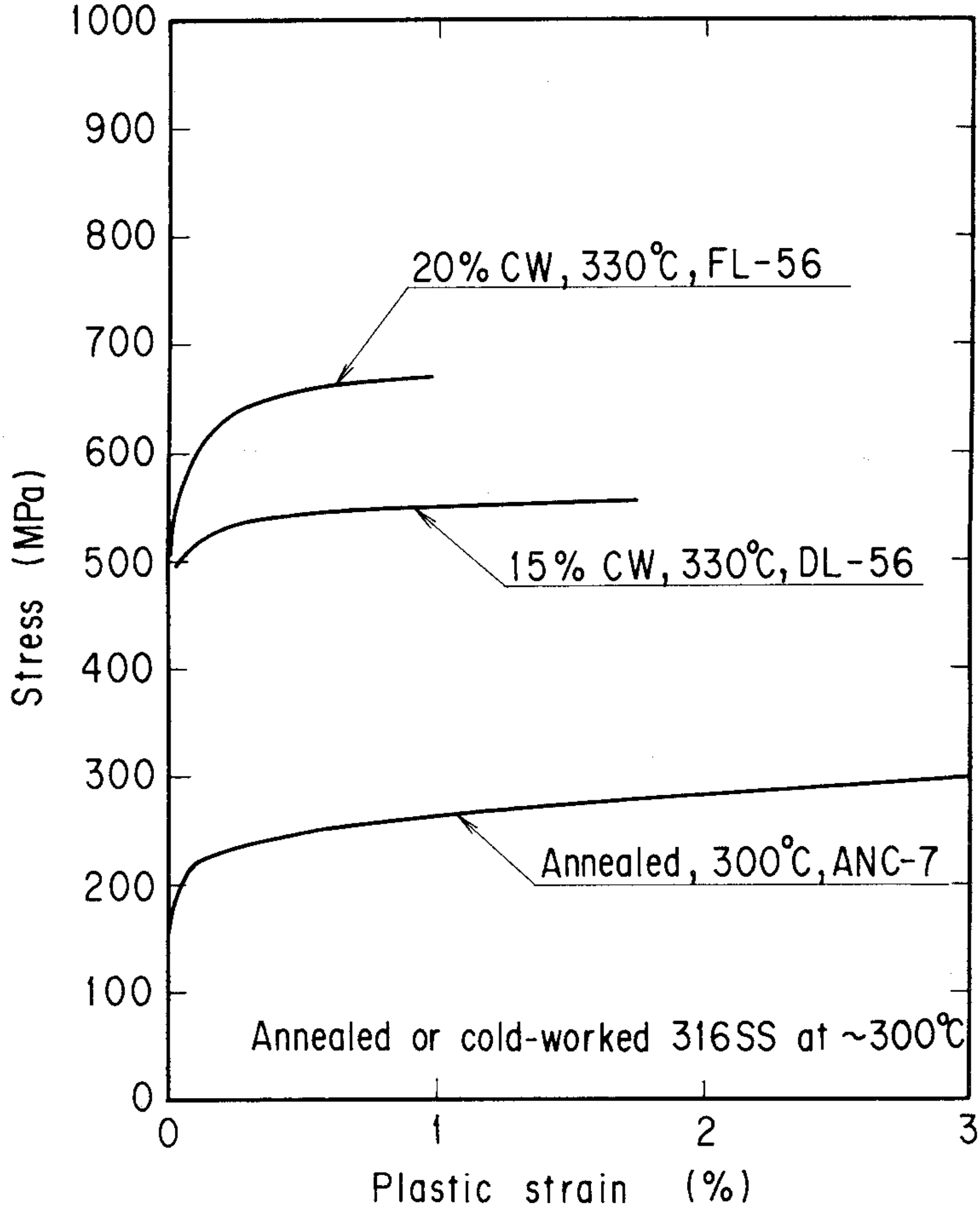


Fig. 3(c) Stress-plastic strain curves at about 300℃

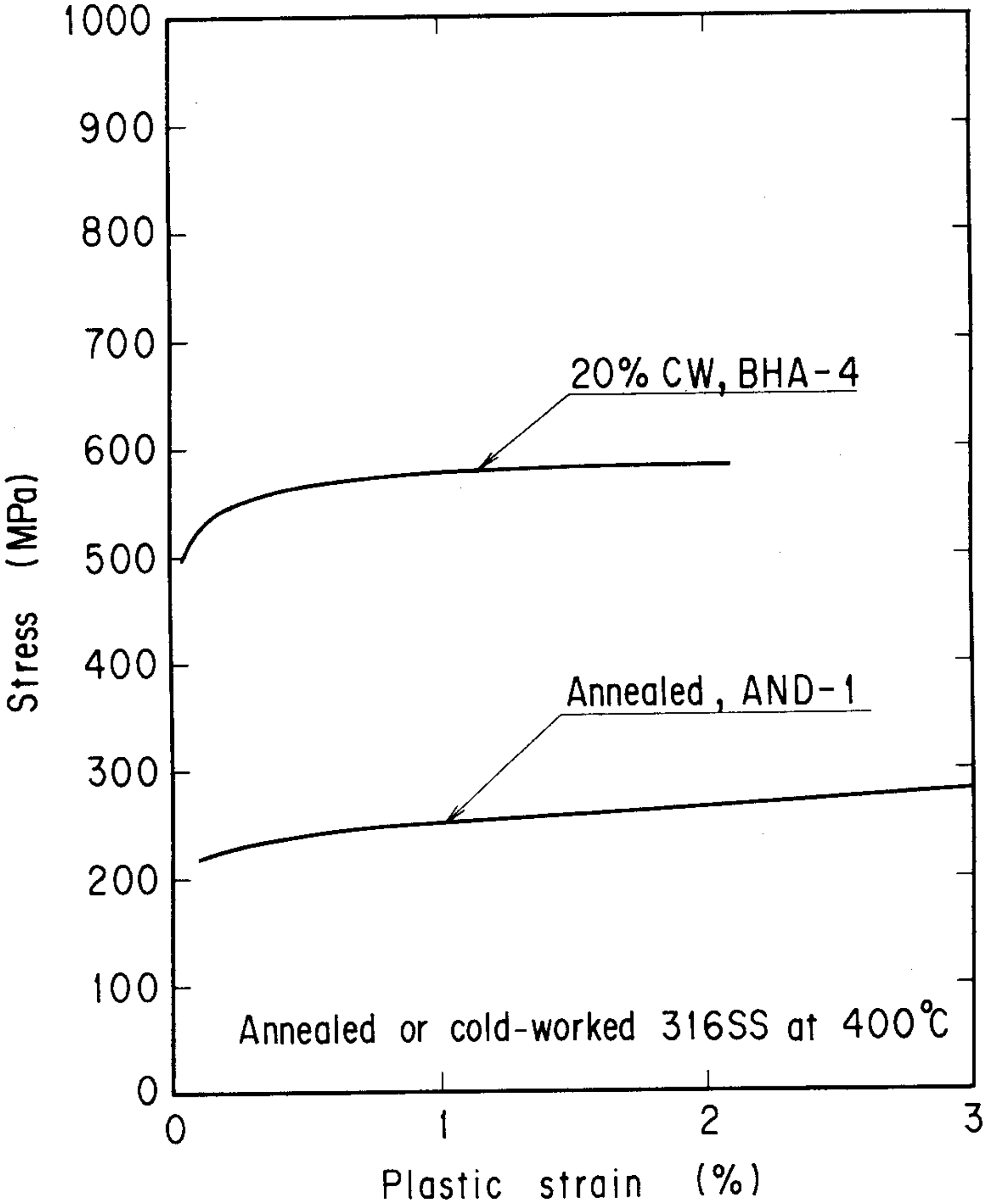


Fig. 3(d) Stress-plastic strain curves at 400℃

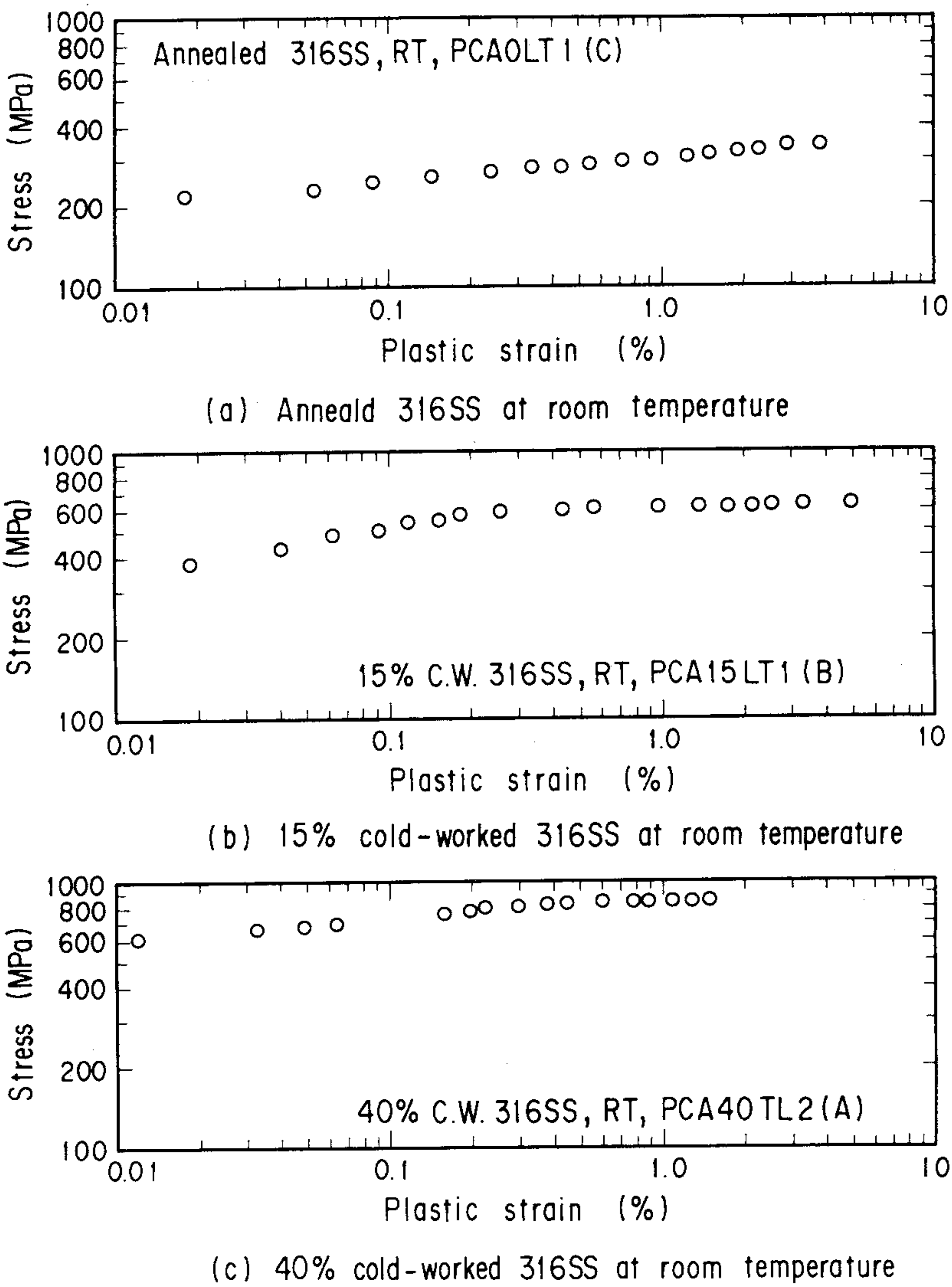
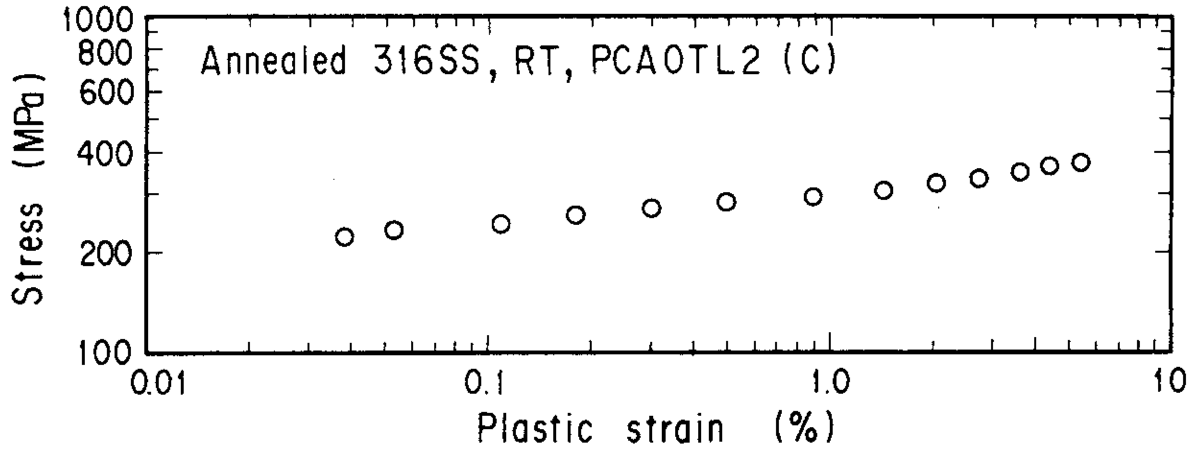
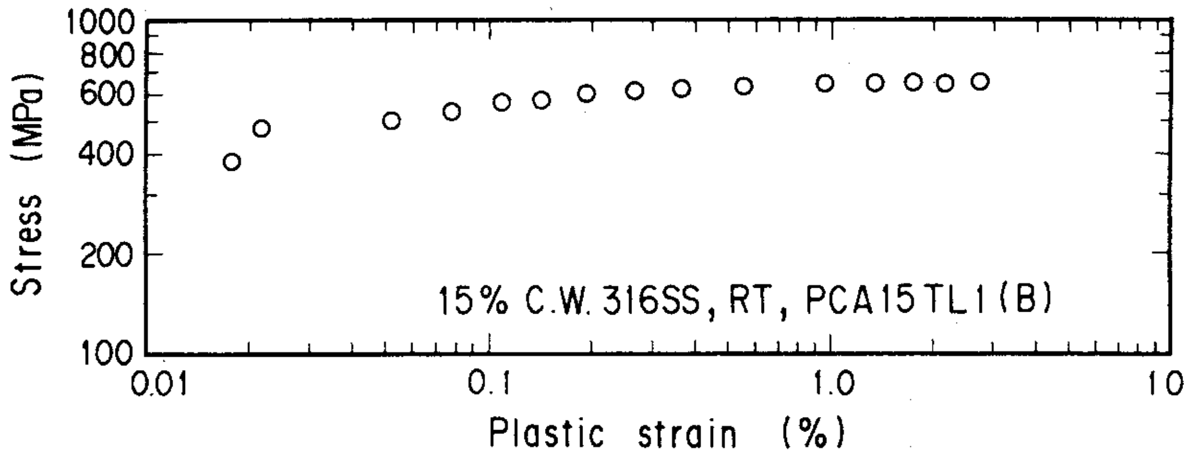


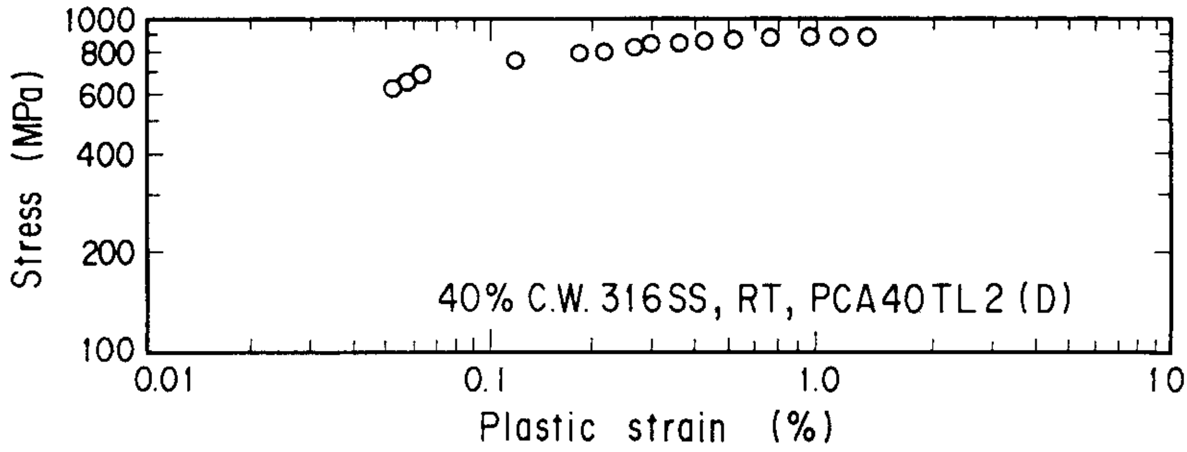
Fig. 4 Stress-dependence of plastic strain



(d) Annealed 316SS at room temperature



(e) 15% cold-worked 316SS at room temperature



(f) 40% cold-worked 316SS at room temperature

Fig. 4 Stress dependence of plastic strain

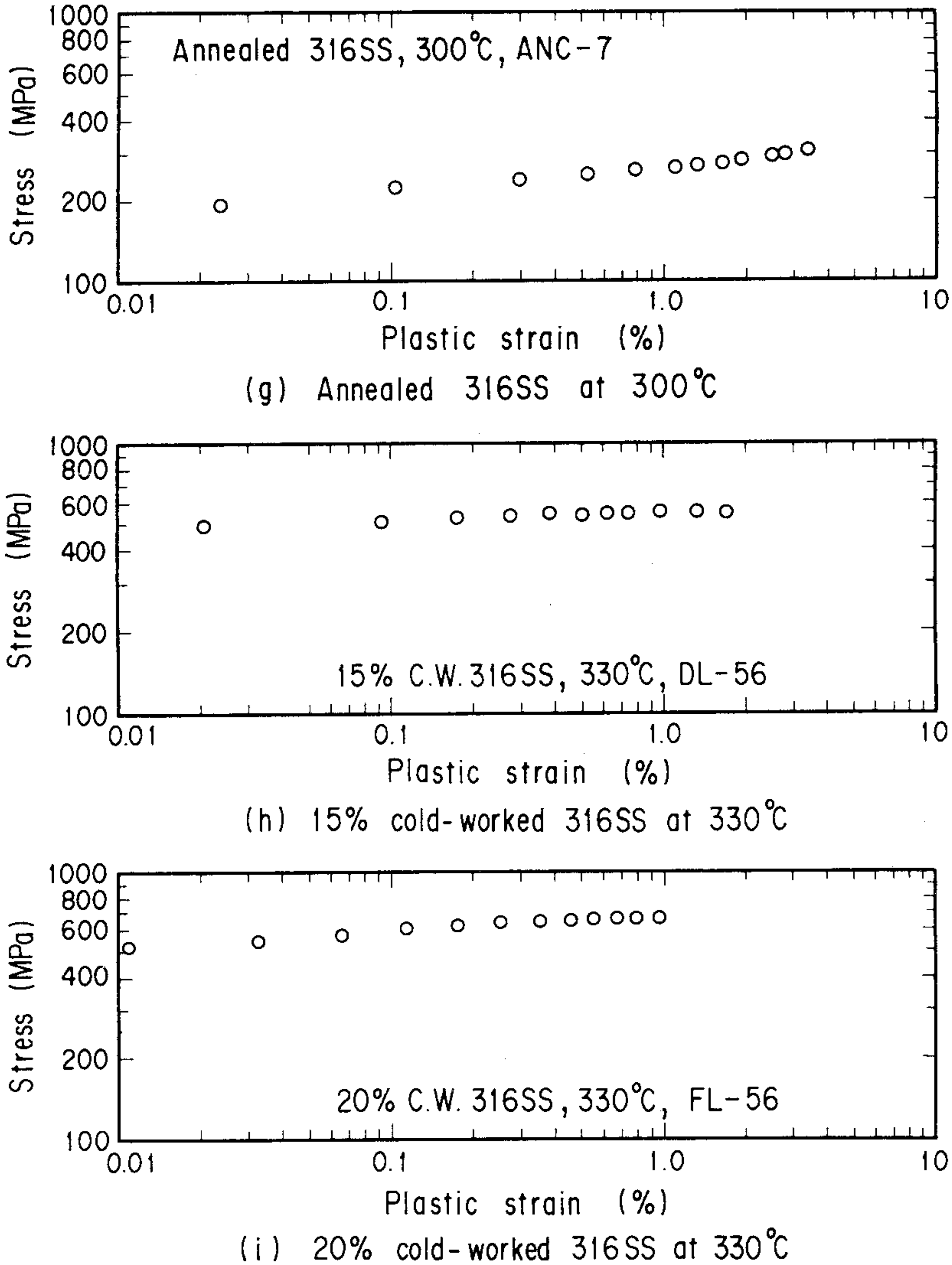
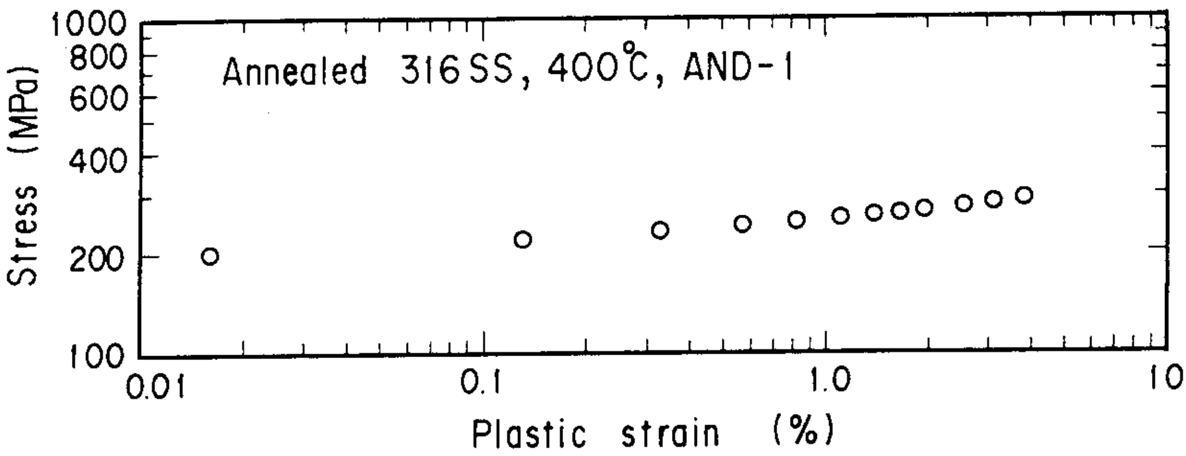
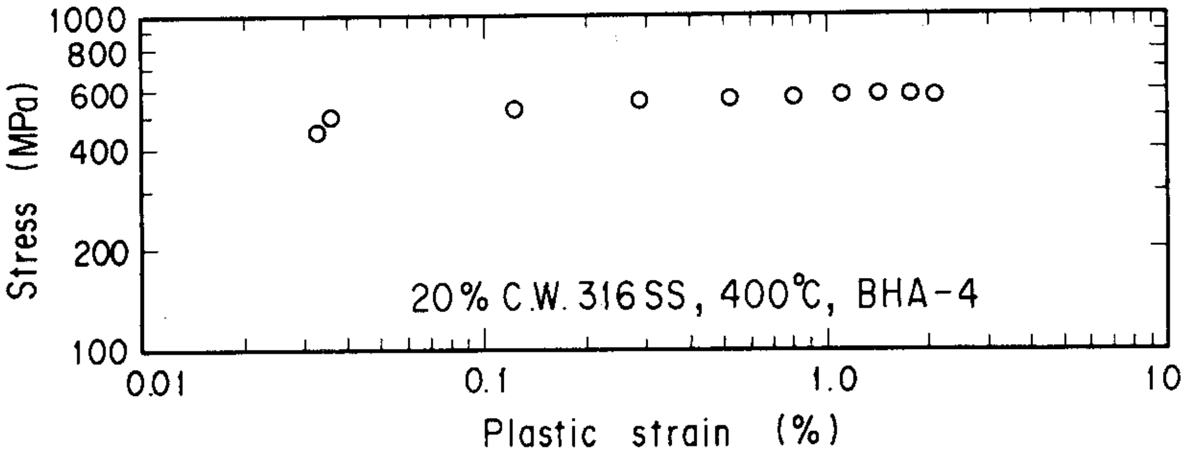


Fig. 4 Stress dependence of plastic strain



(j) Annealed 316SS at 400℃



(k) 20% cold-worked 316SS at 400℃

Fig. 4 Stress dependence of plastic strain

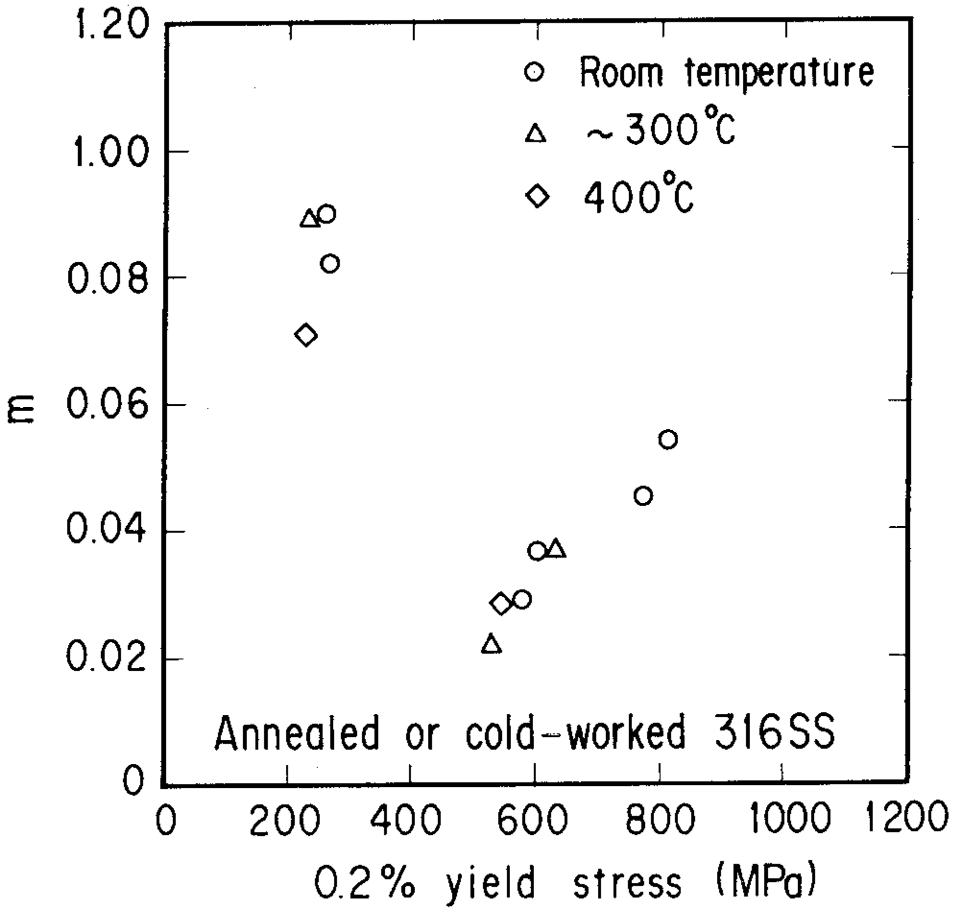


Fig. 5 Relationship between yield stress and parameter m

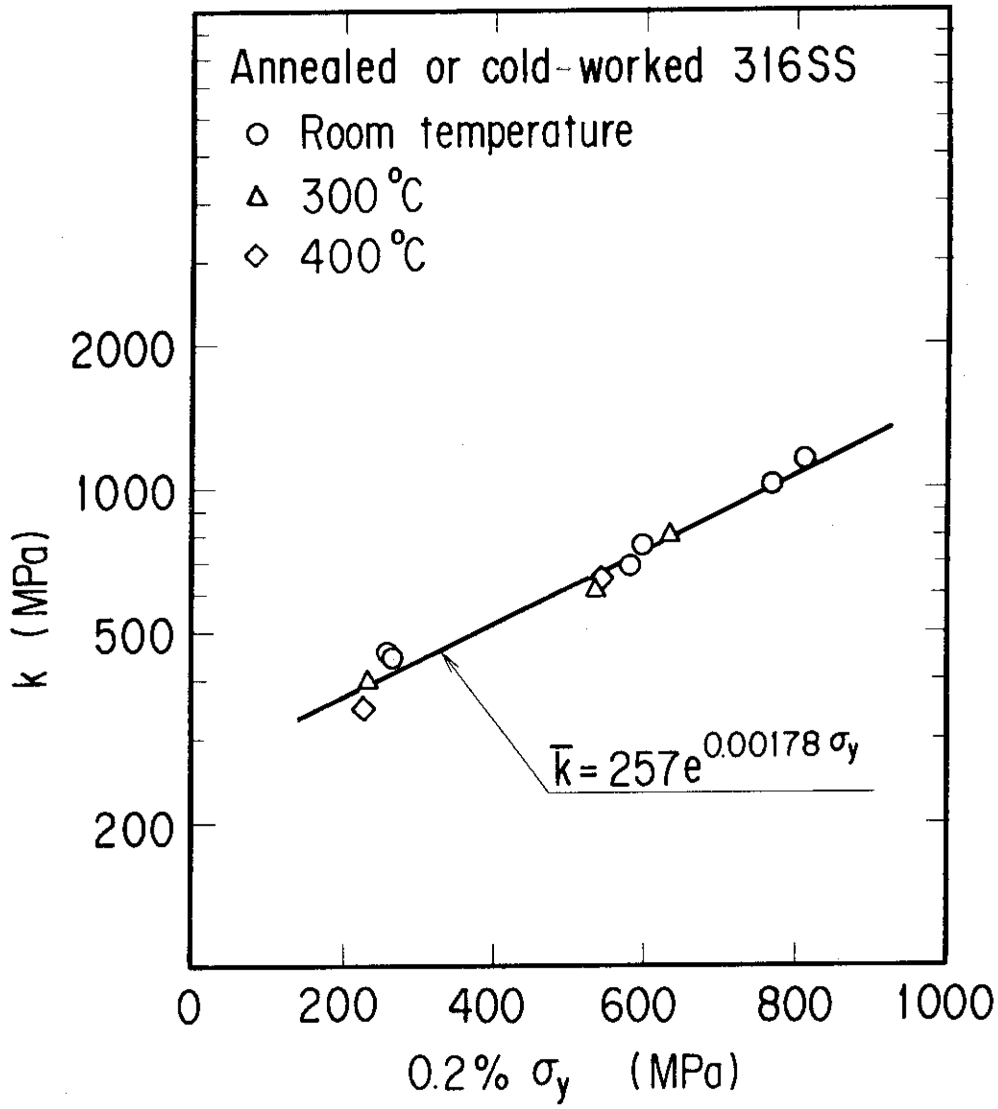


Fig. 6 Relationship between yield stress and parameter k (logarithmic representation)

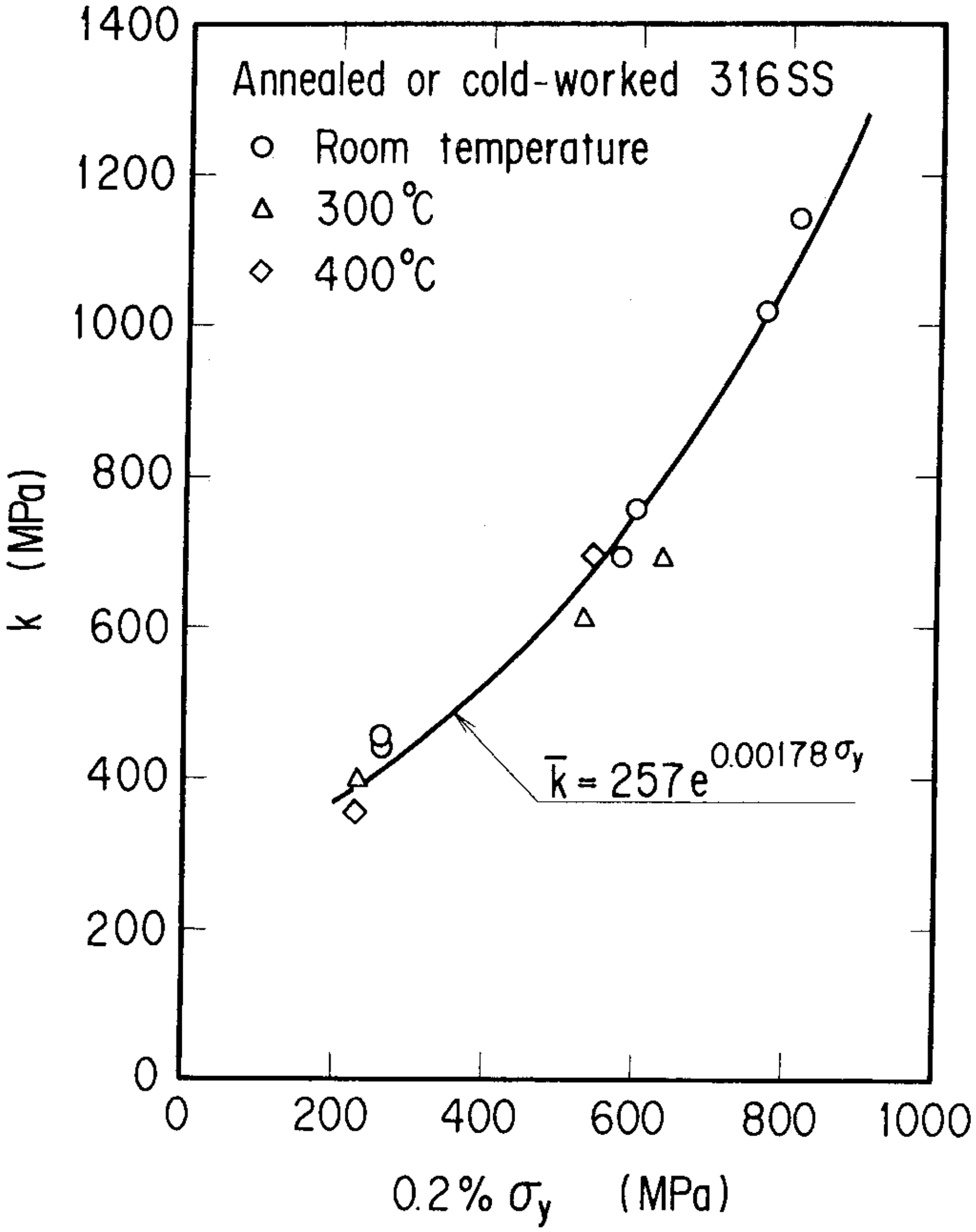


Fig. 7 Relationship between yield stress and parameter k

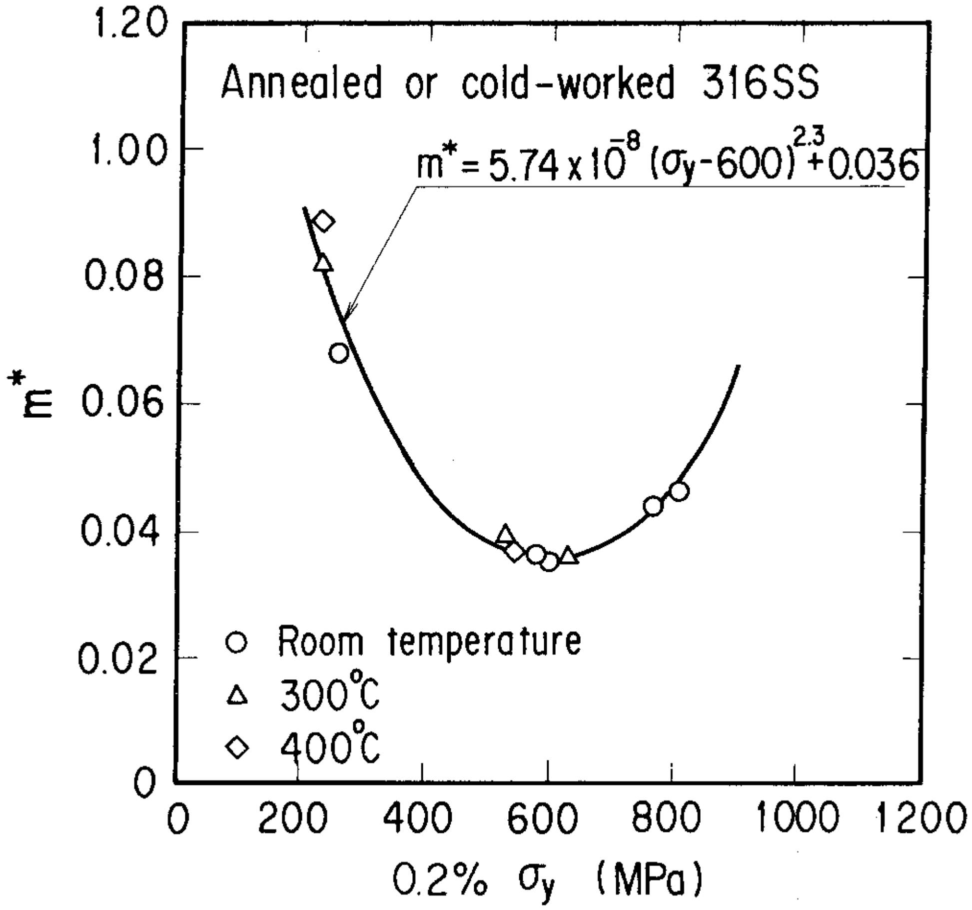


Fig. 8 Relationship between yield stress and parameter m*

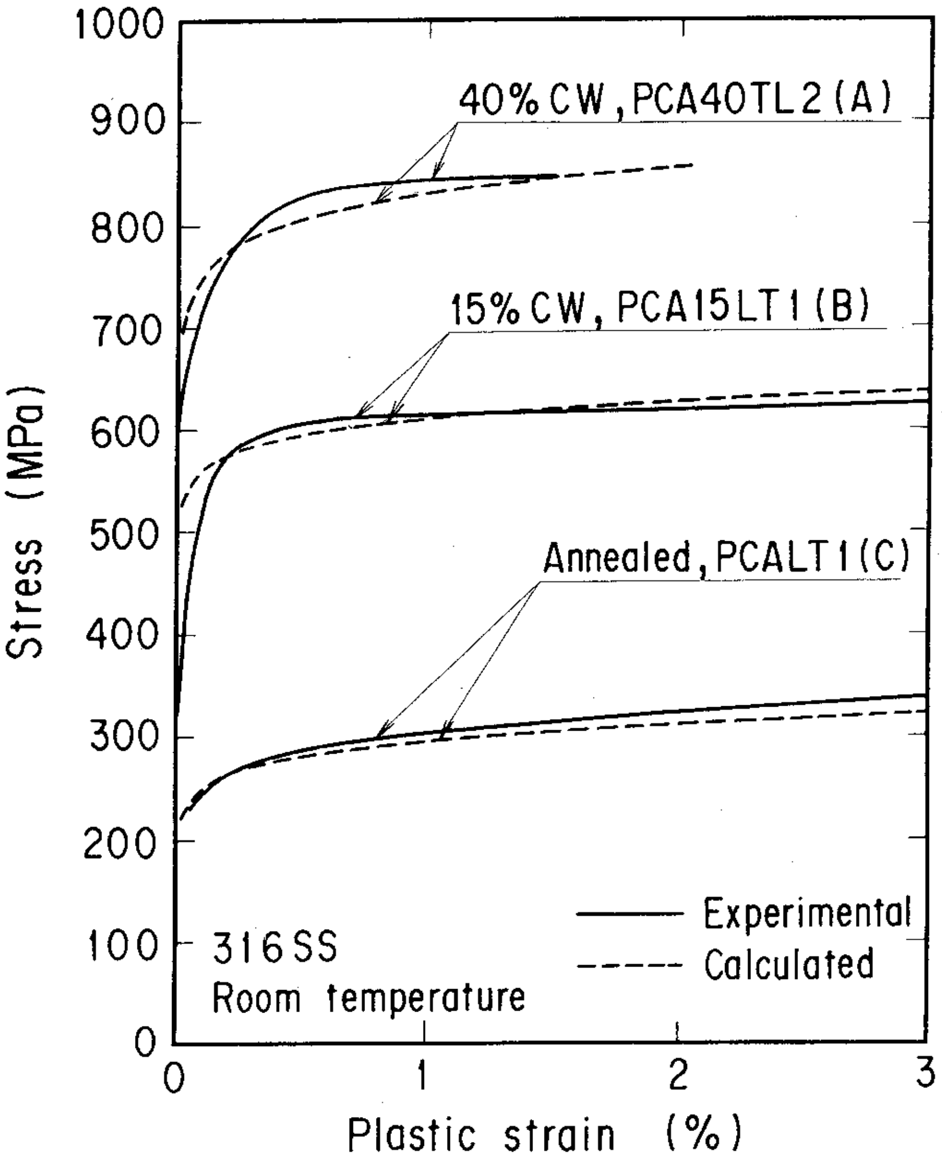


Fig. 9(a) Comparison of the simulated stress-strain curves with the measured ones

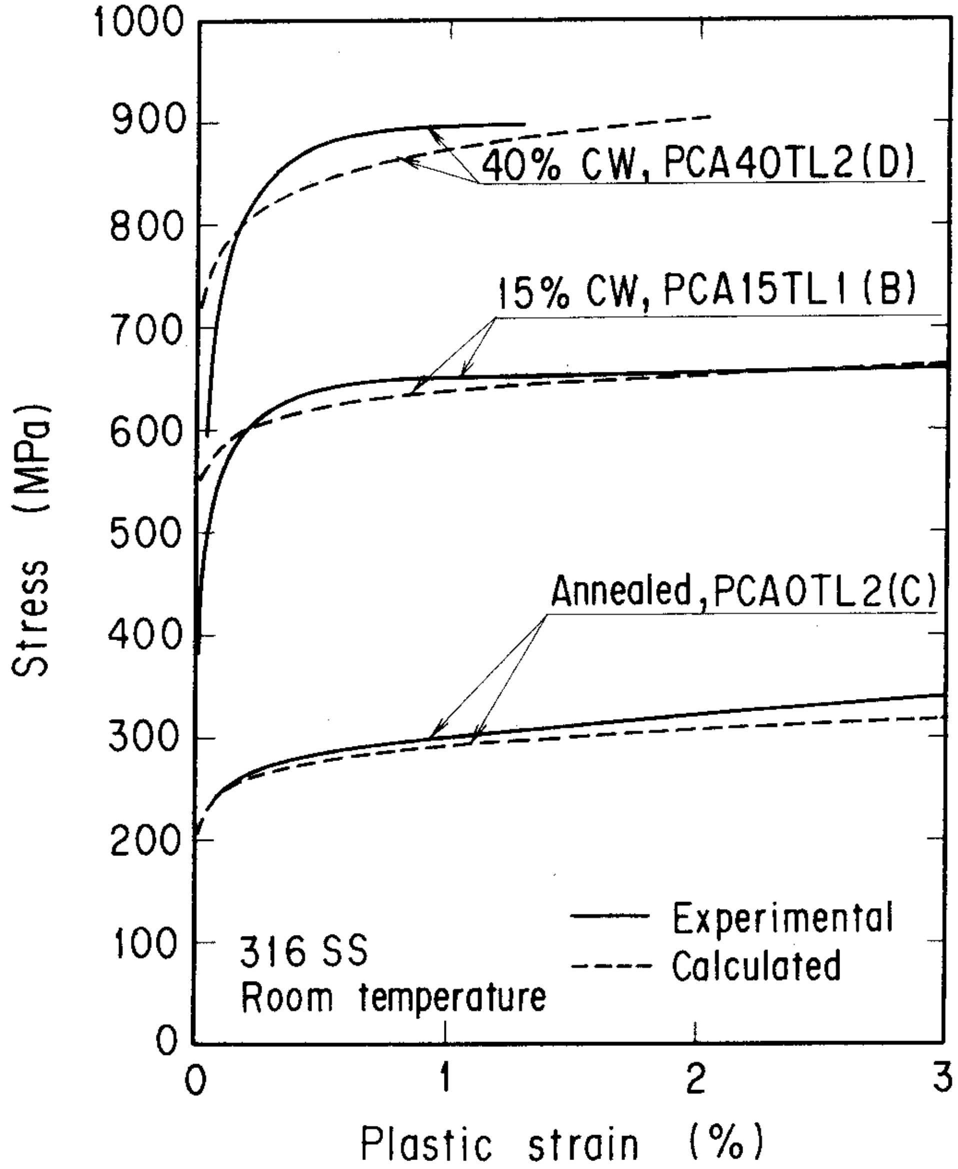


Fig. 9(b) Comparison of the simulated stress-strain curves with the measured ones

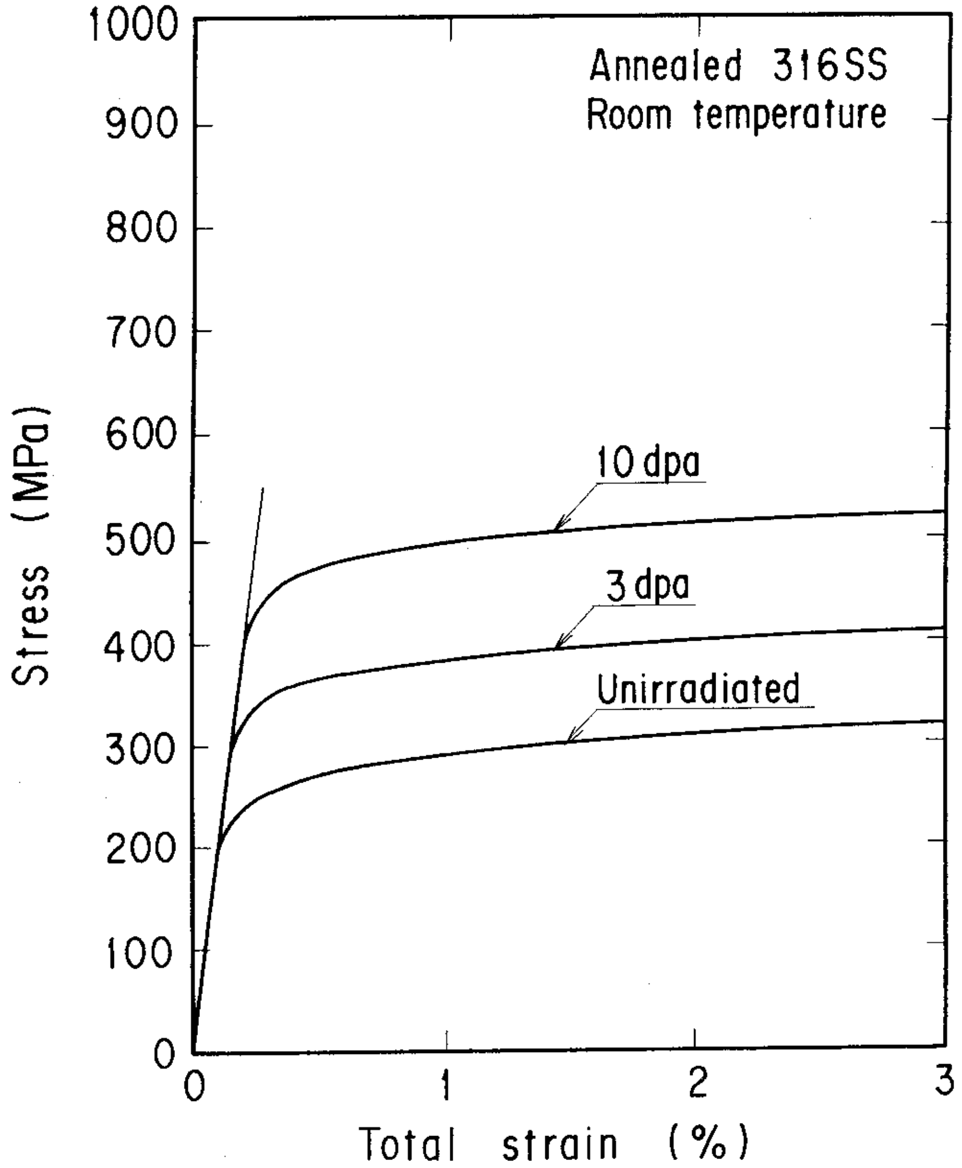


Fig. 10 Stress-strain curves based on the proposed equation at room temperature

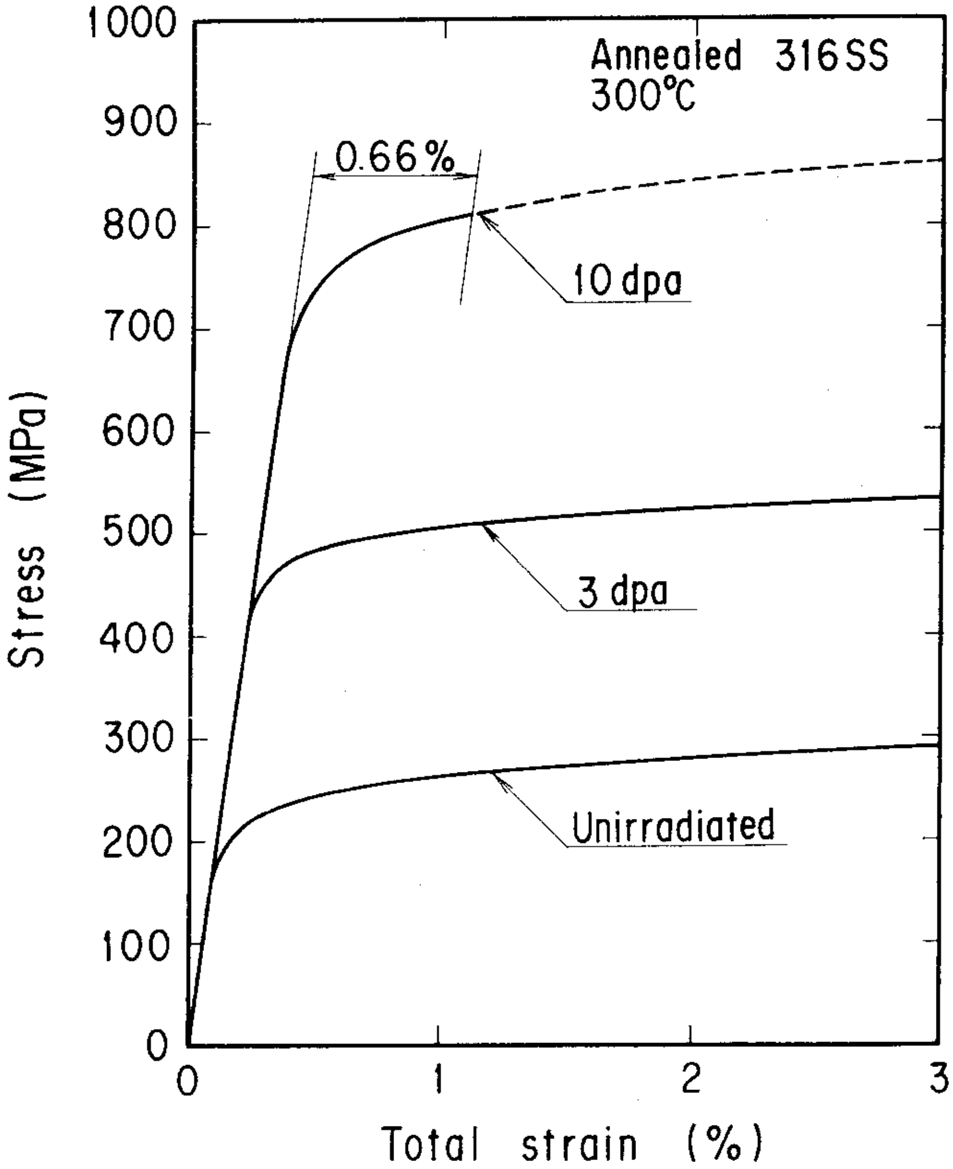


Fig. 11 Stress-strain curves based on the proposed equation at 300℃

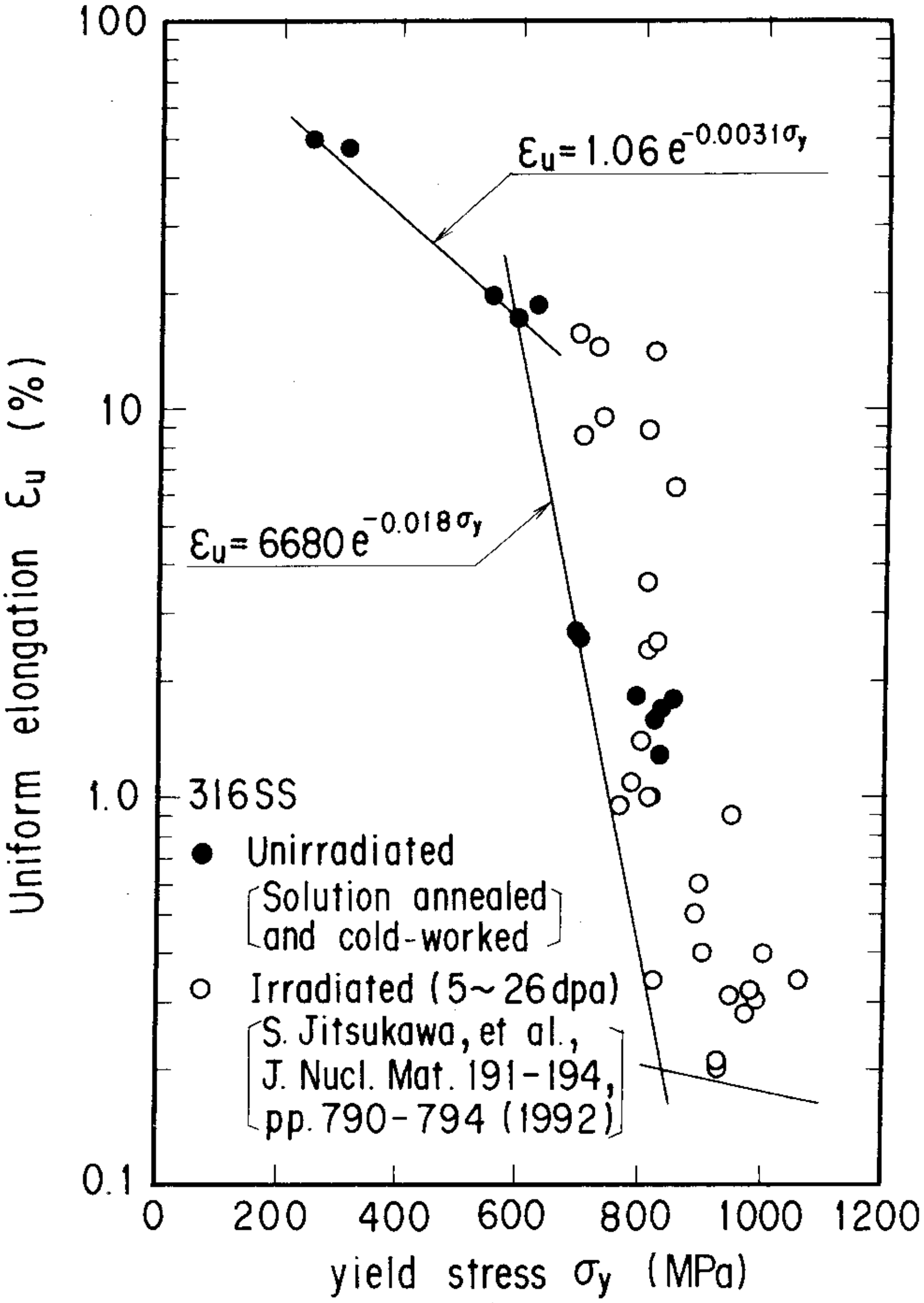


Fig. 12 Yield stress dependence of uniform elongation