Transformation-induced plasticity in two-phase ($\alpha + \gamma$) Fe-Cr-Ni alloys

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The relationship between the fracture elongation and the value of α' martensite per unit tensile strain has been studied for the two-phase ($\alpha + \gamma$) Fe–Cr–Ni alloys containing 10%, 35% and 52% γ. The elongation has a peak in the elongation–test temperature curve. The peak elongation is dependent upon both the delay of necking and a suitable value of α' martensite per unit tensile strain.

1. Introduction

The tensile properties, such as yield strength, tensile strength and fracture elongation, in metastable austenitic steels are usually dependent upon the martensite transformation occurring during tensile testing. The strength increases with decreasing test temperature, and a peak occurs in the elongation–test temperature curve [1–8]. This phenomenon is termed the transformation-induced plasticity, that is, the TRIP effect [2]. It is suggested that a specific amount of α' martensite contributes to tensile elongation [3]. However, it is shown that the α' formation concurrent with straining promotes a higher strain-hardening rate and enhances tensile elongation [2, 4–6]. The temperature range in which the TRIP effect appears is limited by the morphology of α', and the occurrence of a peak elongation is thus characteristic of various metastable austenitic steels. The TRIP effect is exhibited over a wide temperature range in high-Cr austenitic steels but over a narrow temperature range in austenitic steels having plate-like martensites [7]. The tensile specimens containing austenite and α' martensite were deformed in the temperature range between the M_s and M_d temperatures [8]. The α' was formed by cooling to below the M_s temperature. These specimens exhibited a TRIP effect.

In the present study, the tensile properties of the two-phase ($\alpha + \gamma$) Fe–Cr–Ni alloys containing varying amounts of γ, are examined. The amount of α' is then measured, using both X-ray phase analysis and light microscopy. Thus, it is possible to demonstrate how the α' formation contributes to the TRIP effect in these alloys. The objectives of this study are to examine the effect in these alloys. The objectives of this study are to examine the effect of the amount of γ on tensile properties and to assess the relationship between the value of α' per unit tensile strain and the tensile elongation.

2. Experimental procedure

In order to examine the effect of the martensite transformation on the tensile properties, the two-phase ($\alpha + \gamma$) Fe–Cr–Ni alloy, composition 23.19% Cr, 4.91% Ni, 0.025% C, 1.47% Mo, 0.53% Si, 0.51% Mn, 0.91% Al, 0.023% P and the balance Fe, was selected. The specimens containing 10%, 35% and 52% γ were obtained by annealing this alloy for 1 h at 1350, 1200 and 1000° C, respectively. The tensile strains at which α' martensite formed were below 1.0% at −196° C, 1.0% at −150° C, 5.0% at −102° C and 17.0% at −50° C in these specimens. The M_s temperature was around −196° C, and the M_d temperature was approximately −22° C. The M_d temperature was defined as the upper temperature at which α' was found in a fractured specimen.

Tensile properties were measured on 2.0 mm thick sheet specimens with a gauge length of 18.0 mm and a gauge width of 6.0 mm. A tension test was carried out on an Instron-type tensile testing machine at a cross-head speed of 0.5 mm min^{-1}.

A preliminary determination of the amount of α' was made as a function of tensile strain at various test temperatures for the steels used. This was made using X-ray phase analysis and optical microscopy, as previously reported [9].

3. Experimental results

3.1. Tensile properties

The two-phase $(\alpha + \gamma)$ Fe–Cr–Ni stainless steels containing 10%, 35% and 52%γ were tensile tested in the temperature range −196 to 27° C. Tensile properties, such as yield strength, tensile strength and fracture elongation in these specimens are shown in Fig. 1. The amount of γ is the fraction present before deformation. The values of these tensile properties at the respective test temperatures were larger in a 52% γ specimen than in 10% and 35%γ specimens. As the α' martensite is induced within the γ phase by plastic deformation in the temperature range −196 to −22° C, it is deduced that α' formation affects the magnitudes of tensile strength and fracture elongation. As described in Section 2, each tensile strain at which the α' formed at −196, −150, −102 and −50° C was below 1.0%, 1.0%, 5.0% and 17.0%, respectively. Therefore, α' formation had no effect on the magnitude of yield strength. According to the mix-rule in the two-phase alloy [10], the yield strength of a two-phase alloy is the product of the amount of γ and the yield strength of γ, plus the product of the amount of α and the yield strength of α. Both the amount of γ and the yield strength of γ and dominant factors in determining the magnitude of yield strength of the two-phase alloy, as shown in Fig. 1. It follows that the yield strength increases with increasing amount of γ. The tensile strength increased in the tensile specimen having 52% γ before deformation, because the amount of α' martensite in a 52% γ specimen was larger than that in the 10% and 35%γ specimens. The value of fracture elongation increased in the 52%γ specimen, because the value of α' martensite per unit tensile strain is related to elongation, as shown in Section 4.1.

Both yield strength and tensile strength in these specimens also increased with decreasing test temperature. It is known that the yield strength of γ within the specimen varies slightly with lowering of the test temperature [10]. Thus, the increase in yield strength of the two-phase alloy was due to the temperature-dependence of the yield strength and α, i.e. due to the Peierls stress [11]. The temperature-dependence of the tensile strength is brought about by the dependence of the increase in α' martensite content with decreasing test temperature.

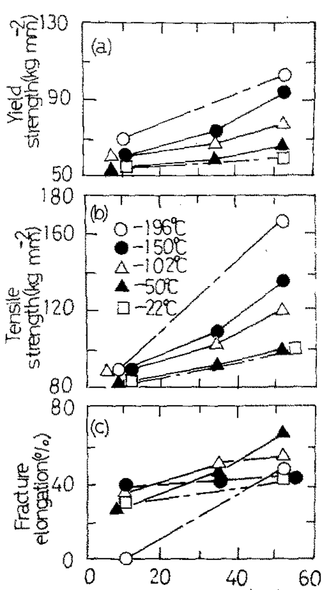

Figure 1 **Yield strength (a), tensile strength (b) and fracture elongation (c) in specimens having 10%, 35% and 52%γ in the test temperature range −196 to −22° C.**

3.2. α' martensite content

The existence of ϵ martensite after straining at −196° C in an 18%Cr, 8%Ni alloy has been reported [12–16]. In the present study, the X-ray and electron microscopy results indicate that ϵ martensite was not present in measurable amounts in the temperature range −196 and

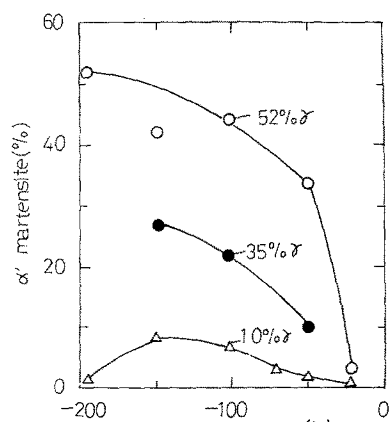

Figure 2 **Variation in the amount of α' martensite with test temperature during deformation to failure of tensile specimens containing 10%, 35% and 52%γ.**

−72° C. When the tensile specimen was deformed to failure, ϵ martensite was not observed within the original austenite using TEM, only α' martensite being present.

Fig. 2 shows the temperature-dependence of the α' martensite content of tensile specimens containing 10%, 35% and 52%γ when deformed to failure. The amount of α' was measured in fractured specimens. The α' content in tensile specimens having 35% and 52%γ increased with decreasing test temperature; in specimens containing 10%γ, variation occurred between −22 and −150° C, but the amount of α' at −196° C was small, being less than 1.0% because the specimen failed brittlely.

3.3. Lath width within a packet martensite

The microstructure was characterized as packets of parallel laths within an original austenite grain. TEM results showed that a packet consisted of bundles of slightly misoriented laths. Each bundle was separated from its neighbour by high-angle boundaries [17–19]; adjacent laths were frequently twin-related [17, 20]. Therefore, the lath widths were measured in order to determine their distribution path.

Fig. 3 shows the temperature-dependence of lath width in a tensile specimen containing 52%γ which was deformed to failure. The same result was also obtained for other tensile specimens. Values were determined from transmission electron micrographs. They were measured along straight test lines, drawn normal to the long direction of laths, on enlarged electron micrographs showing areas of laths. The average value was approximately 0.11 μm over all test temperatures, thus lath width is independent of test temperatures.

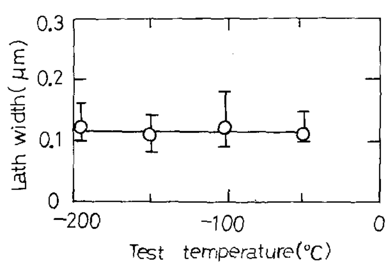

Figure 3 **Temperature-dependence of lath width within a packet martensite, occurring in deformed tensile specimens containing 10%, 35% and 52%γ.**

3.4. Elongation to necking

It is known that a peak occurs in the elongation–test temperature curve for metastable austenitic steels [1–8]. The temperature of the peak occurs between the M_s and M_d temperatures of these alloys, although it occurs at a different temperature for each austenitic steel. In these steels, a peak elongation is obtained for tensile specimens which exhibit α' formation.

As shown in Fig. 1, the peak elongation in tensile specimens containing 10%, 35% and 52%γ occurred at −150, −102 and −50° C, respectively. Elongation to necking is also shown in Fig. 4. The peak temperatures of elongation to necking in tensile specimens containing 10%, 35% and 52%γ were −150, −102 and −50° C, respectively. Thus, the occurrence of peak elongation depends upon the delay in necking. The value of the peak elongation increased as the amount of γ increased, and peak temperature increased with increasing γ content.

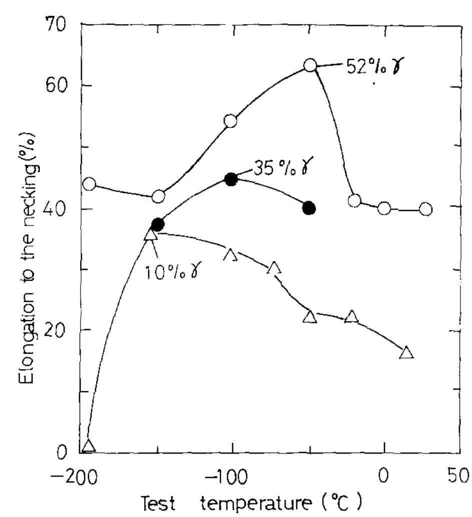

Figure 4 **Variation of elongation to necking with test temperature in deformed tensile specimens containing 10%, 35% and 52%γ.**

4. Discussion

4.1. Transformation-induced plasticity

In metastable austenitic steels, it is found that a peak appears in the elongation–test temperature curve. Bressanelli and Moskowitz demonstrated that the important variable which affects tensile elongation was not the total amount of martensite. Only the martensite formed during incipient necking is considered beneficial [3]. On the other hand, the α' produced during straining can prevent early failure by necking by increasing the strain-hardening rate in high-strength steels with 9.0% Cr, 8.0% Ni, 4.0% Mo, 2.0% Mn and 0.30% C [2]. The peak in the elongation–test temperature curve appeared over a narrow temperature range in case of Fe–29.0 to 31.0% Ni–0.30% C alloys in which the plate-like martensites were observed [4]. In the present study, the α' appeared to contain no internal twinning, but dislocation tangles were observed by TEM. The morphology of α' was a packet martensite which consisted of bundles of parallel laths. Thus, the peak elongation occurred over a wide temperature range.

As shown in Fig. 1, the effect of amount of γ on tensile properties of these alloys is clear. In tensile specimens with 10%, 35% and 52% γ, the peak elongation to necking occurred between −196 and −22° C, and the TRIP effect was observed. Peak elongation appeared at −150, −102 and at −50° C in 10%, 35% and 52% γ tensile specimens, respectively. In these specimens, the necking occurred at a tensile strain of 4.0 to 8.0% before fracture. In case of total elongation, i.e. fracture elongation, the same peak temperatures were also found for each tensile specimen. In the present study, the α' formation during necking, suggested by Bressanelli and Moskowitz, is not an important parameter to the TRIP effect. The α' martensite formed uniformly over the tensile specimen. This implies that the martensite formation during straining has a beneficial effect on elongation. Thus, it is necessary to calculate the value of α' martensite per tensile strain after martensite transformation.

Fig. 5 shows the relationship between α' martensite content per unit tensile strain and the fracture elongation. The amount of α' martensite

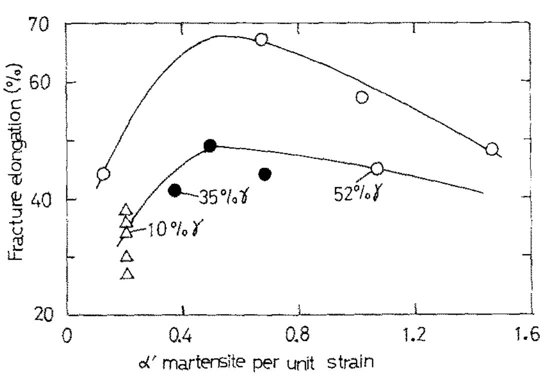

Figure 5 The variation of fracture elongation of tensile specimens containing 10%, 35% and 52% γ with α' martensite content per unit tensile strain.

increased approximately linearly with increasing tensile strain. The α' martensite content per unit in fracture elongation with this value showed a peak; in a tensile specimen with 52% γ, peak elongation appeared when the α' martensite per unit strain was 0.68. Peak elongation in a 35% γ specimen was found to be 0.50, but the value for a 10% γ specimen was about 0.20. This value decreased with decreasing γ content, which implies that a suitable α' martensite content per unit tensile strain is necessary for peak elongation to occur. As described in Section 3.4, the temperature at which peak elongation to necking occurred was similar to the peak temperature of fracture elongation. It follows that the fracture elongation was at a maximum when the later the initiation of delay in necking is also an important factor in the increase in elongation.

5. Conclusions

The effect of γ content on the tensile properties, and the transformation-induced plasticity were examined for the two-phase ($\alpha + \gamma$) Fe–Cr–Ni alloys containing 10%, 35% and 52% γ and the following results were obtained.

(1) The values of yield strength, tensile strength and fracture elongation were larger in the tensile specimen having 52% γ than in the specimens having 10% and 35% γ.

(2) A peak occurred in the elongation–test temperature curves of these specimens which is called the TRIP effect. The peak temperatures in the specimens having 10%, 35% and 52% γ were −150, −102 and −50° C, respectively.

(3) The TRIP effect was dependent upon both delay in necking and a suitable α' martensite content per unit tensile strain.

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