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The morphology of α' martensite in a two-phase $(\alpha + \gamma)$ Fe-Cr-Ni stainless steel

K. WAKASA
Department of Metallurgical Engineering, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo, Japan

T. NAKAMURA
Department of Materials Science and Engineering, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo, Japan

Both α' lath-shaped and ϵ martensites are induced by tensile deformation within γ of a two-phase $(\alpha + \gamma)$ Fe–Cr–Ni stainless steel. α' forms from the γ through the ϵ at an intersection of two ϵ crystals. These are observed both when γ is surrounded by γ and when γ borders α. The amount of strain at which both ϵ and α' nucleate, increases with test temperatures in the range −196 to 50° C. Adjacent α' laths are either twin-related, or 5, 9, 15 or 19° off the twin relationship, as found by analysing electron diffraction patterns.

1. Introduction

In metastable austenitic Fe–Cr–Ni stainless steels such as Fe–18 Cr–8 Ni, Fe–18 Cr–12 Ni and Fe–17 Cr–9 Ni, the martensite transformation to ϵ (h c p) and α' (b c c) martensites occurs during straining or on cooling [1–9]. α' is a lath-shaped martensite within γ, forming from γ and ϵ [5–8]. The lath is also observed at both the intersection of two ϵ crystals and the site where ϵ meets a grain boundary [9–11]. In these cases, the orientation relationship between the γ and the lath is frequently found to be the Kurdumov–Sachs relationship [5–11]. A packet martensite consists of a bundle of these laths, and these laths have small angle boundaries [12–14]. The formation of these laths affects the mechanical properties of Fe–Cr–Ni alloys [15–17]. In the present study, the occurrence of α' is detected in the γ phase of a two-phase $(\alpha + \gamma)$ Fe–Cr–Ni stainless steel by transmission electron microscopy (TEM), the orientation relationships between adjacent α' crystals being examined by electron diffraction.

2. Experimental procedure

A two-phase $(\alpha + \gamma)$ Fe–Cr–Ni stainless steel (composition (wt%); Cr 24.2 and Ni 3.36 in the ferrite (α), and Cr 19.7 and Ni 5.90 in the austenite (γ)) was used. The size of the specimen, which was cut parallel to a rolling direction. was 2.0 mm × 6.0 mm × 18.0 mm. The specimens were annealed by sealing them in a quartz tube, evacuating to about 10^{-4} mm Hg pressure, heating for 1 h at 100° C and then furnace-cooling to room temperature. The specimens were found to contain 52% by volume of the γ phase and have a mean grain size of 8 μm. The temperature at which the α' martensite transformation first started in cooling, $Ms^{\alpha'}$, was measured as approximately −196° C. *Md*, which was defined as the highest temperature where α' was detected in a fracture specimen, was about −24° C.

Tensile deformation was carried out on an Instron type testing machine at a cross-head speed of 0.5 mm min^{-1} in the temperature range −196 to −24° C. Foils were prepared from specimens deformed to various tensile strains for examination

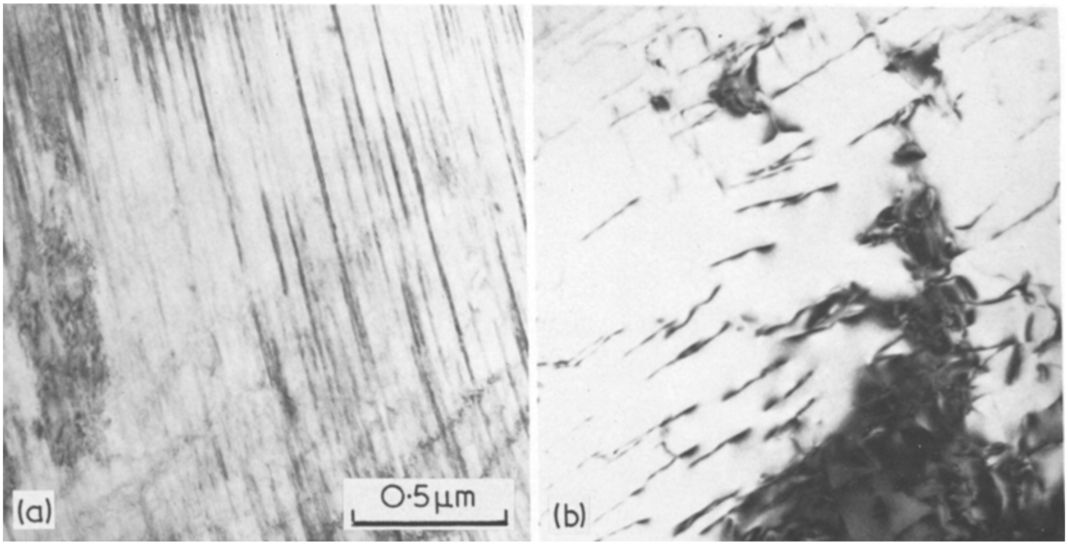


Figure 1 Transmission electron micrographs of two-phase ($\alpha + \gamma$) Fe–Cr–Ni stainless steel; (a) bright field image of a γ twin, (b) bright field image of α'.

in the electron microscope, to elucidate both the microstructure of γ twin, α, ϵ and α', and the orientation relationships between adjacent α'.

3. Results and discussion

3.1. The microstructure of γ and α after tensile deformation

By deforming to 20.0% strain at $-150°$ C, a deformation twin (γ twin) was detected within γ (Fig. 1a), but in all the other γ crystals of the specimen the transformation products were ϵ and α'. By deforming to 5.0% strain at $-24°$ C, the dislocation formed within the α phase lay on the $\{1\,1\,0\}_\alpha$ planes (Fig. 1b). As the amount of strain increased, the distribution of dislocations became gradually inhomogeneous due to the formation of tangles. Fig. 2 shows the transmission electron micrograph of ϵ in a tensile specimen deformed to 5.0% strain at $-202°$ C. The orientation relationship between γ and ϵ was determined to be $(1\,1\,1)_\gamma \parallel (0\,0\,0\,1)_\epsilon$; $[1\,0\,\bar{1}]_\gamma \parallel [1\,1\,\bar{2}\,0]_\epsilon$, and the small amount (~1.0%) of ϵ formed was found not to be a stacking fault but a martensitic phase with a h c p structure [4, 8, 9, 18]. Fig. 3

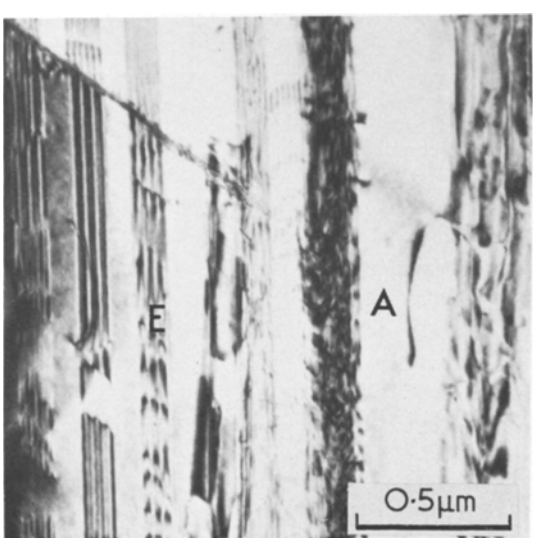


Figure 2 Bright field image of ϵ (E) and γ (A) within the γ phase.

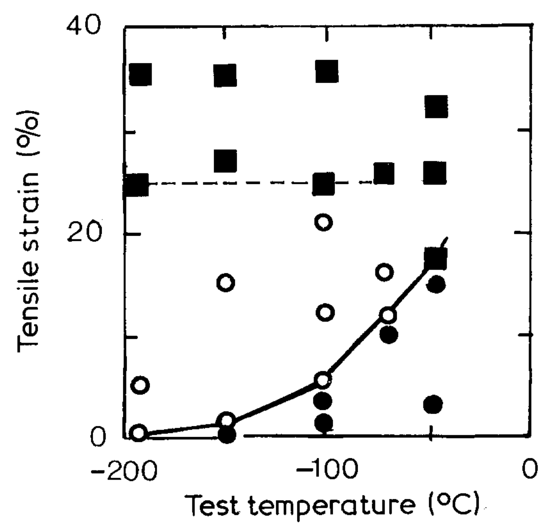
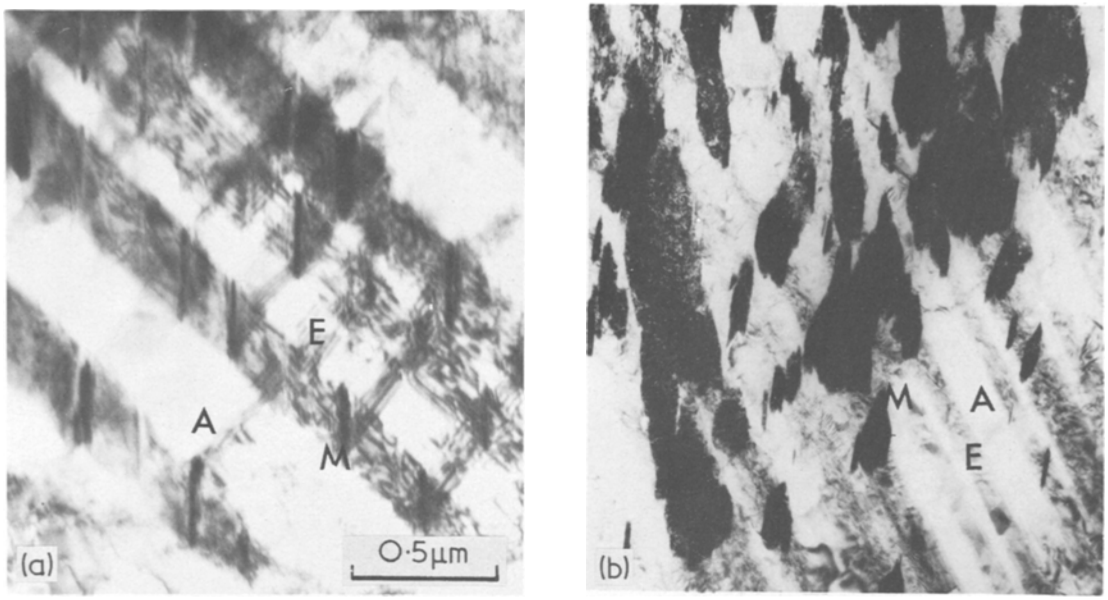


Figure 3 The effect of test temperature on the occurrence of the ϵ and the α' phases within the γ phase of the alloy. (■ only α', ○ ϵ and α', ● no existence of ϵ and α'.)



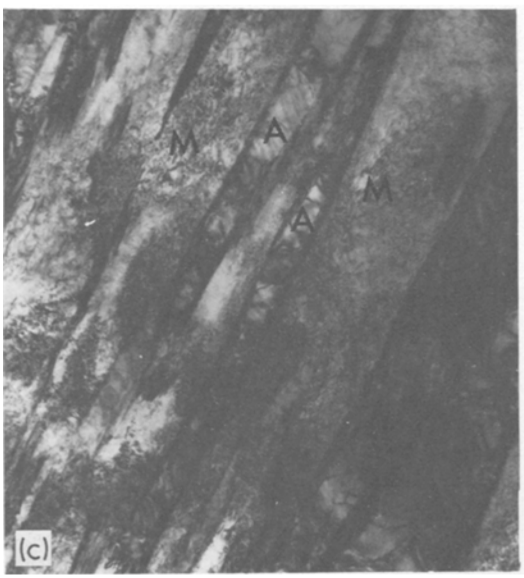


Figure 4 Bright field images of the different formation modes of the α' martensites, (a) at the intersection of two ϵ crystals, (b) within the ϵ crystal, and (c) within the γ phase. (A = γ, E = ϵ and M = α').

shows the effect of test temperature on the amount of tensile strain at which ϵ and α' form within the γ during tensile straining. This amount increased with increasing test temperatures from -196 to -72° C. At any tensile strain at above -50° C, ϵ was not detected. The existence of ϵ was not observed in any specimens deformed to greater than 25.0% in the temperature range -196 to -72° C, because ϵ had transformed to α'. As previously described in Section 2, the $Ms^{\alpha'}$ temperature was about -196° C. Furthermore, the Ms^{ϵ}, where the occurrence of ϵ was first induced by cooling, was about -196° C. Thus, the Ms temperatures detected for ϵ and α' in the present alloy are similar to those previously reported in an Fe–Mn alloy [19, 20].

3.2. The morphology of α' crystal

An optical examination of the morphology in the present alloy shows that it is a lath-shaped martensite [21, 22]. The orientation relationship between γ and α', which is obtained from analysis of the foils, is found to be the Krudjumov–Sachs relationship noted previously in austenitic Fe–Cr–Ni stainless steel [7–9, 18, 23, 24]. α' occurred at

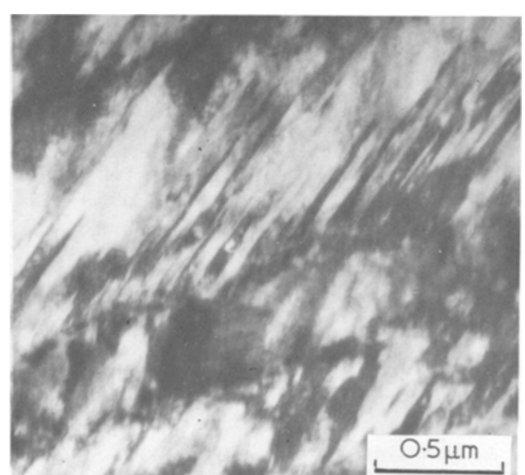


Figure 5 Bright field image of α' lath.

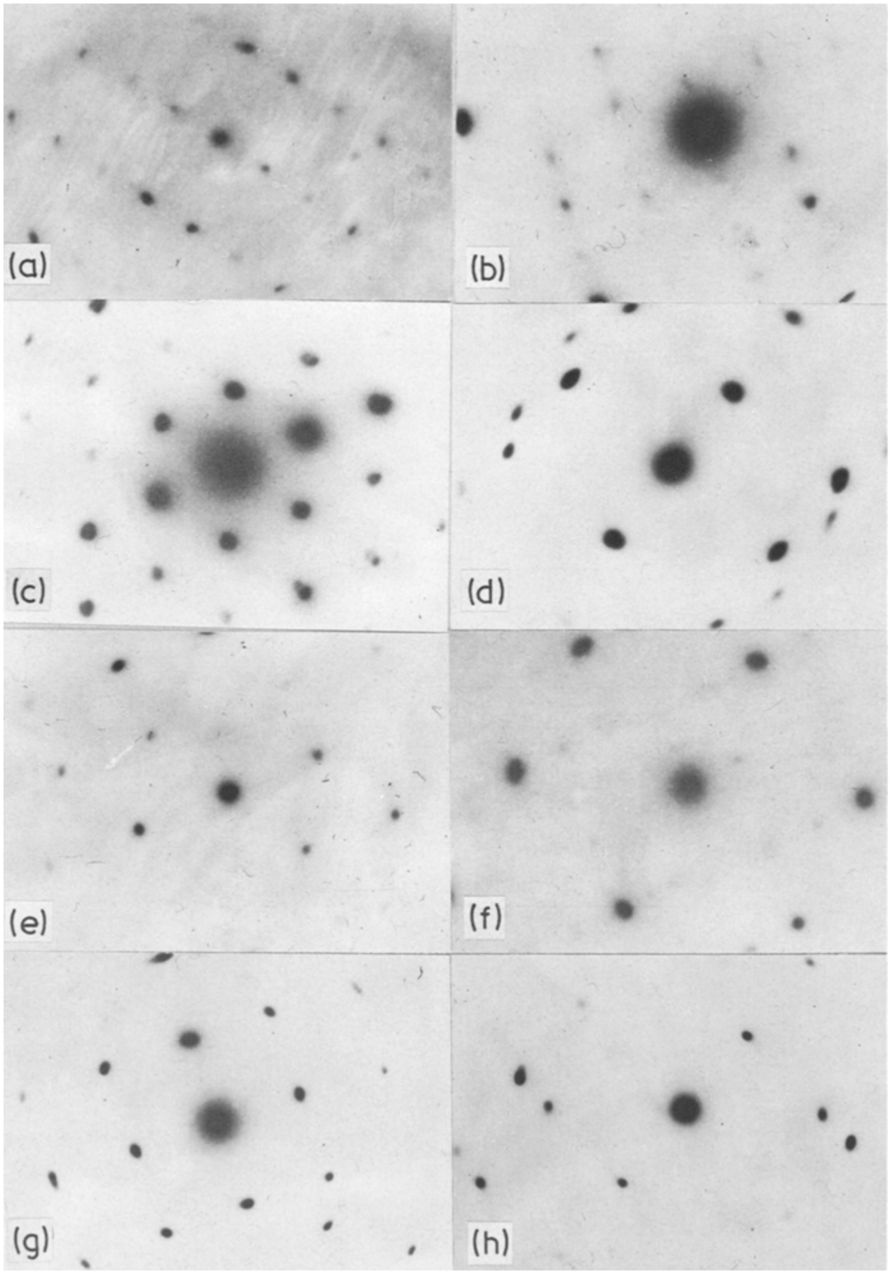


Figure 6 Typical electron diffraction patterns obtained at the lath boundary; (a) the electron beam directions of $[\bar{3}\,1\,1]_\alpha$ and $[\bar{3}\,1\,\bar{1}]_\alpha$, (b) $[1\,0\,1]_\alpha$ and $[0\,\bar{1}\,1]_\alpha$, (c) $[1\,1\,\bar{1}]_\alpha$ and $[1\,1\,1]_\alpha$, (d) $[1\,1\,0]_\alpha$ and $[1\,1\,3]_\alpha$, (e) $[1\,1\,1]_\alpha$ and $[\bar{1}\,\bar{1}\,3]_\alpha$, (f) $[1\,0\,2]_\alpha$ and $[\bar{1}\,\bar{1}\,1]_\alpha$, (g) $[1\,1\,1]_\alpha$ and $[0\,0\,1]_\alpha$, (h) $[0\,0\,1]_\alpha$ and $[1\,1\,0]_\alpha$.

the intersection of two ϵ crystals, through the ϵ, and from the γ, as shown in Figs. 4a, b and c. They were observed for tensile specimens deformed to 1.1% strain at $-196°$ C, (Fig. 4a), 11.5% strain at $-102°$ C, (Fig. 4b), and 15.5% strain at $-196°$ C, (Fig. 4c), respectively. In (a) and (b), the α' formation was observed for γ which was surrounded by γ. In (c), α' formed directly through γ which was surrounded by γ. At the other test temperatures, namely -150, -72, -50 and $-24°$ C, the morphology of α' was the lath-shaped martensite. It is thus evident from the TEM studies that α' laths are formed in the temperature range -196 to $-24°$ C.

3.3. The orientation relationships between adjacent α' observed by TEM

The occurrence of both a twin-related α' and an off-twin-related α' is expected if the adjacent α' contains the various variants of the Kurdjumov–Sachs relationship [17, 25, 26]. For example, when the relationship is given by $(1\,1\,1)_\gamma \| (0\,1\,1)_\alpha$ and $[\bar{1}\,1\,0]_\gamma \| [\bar{1}\,\bar{1}\,1]_\alpha$, 6 variants are obtained by choosing two different $\langle 1\,1\,1 \rangle_\alpha$ directions to be parallel to each of three $\langle 1\,1\,0 \rangle_\gamma$ directions. Similarly, as each of the $\{1\,1\,1\}_\gamma$ is associated with 6 variants, 24 variants are obtained. In case of $(\bar{1}\,1\,\bar{1})_\gamma \| (1\,1\,0)_\alpha$, combinations such as $[1\,0\,\bar{1}]_\gamma \| [\bar{1}\,1\,\bar{1}]_\alpha$ (1) and $[\bar{1}\,0\,1]_\gamma \| [\bar{1}\,1\,1]_\alpha$ (2); $[0\,\bar{1}\,\bar{1}]_\gamma \| [\bar{1}\,1\,1]_\alpha$ (3); $[0\,1\,1]_\gamma \| [\bar{1}\,1\,\bar{1}]_\alpha$ (4); $[\bar{1}\,\bar{1}\,0]_\gamma \| [\bar{1}\,1\,\bar{1}]_\alpha$ (5) and $[1\,1\,0]_\gamma \| [\bar{1}\,1\,1]_\alpha$ (6) indicate a twin relationship, while all the other combinations of variants are not twin relationships.

Fig. 5 shows the transmission electron micrograph of α' in a tensile specimen deformed to 30.0% strain at $-196°$ C. This was a packet martensile of parallel laths of average width 0.11 μm, each lath having a lath boundary. This implies that specific orientation relationships are detected between adjacent α'. Electron diffraction patterns, indicating their relationships, were thus obtained as shown in Figs. 6a to h. A twin relationship was found in Figs. 6a, b and c, while the orientation relationship, which is a twin relationship to within 5°, was found in 6d. The diffraction spots in Figs. 6a and b were twin-related with respect to twin planes such as $(1\,1\,2)_\alpha$ and $(\bar{1}\,2\,1)_\alpha$ respectively. The diffraction patterns of Figs. 6e to h were 9°, 15°, and 19° off twin relationships, respectively. It would appear that both twin and off-twin relationships are required to describe these patterns, and these may be produced from appropriate combinations of Kurdjumov–Sachs variants.

4. Conclusions

(1) α' lath-shaped martensite is formed through both the γ and the ϵ phases and at the intersection of two ϵ crystals within the γ phase of a two-phase $(\alpha + \gamma)$ Fe–Cr–Ni stainless steel. The formation of the α' martensite was apparently independent of the α phase morphology.

(2) The amount of tensile strain, at which the ϵ and the α' formed by tensile deformation, increased with increasing test temperature. ϵ was not detected for specimens which were deformed to greater than 25.0% strain in the temperature range -196 to $-72°$ C, because all the ϵ then transformed completely to α'. At temperatures greater than $-50°$ C, ϵ was not detected, because the $\gamma \rightarrow \alpha'$ martensite transformation occurred directly without the intermediate ϵ phase.

(3) The orientation relationships between adjacent α' laths in a packet martensite may be divided into two classes, namely (i) a twin relationship and (ii) an off-twin relationship.

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