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A low-temperature study to examine the role of ε-martensite during strain-induced transformations in metastable austenitic stainless steels

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Abstract

A low-temperature study of the mechanical behaviour of a metastable semi-austenitic stainless steel was carried out. This class of stainless steels is found to show a characteristic hump followed by softening in their stress–strain curves, especially at low temperatures, much like dynamically recrystallizing steels. Experiments are carried out at sub-zero temperatures to examine this phenomenon. Samples are subjected to various metallographic, X-ray and transmission electron microscopy techniques to identify the evolution of the different phases. The presence of an intermediate phase ε-martensite is detected which might cause a softening in the stress–strain behaviour, comparable with the formation in other low stacking fault energy stainless steels.

Keywords: Martensitic transformation; Magnetic materials

1. Introduction

Metastable austenitic stainless steels are designed to be thermodynamically unstable so that a phase transformation to martensite can take place due to a drop in temperature, elastic stressing, plastic straining or any combination of these events. It improves the formability of these steels, as necking is delayed. In the case of strain-induced martensite formation due to plastic straining, a solid-state phase transformation takes place where concurrently there is a latent heat of transformation, and adiabatic heat is generated due to plastic deformation. The lattice structure of the polycrystal changes from face-centred cubic (fcc) austenite (γ) to hexagonal close-packed (hcp) martensite (ε) and/or to body-centred cubic (bcc) martensite (α′) [1–8].

$$\gamma \rightarrow \epsilon \rightarrow \alpha' \tag{1}$$

and/or

$$\gamma \rightarrow \alpha' \tag{2}$$

A careful study of the stress–strain pattern of these steels reveals that, at lower temperatures of straining, the material goes through an initial softening trough, before the stress again monotonically increases with strain. Fig. 1 illustrates this phenomenon as seen in Sandvik Nanoflex stainless steel. This behaviour is similar to tests done on type 304 stainless steel [3]. The objective of this study was to corroborate that the softening in Sandvik Nanoflex at early stages of straining, especially when deformed at low temperatures just above the M_s, was due to the presence of ε-martensite as an intermediate phase in the transformation process.

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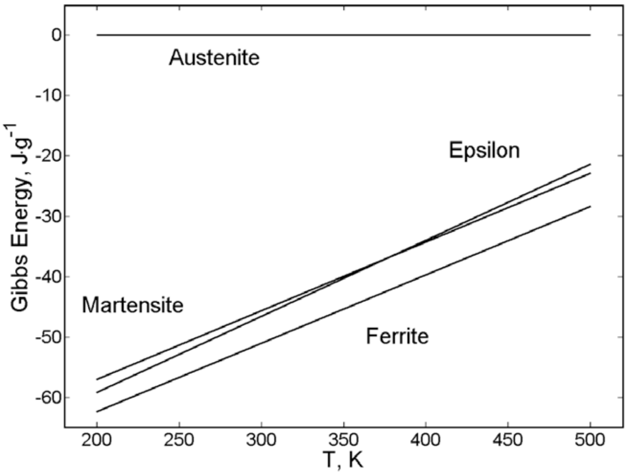

Fig. 1. Free energies of various phases in Sandvik Nanoflex relative to austenite [16].

2. A contextual review of the literature

2.1. Formation of ε-martensite

Fundamental studies, including the in situ observations of the formation of martensite in stainless steel were carried out in the late 1970s by Brooks et al. [9,10]. It was shown that the ε-martensite occurs in regions where appropriately, but usually irregularly, spaced stacking faults are formed, while α′-martensite nucleation is associated with dislocation pile-ups on the active slip plane. Stacking faults in stainless steel have been shown to have a supplementary displacement, in addition to the expected $\frac{1}{3}$<1 1 1>, which has the same sense and direction as the change in interplanar spacing of the close-packed planes which occurs in the $\gamma_{\mathrm{fcc}} \rightarrow \varepsilon_{\mathrm{hcp}}$ transformation. Theoretical electron micrographs have been computed to determine the magnitude of the displacement for a series of defect configurations. These show that the displacement varies linearly with the number of overlapping faults. The nucleation and growth of ε-martensite is correlated with the defects in the structure. It is concluded that the stacking faults formed during cooling or deformation are the martensite embryos, as even a single glide fault contains close-packed planes of the appropriate hcp spacing, α′-martensite nucleates from pile-ups of dislocations and the observed growth suggests that this is influenced by these dislocations.

Bracke et al. [11] found that, during strain-induced martensite formation in an austenitic stainless steel, α′-martensite nucleated at the intersection of two ε-martensite laths. Detailed observations of the crystal structures in this zone allowed the incorporation of the relaxation of the transformation strains by the introduction of retransformation partial dislocations. The nucleation of the low-temperature hcp ε and bcc α′ phases produced by deformation in a 304 stainless steel was studied by Venables [2] as early as 1962, using transmission electron microscopy (TEM). The ε-phase was found to be an intermediate phase in the nucleation of α′-martensite from the austenitic matrix.

In a recent and novel study with three-dimensional X-ray diffraction (XRD), Hedström et al. [12] carried out tensile experiments in the elastic zone and followed the transformation behaviour of individual grains of an AISI301 stainless steel. The formation of ε-martensite was found to be highly localized, and the parent austenite grain had a high Schmid factor for the active {1 1 1}b1$\bar{2}$1 N slip system during fcc to hcp transformation. Thus, such conditions offer the most favourable orientation for the transformation to undergo.

However, thermodynamic study of the transformation of $\gamma_{\mathrm{fcc}} \rightarrow \varepsilon_{\mathrm{hcp}}$ is rare in the literature. Recently, Wu et al. [13], presented analytical expressions of crystallographic features, including the orientation relationship, the habit plane orientation and dislocation configuration in the habit plane, based on derivations in both reciprocal and direct spaces in two dimensions. They have given examples of applications to fcc/bcc and bcc/hcp systems, with results which are functions of lattice parameters. In studies by Guo et al. [4] and Hsu and Zuyao [14], the γ → ε transformation mechanism is elaborated. The stacking fault energy (SFE) or the stacking fault probability (SFP) plays an important role in the determination of the critical driving force ΔGγ→ for the martensitic transformation fcc(γ) → hcp(ε) in ternary Fe–Mn–Si alloys, ΔGγ→ increases with the content of Mn and decreases with that of Si. Thermodynamic prediction of M_s in ternary Fe–Mn–Si alloys is established. The fcc(γ) → hcp(ε) martensitic transformation in Fe–Mn–Si is semi-thermoplastic, and the nucleation process does not strongly depend on soft modes. Nucleation of martensite is not dominated by a pole mechanism. Based on the phenomenological theory of martensite crystallography, a shuffle on (0 0 0 1) hcp planes is required when d111 ≠ d0002. The derived principal strains for the Bain distortion are smaller, i.e. more reasonable than the values given by Christian [15]. Alloying elements, which strengthen the austenite, lower the SFE of the γ phase and reduce the TγN temperature, may be beneficial to the shape memory effect (SME) of Fe–Mn–Si-based alloys.

An attempt has been made to understand the driving force for the transformation for Sandvik Nanoflex steel [16]. In this case, ferrite is the stable form at low temperatures but is kinetically inhibited from forming from the higher temperature austenite. As the temperature is reduced, however, martensite can be formed from austenite by a diffusionless reaction at the temperature where the Gibbs energies are identical. The Gibbs energy of martensite is related to the Gibbs energy of ferrite through the additional contribution arising from the distortion of the crystal lattice. An ε-martensite with hcp structure may also be seen when austenite transforms to martensite. Fig. 1 schematically shows the difference in Gibbs energies between austenite, ferrite and martensite in Sandvik Nanoflex. The thermophysical properties of the metal change during this process as a function of strain, strain rate and temperature. The transformation is believed to be initiated by either a local concentration of stresses or strain-induced