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STRESS ASSISTED TRANSFORMATION IN Ti-10V-2Fe-3Al

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Introduction

In α and $\alpha+\beta$ Ti alloys, a martensitic decomposition of the β -phase occurs during quenching from above the β -transus temperature, to below the martensite start temperature, designated M_s . In β -Ti alloys, the M_s temperature is depressed, and the β -phase can be retained in a metastable state during quenching. In many of the "leaner", or less stabilized β alloys, martensitic decomposition can be encouraged by externally stressing the β solution treated and quenched (β -ST) material. The temperature below which deformation assisted martensite can form is designated M_d . In a number of β -alloys M_d lies above room temperature. As a result, stress "assisted" or stress "induced" reactions have been reported in the β -stabilized Ti-Mo [1] and Ti-V [2] systems, as well as in other more complex systems. The structure of the stress assisted martensitic products in β -Ti alloys has been reported as FCC [3], HCP [4], and most recently as orthorhombic [5,6] or α' . This paper will present some characteristics of such a stress assisted reaction, as observed in a commercial β -alloy, Ti-10V-2Fe-3Al.

Experimental

The material used in this study was forged and then hot rolled into plate at TIMET. The exact heat chemistry was determined as:

Element	V	Fe	Al	O	N	C	Ti
concentration (weight percent)	10.3	2.2	3.2	0.15	.009	.016	Bal.

All specimens were encapsulated 'in vacuo', solution treated, and quenched in agitated water. The resulting microstructures were verified to contain no martensite. Specimens solution treated above the β -transus (β -ST) contained only recrystallized β grains, with a random distribution of inclusions, rich in Ti, P, Si and S. Specimens solution treated below the β -transus ($\alpha+\beta$ -ST) were found to contain unrecrystallized β grains, inclusions, and coarse ($> 10 \mu\text{m}$ dia.) globular primary α (or α_p). All conditions were also found to contain athermal ω (ω_{ath}).

External stressing, and tensile testing of the ST material was done using an Instron machine at a strain rate of 0.00055 sec^{-1} . Strains were measured using a clip-on extensometer.

Optical metallographic specimens were prepared by electropolishing in a 5% H₂SO₄ + 1% HF + 94% methanol solution and etching with equal parts of 10% oxalic acid in water and 1% HF in water. Thin foils for Transmission Electron Microscopy (TEM) were prepared in a twin jet electropolishing unit, using a 5% H₂SO₄ + 95% methanol solution. A small amount of ion thinning was also done to eliminate any artifacts of preparation. Both JEOL 120CX, and JOEL 100C electron microscopes were used.

Specimens selected for X-ray diffraction study were cut so that the rolling direction was in the plane of the surface. The X-ray equipment used for this study consisted of a Norelco-Schultz type pole figure goniometer, fitted to a G. E. horizontal X-ray diffractometer. Copper K_α radiation was used. A modified pole figure diffraction technique was employed, producing 20 diffraction scans as a function of declination angle. Due to a strong β rolling texture, declination angles from 0° to 60° had to be used to obtain a complete set of peaks.

Results

An extensive stress assisted reaction was observed upon externally stressing Ti-10V-2Fe-3Al in the β-ST condition. The resulting plates were visible both optically and in TEM (Fig. 1). The X-ray diffraction techniques discussed earlier conclusively identified that the transformed microstructure contained orthorhombic martensite (or α''). Electron diffraction showed that the martensite plates were accompanied by mechanical twinning of the {112} <111> type. Although the relative amounts of these two products is difficult to quantitatively determine, it appears that the amount of twinning is relatively small. The location of the α'' X-ray peaks, and the indexing of these peaks, is illustrated in Table 1. The lattice parameters of the α'' unit cell were determined to be:

$$a = 3.01\text{\AA}$$

$$b = 4.83\text{\AA}$$

$$c = 4.62\text{\AA}$$

Selected Area Electron Diffraction (SAD) demonstrated that the α'' plates are oriented with the β matrix in the following manner (Fig. 2):

$$(110)_{\beta} \parallel (001)_{\alpha''}$$

$$[1\bar{1}1]_{\beta} \parallel [110]_{\alpha''}$$

Dark field imaging of α'' spots highlighted the martensitic plates (as shown in Fig. 1c). The plates appeared "mottled" or "spotty". Imaging of ω_{ath} diffraction spots demonstrated that ω_{ath} appears to exist uniformly throughout the β matrix and within the deformation products (Fig. 3a). Imaging of the twinned β reflections and ω_{ath} spots simultaneously illustrates that ω exists within twinned β plates (Fig. 3b). It also appears that the ω distribution is unaltered by the α''. That is, ω_{ath} is contained within α'' plates.

The tensile stress-strain behavior of ST Ti-10V-2Fe-3Al is shown in Figure 4. The stress needed to initiate the α'' reaction at room temperature is shown to be dependent upon the ST temperature. In the β -ST condition, a stress of only 250 MPa was required. Decreasing the ST temperature, and increasing the α_p content, suppresses the α'' reaction. The general shape of these curves is also of interest. Following the initial yield, a nearly flat, low work hardening region was found. Following this flat region, the curve takes a sudden upturn and passes through an inflection point. Finally, a "second yield point" is achieved, after which all conditions exhibited nearly the same behavior.

Before discussing these results, two practical observations of this reaction should be presented, which may be of interest to prospective users of Ti-10V-2Fe-3Al, and β -Ti alloys, in general. First, when quenching thick sections of β -ST material (greater than ~ 2 cm thickness), quenching strains were found to be sufficient to martensitically transform the β to α'' at the material's surface. Secondly, all machining and, in fact, simple scribe marking, done while the material was in the β -ST or near β -ST condition was found to locally initiate the α'' reaction.

Discussion

The structural transformation involved in the $\beta \rightarrow \alpha''$ reaction can be more easily visualized if the bcc β matrix is thought of as its orthorhombic crystallographic equivalent.* This equivalence is demonstrated in Figure 5. Similarly, it is useful to visualize the α and α' hexagonal structures in terms of their orthorhombic representations, for example, the Burger's α - β orientation relationship:

$$\begin{aligned} (1\bar{1}0)_{\beta}^{\text{bcc}} \parallel (0001)_{\alpha}^{\text{hcp}} \\ [111]_{\beta}^{\text{bcc}} \parallel [11\bar{2}0]_{\alpha}^{\text{hcp}} \end{aligned}$$

can simply be rewritten as:

$$\begin{aligned} (001)_{\beta}^{\text{ortho.}} \parallel (001)_{\alpha}^{\text{ortho.}} \\ [110]_{\beta}^{\text{ortho.}} \parallel [110]_{\alpha}^{\text{ortho.}} \end{aligned}$$

Indeed, the $\alpha \rightarrow \beta$ Burger's reaction itself can be visualized as a simple "adjustment" of the β orthorhombic structure. Specifically, it involves a distortion of the cell parameters:

$$\begin{aligned} a_{\beta} &\rightarrow a_{\alpha} \\ b_{\beta} &= \sqrt{2} a_{\beta} \rightarrow b_{\alpha} = \sqrt{3} a_{\alpha} \\ c_{\beta} &= \sqrt{2} a_{\beta} \rightarrow c_{\alpha} = 1.58a_{\alpha} \end{aligned}$$

*This representation is fully equivalent to bcc but is not normally used because it is customary to describe a structure by its highest possible symmetry group, i.e. bcc.

and the following repositioning of the atoms:

$$\begin{aligned}(0,0,0)_{\beta} &\rightarrow (0,0,0)_{\alpha} \\ (a/2,b/2,0)_{\beta} &\rightarrow (a/2,b/2,0)_{\alpha} \\ (0,b/2,c/2)_{\beta} &\rightarrow (a/6,b/2,c/2)_{\alpha} \\ (a/2,0,c/2)_{\beta} &\rightarrow (a/2,b/6,c/2)_{\alpha}\end{aligned}$$

The above movements provide a viable mechanism for hexagonal martensite formation. The α'' structure, however, is best thought of as a compromise structure; that is, an orthorhombic compromise of both the β and α' structures. In α'' forming systems, the structural shifts required to form hexagonal α' do not go to completion, but instead stop midway, before the α' orthorhombic structure is achieved. It is not clear what controls the progression of this reaction but one generalization can be presented. Systems with highly unstable β structures at room temperature (α alloys, for example) generally complete the $\beta \rightarrow \alpha'$ reaction during quenching, while alloys of greater β stability prefer to "stop" at an intermediate structure. Further, all carefully characterized stress assisted martensites have been reported as orthorhombic [5]. Two reports of the non-orthorhombic stress assisted martensites [4,7], were not studied in a fashion which would permit resolution of an orthorhombic lattice.

The athermal omega "sub-structure" found in the α'' plates is also more fully understood using the above viewpoint. It is known that the hexagonal ω structure also can be visualized as a bcc structure, with the $\{111\}$ planes periodically displaced in the $\langle 111 \rangle$ direction. If the ω -phase structure is visualized this way, the coherency between the ω structure and the surrounding β matrix is readily understood. Upon quenching, Ti-10V-2Fe-3Al is found to form a uniform distribution of fine ω_{ath} . Upon stressing at room temperature, which is below M_d , the residual orthorhombic β matrix is distorted to α'' . The islands of ω_{ath} may either revert to β and then to α'' , or they may maintain their identity while the surrounding matrix transforms. Our observations indicate the latter occurs, at least in Ti-10-2-3.

Energetically, retention of ω_{ath} inside α'' can be justified using the following argument. In the unstressed β -ST condition, the ω structure is energetically more favorable than either β , α' , and α'' . Since the $\beta \rightarrow \omega$ transformation is known to require little or no thermal activation, ω forms during the quench. But this reaction is prevented from going to completion, due to the unusual nature of this phonon controlled transformation mechanism. Upon stressing, the α'' phase forms because it is more stable than β , but it is not necessarily more stable than ω . Thus the β can be transformed to α'' , while the ω_{ath} is left intact. The apparent implication of this finding is that the changes in coherency and strain energy as the orthorhombic β lattice is distorted to α'' are not large enough to disrupt the ω_{ath} particles.

The finding of ω_{ath} within twinned β plates is also expected, since ω particles which are destroyed by twinning should quickly reform after the twin interface has passed.

The orthorhombic distortion associated with α'' formation also provides a basis for understanding the unusual stress-strain behavior of ST Ti-10V-2Fe-3Al. Since the lattice undergoes a shape change, α'' formation is accompanied by plastic strain. Under an externally applied stress, the $\beta \rightarrow \alpha$ reaction distorts the lattice in such a manner as to alleviate the applied stress. More completely stated, the transformation strains from the $\beta \rightarrow \alpha$ reaction tend to accommodate elastic strains, and thereby reduce the strain energy of the system.

Referring to the β -ST condition of Figure 4, it can be seen that the nucleation of α'' plates begins at 250 MPa. These first plates grow until a barrier, such as a grain boundary, is encountered. There also is evidence that, upon encountering a grain boundary, a plate may stimulate nucleation of new α'' plates in a neighboring grain. Since the stress required to nucleate α'' is fairly constant during these early stages, an extended flat portion is found on the stress-strain curve. As more and more β is transformed in this manner, the frequency of nucleation, as well as the volume transformed per nucleation event begin to decrease. As this happens, the stress required to produce a given volume of α'' (or a given plastic strain increment) begins to increase. Since the stress-strain curves are obtained at constant strain rate, the result is an increasing increment of stress for each corresponding increment of strain leading to an inflection in the curve. Following this inflection, there appears to be a region of rapid work hardening. In reality, this is simply a return to nearly elastic behavior, due to difficulty in producing additional α'' . Finally, the applied stress becomes sufficiently large to move dislocations in a more classical sense, and a second and true yield point is observed.

In the $\alpha + \beta$ -ST conditions the β matrix contains α_p . Although the α_p is too coarse to directly affect strength, it does tend to increase the chemical stability of the surrounding β matrix because of the solute partitioning between α and β . Thus, as the ST temperature is reduced, and the amount of α_p is increased, the M_s temperature is further suppressed and M_d approaches room temperature. A greater stress is then needed to initiate the α'' distortion. This is illustrated in Figure 4. Finally, where the β composition is rich enough in Fe and V to depress M_d below room temperature, the material deforms by slip and no α'' is formed.

Conclusion

It has been shown that the β -phase in Ti-10V-2Fe-3Al is sufficiently stabilized to depress the M_s temperature below room temperature, but that the deformation induced martensite start temperature (M_d) lies above room temperature. It also has been shown that solution treating in the two phase ($\alpha + \beta$) region enrich the β -phase composition with respect to Fe and V and thus depresses the M_d temperature. In the fully diluted β -phases, a stress of 250 MPa was required before the alloy began to transform to an orthorhombic martensite (α''). A small amount of mechanical twinning of the β matrix was also observed. Further, the preceding ω_{ath} dispersion was found to be preserved within the β twins, and appears to also be preserved during the $\beta \rightarrow \alpha''$ reaction.

The crystallography of the $\beta \rightarrow \alpha''$ transformation has been analyzed in a novel way by converting the bcc β -phase structure to an equivalent orthor-

hombic structure. Using this analysis, the $\beta \rightarrow \alpha''$ can be seen to require simple atomic shuffles. The relatively low activation barrier for α'' formation can be understood on this basis. This analysis is described and illustrated.

Acknowledgments

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Table 1. X-ray Diffraction Peaks for Ti-10V-2Fe-3Al
 β Solution Treated, Quenched, and Compressed
to 900 MPa

Diffraction Angle - 2θ *	Crystal Plane		d Spacing
	β	α''	
35.35		(110)	2.54
36.90		(020)	2.44
39.35 **		(002)	2.29
39.50	(110)		2.82
40.35 +		(111)	2.24
41.60 *		(021)	2.17
53.60		(112)	1.71
54.60 **		(022)	1.68
57.05	(200)		1.62
61.65 +		(200)	1.51
65.10		(130)	1.43

* Broad low intensity peak

** Broad very low intensity peak

+ Narrow high intensity peak

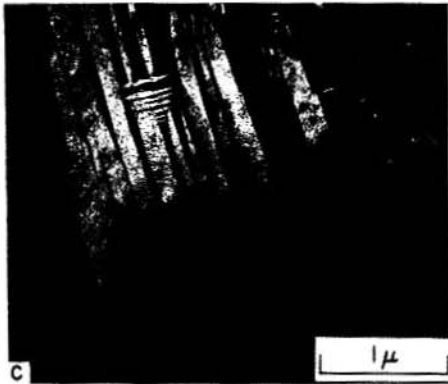
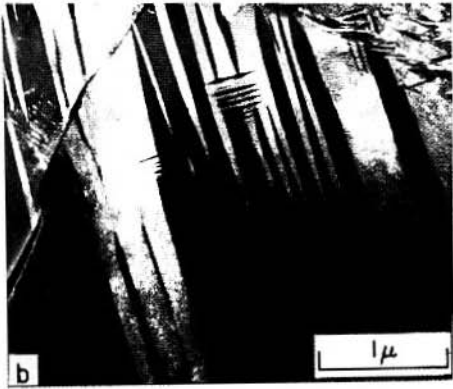
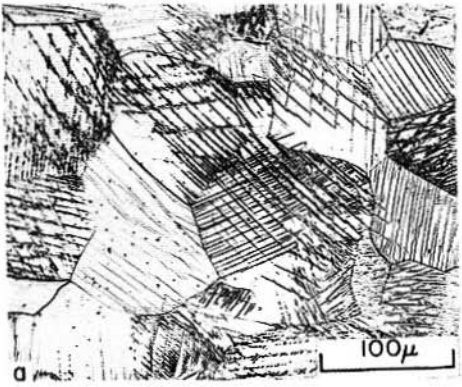


Fig. 1 - Stress induced martensite shown- a) optically, b) in TEM bright field, and c) in TEM dark field.

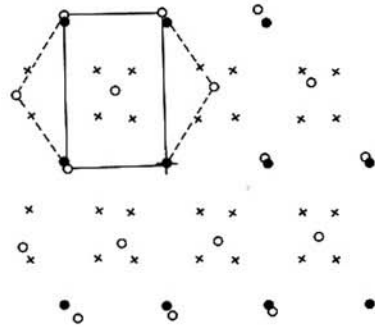
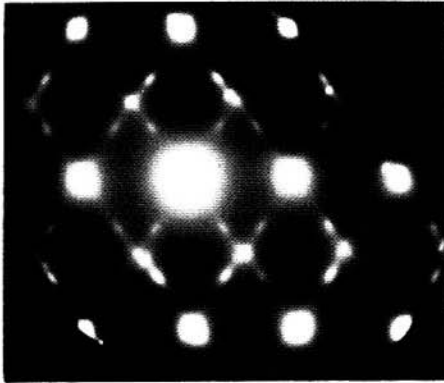


Fig. 2 - a) $\langle 110 \rangle$ zone electron diffraction spot pattern, and b) schematic representation of the same, with open circles representing the $\langle 001 \rangle$ zone α reflections, solid circles representing $\langle 110 \rangle$ zone β reflections, and crossed lines representing $\langle 1120 \rangle$ zone ω reflections (two variants). The solid lines in a) represent the $\langle 001 \rangle$ orthorhombic cube face symmetry, while the dashed show the distortion from hexagonal symmetry.

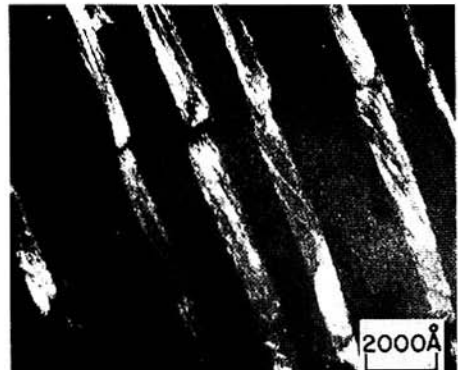
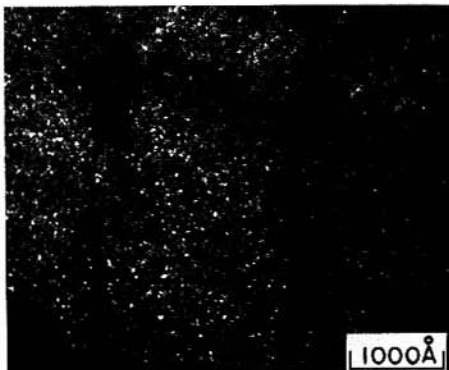


Fig. 3 - a) Athermal ω , uniformly dispersed throughout the β and the stress-assisted transformation plates, and b) shows dark field imaging of twinned β reflection and ω_{ath} reflection.

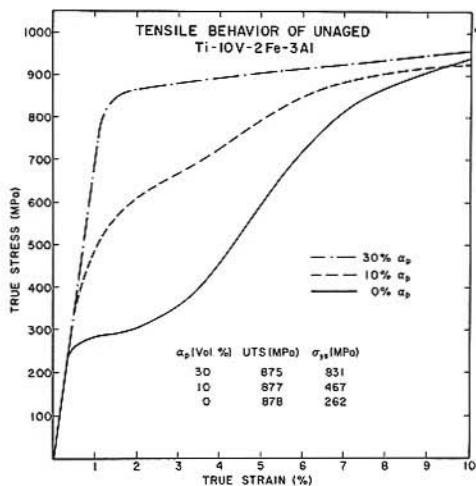


Fig. 4 - True stress-true strain curves for Ti-10V-2Fe-3Al solution treated at 720°C, 780°C, and 850°C.

Fig. 5 - Illustration showing the equivalency of the bcc and orthorhombic representations of the β -phase.

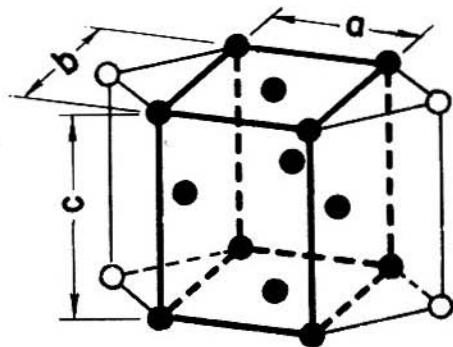
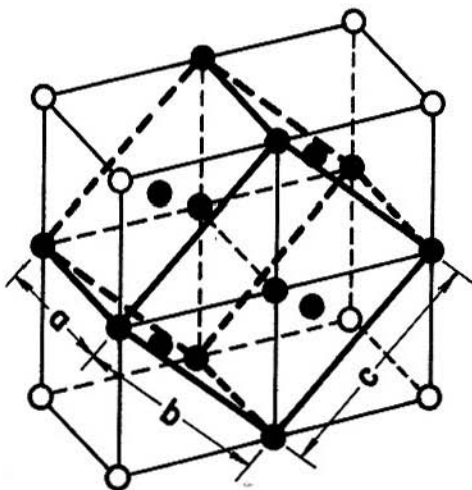


Fig. 6 - Illustration demonstrating the equivalency between the hcp and the orthorhombic representations of the α and α' phases.