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PLASTIC DEFORMATION AND TRANSFORMATION OF A STEEL

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Mechanical properties of the usual metallic materials such as yield stress, stress–strain curve and uniform-strain limit are scarcely affected by hydrostatic pressure. However, tensile tests of a 17Cr–7Ni–1Al steel, which was a strain-induced transforming material, were carried out at 0.1, 300 and 600 MPa hydrostatic pressure, and the mechanical properties of the material were found to be considerably changed by the pressure. The martensitic transformation temperature, $M_s^{\gamma\to\alpha'}$, decreased under pressure. The volume fraction of α-martensite induced by tensile deformation increased with strain, but was suppressed by hydrostatic pressure. The yield stress increased with presure. The relationship between yield stress and hydrostatic pressure was expressed by a yield function. The stress–strain curve was strongly changed by pressure. The uniform-strain limit increased with hydrostatic pressure. It was found that these changes were not caused by the mechanical effect of hydrostatic pressure, but by its thermodynamic effects.

1. Introduction

Modern plasticity theory is based on the experimental fact that the yielding of a metal is, to a first approximation, unaffected by a moderate hydrostatic pressure or tension [1, 2]. Theory also predicts that, as hydrostatic pressure has no effect on yielding behaviour, it should also have no effect on the form of the stress–strain curve and on the initiation of necking [3].

Tensile tests on a 17Cr–7Ni–1Al steel were carried out at atmospheric pressure, and at high hydrostatic pressures within the range over which ε-martensite was not induced. The influence of hydrostatic pressure on the martensitic transformation temperature $M_s^{\gamma\to\alpha'}$, on the change in quantity of the strain-induced α-martensite, and on the change in the stress–strain curve, and the relationship among these phenomena, are reported in the present paper.

2. Materials and experimental procedure

The specimen used in the experiment was cold-drawn wire having a diameter of 1.1 mm. The chemical composition of the specimen was C: 0.088, Si:0.47, Mn:0.60, Cr:17.15, Ni:7.03, Al:1.06 wt%, respectively. The specimens were annealed for 1.8 ks at 1323 K and were water-quenched after being cut to the length of the test piece. These test pieces were called Specimens A. The remnants were kept at 1273 K (Specimens B), 1243 K (Specimens C) for 5.4 ks in each case and water-quenched.

The apparatus for tensile tests at high pressure is fully reported elsewhere [4]. Unleaded gasoline was used as a pressure-transmitting medium. The tensile test could be carried out at any pressure up to the maximum of 1.5 GPa. However, the testing temperature could not be changed from the room temperature of 288 K. The tensile test was carried out at atmospheric pressure and at pressure of 300 and 600 MPa, because ε-martensite was not induced in the specimen at pressures up to 600 MPa.

3. Experimental results and discussion

3.1. Change in $M_s^{\gamma\to\alpha'}$ caused by heat treatment

The three kinds of Specimens A, B and C were found to consist of γ-phase for the most part, and of a small quantity of δ-phase. No differences in the optical-microscopic microstructure were found among specimens A, B and C. No ε-martensite was observed in all the specimens. The results of the measurement of the transition temperature $M_s^{\gamma\to\alpha'}$ for Specimens A, B and C at

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Table I
Martensitic transformation temperatures $M_s^{\gamma\to\alpha'}$(K)

Pressure (MPa)	0.1	300	600
Specimen A	229	205	176
Specimen B	258	236	214
Specimen C	278	258	235

atmospheric pressure are shown in the column headed 0.1 MPa in table I.

3.2. Change in $M_s^{\gamma\to\alpha'}$ caused by hydrostatic pressure

The change in $M_s^{\gamma\to\alpha'}$ caused by hydrostatic pressure was calculated by using the thermodynamic quantities and lattice constants obtained by X-ray analysis. The thermodynamic equation involving the effects of the chemical composition of the material, derived by Kaufman et al. [5, 6], was used to calculate $M_s^{\gamma\to\alpha'}$. The difference in free energy during the $\gamma \to \alpha'$ transformation under a hydrostatic pressure $\Delta F^{\gamma\to\alpha'}$ is expressed by

$$
\begin{aligned}
\Delta F^{\gamma\to\alpha'}(x, y, T, P) &= \Delta F^{\gamma\to\alpha'}(x, y, T) \\
&\quad + P\Delta V^{\gamma\to\alpha'}(x, y) \\
&= -4.184\{(1 - x - y)(1202 - 2.63 \\
&\quad \times 10^{-3}T^2 + 1.54 \times 10^{-6}T^3) \\
&\quad + y(460 + T) + x(-3700 + 7.09 \\
&\quad \times 10^{-4}T^2 + 3.91 \times 10^{-7}T^3) \\
&\quad + y(1 - x - y)(-2800 + 0.75T) \\
&\quad + x(1 - x - y)[3600 + 0.58T(1 - \ln T)]\} \\
&\quad + P\Delta V^{\gamma\to\alpha'}\ \mathrm{J\,mol^{-1}}\,, \qquad (1)
\end{aligned}
$$

where x and y represent the atomic fraction of nickel and chromium and T and P represent temperature and hydrostatic pressure, while ΔV represents the volume change in the transformation. Eq. (1) was compensated for the effects of small amounts of elements such as aluminium and carbon. The $M_s^{\gamma\to\alpha'}$ temperatures obtained by the calculation are also shown in table I. The change in $M_s^{\gamma\to\alpha'}$, $\mathrm{d}M_s^{\gamma\to\alpha'}/\mathrm{d}P$, caused by hydrostatic pressure is about -70 to -100 deg GPa^{-1}.

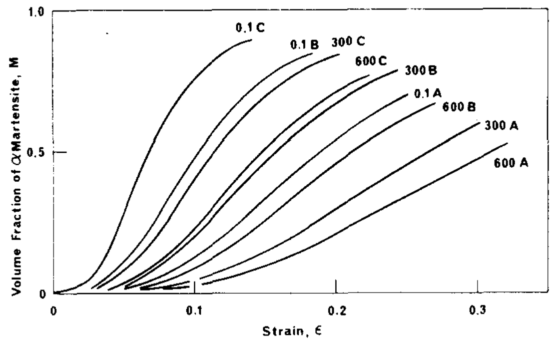

Fig. 1. Changes in volume fraction of α-martensite with strain.

3.3. Strain-induced transformation

The change in the volume fraction of strain-induced α-martensite, M, is plotted against the strain (true strain) during the tensile test in fig. 1. The numbers and letters in fig. 1 represent the experimental pressure (MPa) and the kind of specimens. The volume fraction of the strain-induced α-martensite, M, was expressed as a function of strain, ε, and ΔT which was the difference between the experimental temperature and $M_s^{\gamma\to\alpha'}$ in the next equation:

$$M = \varepsilon^3/\{\varepsilon^3 + 0.1[\Delta T/(288 - \Delta T)]^2\}\,, \qquad (2)$$

where,

$$\Delta T = 288 - M_s^{\gamma\to\alpha'}\,.$$

3.4. Change in yield stress caused by hydrostatic pressure

The yield stress of the three kinds of specimens increased at high hydrostatic presures, and was expressed by the next yield condition [7],

$$J_2^{1/2} = \alpha_0 + \alpha_1 I_1 + \alpha_2 I_2^2\,, \qquad (3)$$

where,

$$J_2 = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6\,,$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3\,.$$

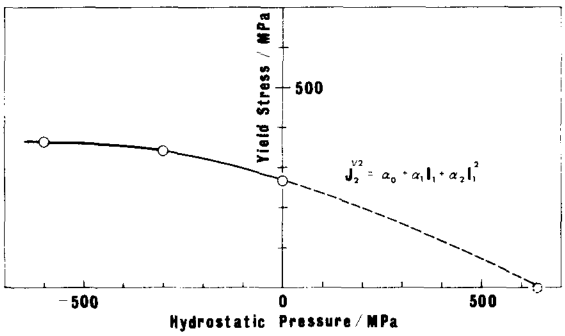

Fig. 2. Yield stresses versus hydrostatic pressure for Specimen B.

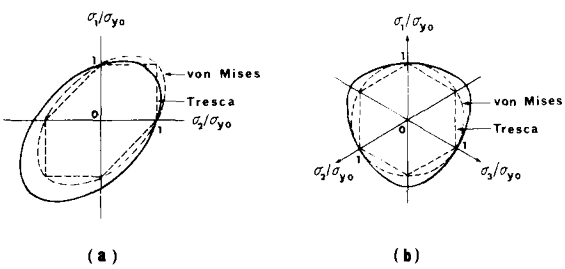

Fig. 3. (a) Two-dimensional intersection of the yield surface. (b) Projection of the surface at the π-plane.

σ_1, σ_2 and σ_3 are three principal normal stresses. The yield stress of Specimen B is shown in fig. 2. The two-dimensional intersection of the yield surface at atmospheric pressure and the projection of the surface with the π-plane are shown in fig. 3.

3.5. *Change in stress–strain curve caused by hydrostatic pressure*

Stress–strain curves of the specimens are shown in fig. 4. The shapes of the nine $\sigma-\varepsilon$ curves shown in fig. 4 were closely related to those of the volume fraction of the transformed α-martensite of each specimen against strain as shown in fig. 1. Stress–strain curves in fig. 4 were expressed in the next equation as a function of strain, ε, and volume fraction of α-martensite, M, of eq. (2).

$$\sigma = 144\varepsilon^{0.3}(1 - M) + 180(\varepsilon - 0.0082)^{0.1}M . \quad (4)$$

3.6. *Change in uniform-strain limit caused by hydrostatic pressure*

The relationship between the uniform-strain limit, ε_u, and ΔT is expressed by the following equation and is shown in fig. 5,

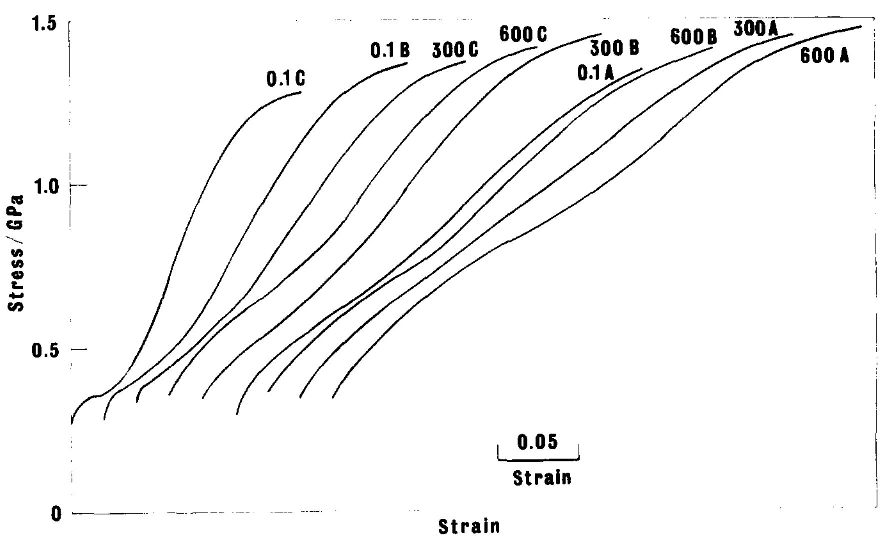

Fig. 4. Stress–strain curves at various pressures.

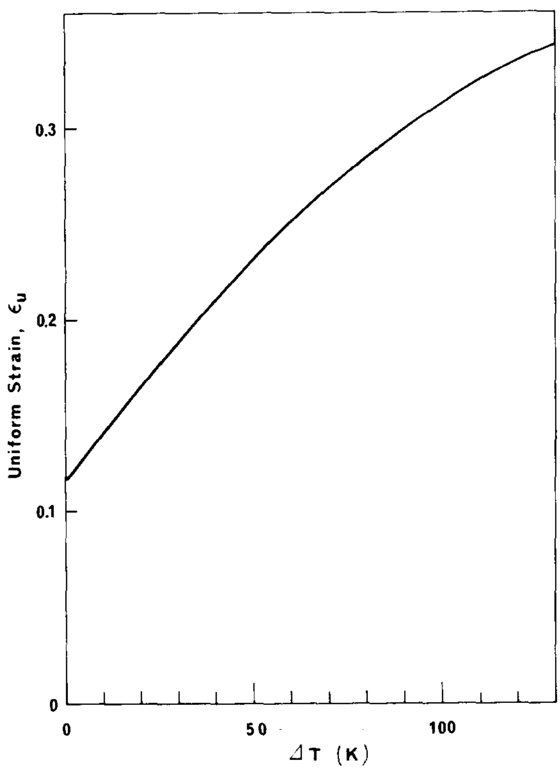

Fig. 5. Uniform-strain limit against ΔT.

$$\varepsilon_u = 1.16 \times 10^{-1} + 2.67 \times 10^{-3} \Delta T - 7.06 \times 10^{-6} \Delta T^2 . \tag{5}$$

The change in uniform-strain limit due to pressure is considered to be the same as transformation-induced plasticity.

4. Conclusion

Tensile tests of a 17Cr–7Ni–1Al steel were carried out under pressures and the mechanical properties of the material were found to be strongly changed by hydrostatic pressure. The results were not caused by the direct mechanical effect of hydrostatic pressure on the deformation of the materials but were caused by the thermodynamic effect of a hydrostatic pressure.

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