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Transformation softening in three titanium alloys

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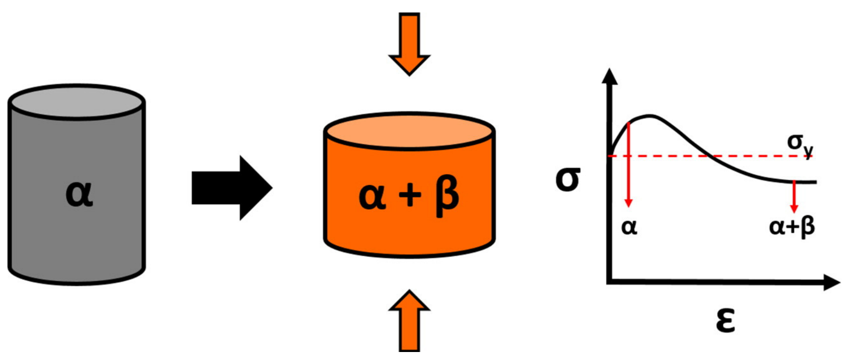
HIGHLIGHTS

- Dynamic transformation is shown to take place in three titanium alloys.
- The driving forces are calculated using the concept of transformation softening.
- A thermodynamic explanation for the downward shift of the beta transus temperature is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

The high temperature flow stress data of Koike et al. (2000) determined on a Ti-5.5 wt%Al-1.5 wt%Fe alloy are reanalyzed in terms of transformation softening. They observed that the harder alpha transforms dynamically into the softer beta phase when deformation is being carried out below the beta transus temperature. These observations are interpreted here as being driven by the thermodynamic requirement to do the least possible work during deformation. Tests were carried out on a near-alpha Ti alloy (IMI-834) in order to test the generality of these results. Here the driving force for transformation is taken as the flow stress difference between the work hardened alpha and the yield stress of the fresh beta that takes its place. This type of analysis is then applied to the experimental results of Xu and Zhu (2010) on C.P. Ti grade 2, which also display marked sub-transus softening. Such behavior is shown to be consistent with the occurrence of transformation softening.

1. Introduction

The dynamic transformation of austenite to ferrite was first reported by Yada and co-workers in the 1980's [1–3]. These experiments were carried out in compression as well as in rolling at temperatures above the Ae_3, that is the transformation temperature above which only austenite is stable in conventional steels. Deformation at these elevated temperatures led to the appearance of fine-grained ferrite, which, being unstable at these temperatures, slowly retransformed back into austenite. Similar observations were later reported by researchers in Korea [4], Germany [5], Australia [6], China [7] and Japan [8]. In all these cases, deformation at temperatures within the austenite phase field led to the formation and appearance of appreciable volume fractions of ferrite.

The rapid formation of dynamically transformed (DT) ferrite was shown more than twenty years later to take place displacively and to result in the appearance of Widmanstätten ferrite plates only some 200 nm thick [9]. These sub-microscopic plates gradually coalesced into visible polygonal ferrite grains during deformation, which then

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retransformed back into austenite on unloading by much slower, diffusional processes [9]. Still more recently, a thermodynamic basis for this unusual phenomenon was proposed, according to which the driving force for dynamic transformation is the softening associated with the replacement of high flow stress austenite by low flow stress ferrite [10–12]. This driving force was shown to be sufficient to overcome the Gibbs energy difference between the austenite and ferrite at the temperatures of interest.

Such deformation-induced transformations have also been shown to take place in Ti alloys. For example, Koike et al. [13] reported that concurrent deformation lowered the β transus temperature of their material (Ti-5.5 wt%Al-1.5 wt%Fe alloy) by about 100 °C. Similar behaviors were also observed by Yang et al. (1991) [14] and Ding et al. (2000) [15] in Ti-6 wt%Al-4 wt%V, wherein deformation increased the volume fraction of β. It is the aim of the present paper to examine the dynamic transformation behavior of Ti alloys more closely and to assess the degree to which the transformation softening model applies to these materials.

2. Transformation softening in Ti-5.5 wt%Al-1.5 wt%Fe

We begin with the classic observations of Koike and co-workers obtained on a Ti-5.5 wt%Al-1.5wt%Fe alloy and published in 2000 [13]. They deformed their materials over the temperature range from 727 to 927 °C and reported that deformation modified the alloy pseudo-binary diagram, as shown in Fig. 1a. As can be seen from the diagram, deformation *lowered* the β transus temperatures by about 100 °C. This is opposite to the effect in Fe-C alloys, where deformation *raises* the transformation temperature of Fe-α to Fe-γ (Ae_3). Nevertheless, this observation is consistent with the concept of the replacement of the harder by the softer phase. Note that in titanium alloys, it is well-known that β is softer than the α phase when both are present due to the larger number of available slip systems in the former phase. This can be seen in Ref. 13, wherein significantly lower flow curve levels are associated with the deformation of single phase β than when samples are deformed in the two phase region. Similar observations were also reported in Ref. 16.

Koike and co-workers found that the β volume fractions increased by 15 to 40% over the sub-transus temperature range 727 to 927 °C, respectively [13]. They then evaluated the increase in the free energy of the α phase required to account for the 100 °C displacement of the transus, see Fig. 1a, as being about 500 J/mol, but were unable to provide a rationale for this effect [13]. However, the driving force attributable to transformation softening falls almost exactly in this range, as will be shown below, so that the mechanism observed to operate in ferrous materials becomes a ready candidate for a possible explanation of their puzzling observations.

The driving force for the transformation consists of the softening achieved (per mol of material) when the work hardened hard phase transforms into an equal quantity of the undeformed softer phase.

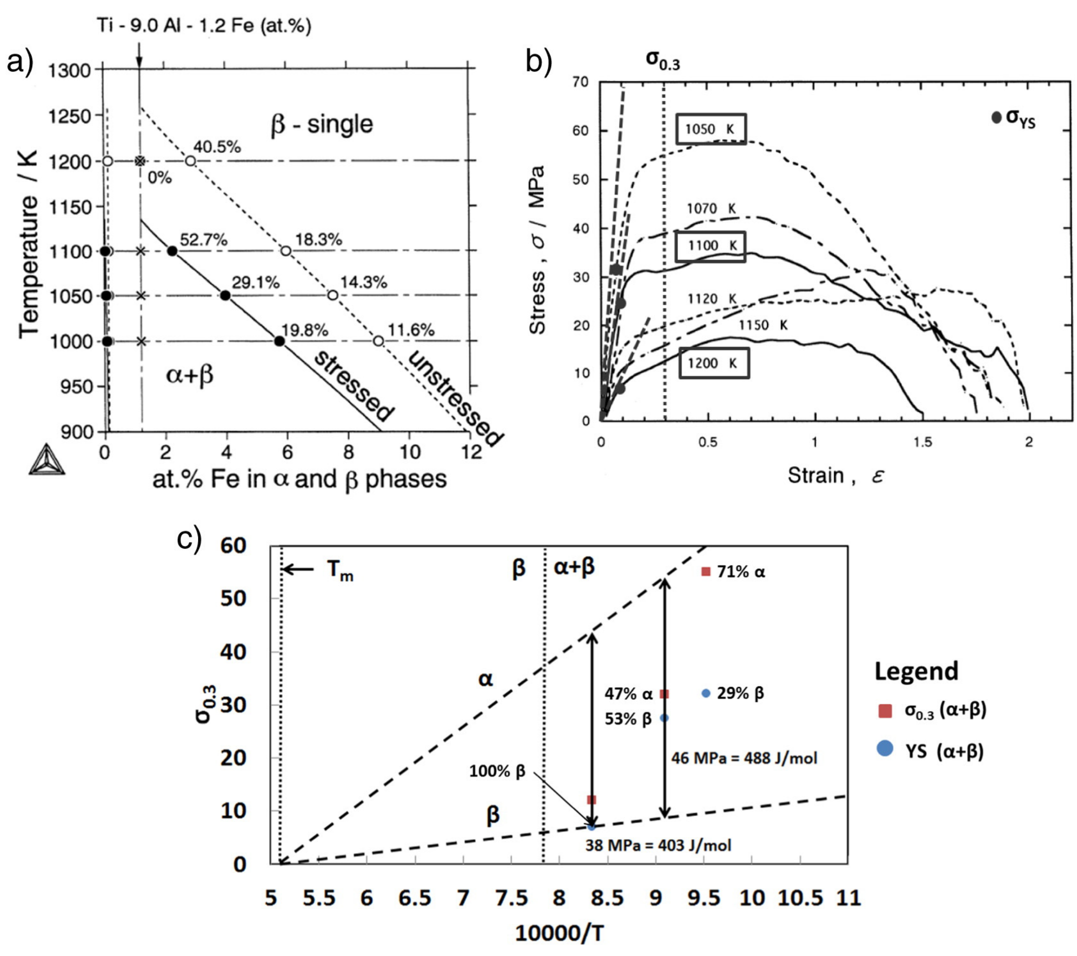

Fig. 1. a) A pseudo-binary phase diagram of Ti-5.5 wt%Al-1.5 wt%Fe (Ti-9 at.%Al-1.2 at.%Fe) associated with deformed (solid line) and undeformed (broken line) samples. An increase in β phase volume fraction was detected after straining [13]. b) Tensile flow curves determined by Koike et al. on a Ti-5.5 wt%Al-1.5 wt%Fe alloy over the temperature range 777 to 927 °C at a strain rate of 0.001 s^{-1}. [13] The estimated yield stresses are marked with solid circles. c) Dependences of the flow stress of the α phase at $\varepsilon = 0.3$ and the yield stress of the β phase on inverse absolute temperature in the Ti-5.5 wt%Al-1.5 wt%Fe alloy. The driving forces are calculated by measuring the differences between the α flow stresses at $\varepsilon = 0.3$ and the yield stresses of the fresh β that takes its place. Linear dependences of the various flow stresses on inverse absolute temperature are assumed here and the fitted lines all approach zero stress at the melting point (1 MPa = 10.6 J/mol).