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## STRAIN INDUCED TRANSFORMATIONS AND PLASTICITY IN TRANSAGE Ti-11.6V - 2Al-2Sn-6Zr (T134) AND Ti-11.5V - 2Al-2Sn-11.3Zr (T129) ALLOYS

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**Abstract.**- An investigation is reported on two  $\beta$  quenched titanium Transage alloys, namely (i) T 134 which contains only orthorhombic  $\alpha''$  martensite and (ii) T 129 which contains mainly retained  $\beta$  and a small amount of  $\alpha''$  after quenching from the  $\beta$  phase. Strain induced shear transformations of  $\beta$  to  $\alpha''$  and the  $\alpha''$  to hexagonal  $\alpha'$  take place in the temperature range 77-373K and are associated with enhanced ductility.

**Introduction.**- The martensitic structures observed in quenched titanium alloys are of two types (i) hcp  $\alpha'$  and (ii) orthorhombic  $\alpha''$  in alloys of high and low  $M_s$  respectively. Strain induced transformation of metastable retained  $\beta$  phase has been reported to result in the formation of  $\alpha'$ (1-3),  $\alpha''$ (4-9) or bc tetragonal  $\tau$  martensite (10,11).  $\{112\}$  and/or  $\{332\}$  twinning of the  $\beta$  has also been reported (4-6,12). Williams (4) has suggested that, apart from twinning, the strain induced  $\beta$  transformation will result in  $\alpha''$  only and noted that the addition of Al in Ti-V,Mo based alloys promotes this reaction. There are conflicting reports as to whether strain produces  $\alpha''$  or  $\tau$  (7,8,10,11) but  $\tau$  has been identified in Ti-Nb,Ta based alloys. Very recently a study of deformation induced martensite formation in Transage 129 has indicated (9) that in this Ti-V-Zr based system the strain induced product is  $\alpha''$  but that unusual texture effects can give rise to X-ray diffractometry results which appear to indicate the presence of hexagonal  $\alpha'$ . It was suggested that this anomaly could be responsible for much of the disagreement in the literature concerning the crystallographic structure of strain induced products and specifically could account for reports of  $\alpha'$  in Transage 129 (1).

The present study examines the strain induced transformations in Transage alloys T129 and T134 in the temperature range 77-373K.

**Materials and Specimen Preparation.**- The alloy compositions (wt %) were

Ti-11.9V - 2.13 Al - 2.02 Sn - 5.96 Zr - 0.1 Fe (T134)

and Ti-11.6V - 2.0 Al - 2.03 Zn - 11.3 Zr - 0.1 Fe (T129)

3mm thick strip specimens for cold rolling and 18mm gauge round bar tensile samples were taken with the rolling direction or tensile axis parallel to the rolling direction of the as received material. Specimens were  $\beta$  solution treated at 1088K for  $1.3 \times 10^3$ s and water quenched. Tensile tests were carried out in the range 77-373K using an Instron test machine. A Philips X-ray diffractometer was used to determine crystallographic changes: Lattice parameters were measured to an accuracy of  $\pm 0.001\text{\AA}$ . A JEOL 120CX electron microscope was used for microstructural studies.

**Results.**— The  $\beta$  quenched T134 alloy contained only orthorhombic  $\alpha''$  ( $a_{\alpha''} = 3.009\text{Å}$ ,  $b_{\alpha''} = 4.977\text{Å}$ ,  $c_{\alpha''} = 4.652\text{Å}$ ,  $b/a\sqrt{3} \sim 0.955$ ). T129 contained mainly retained  $\beta$  with a small amount of  $\alpha''$  ( $a_{\alpha''} = 3.022\text{Å}$ ,  $b_{\alpha''} = 4.959\text{Å}$ ,  $c_{\alpha''} = 4.662$ ,  $b/a\sqrt{3} \sim 0.947$ ). For the T134 alloy cold rolled at room temperature the X-ray diffraction profiles (Fig. 1a) show progression of the orthorhombic  $\alpha''$  symmetry towards the hexagonal  $\alpha'$  symmetry represented by the increase of the  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio from 0.955 towards unity as the strain increases. The hexagonal  $\alpha'$  symmetry ( $b_{\alpha'}/a_{\alpha'}\sqrt{3} = 1$ ,  $a_{\alpha'} = 2.941\text{Å}$ ,  $c_{\alpha'} = 4.682\text{Å}$ ) was obtained in the deformed T134 alloy after  $\sim 15\%$  thickness reduction and no further change occurred on further deformation up to 40%. For the deformed T129 alloy (Fig 1b) the initial transformation of the retained  $\beta$  to orthorhombic  $\alpha''$  occurred before the continuous transition of the  $\alpha''$  phase  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio from  $\sim 0.947$  to unity ( $a_{\alpha'} = 2.941\text{Å}$ ,  $c_{\alpha'} = 4.689\text{Å}$ ) which was achieved after  $\sim 25\%$  reduction. The uniform tensile strain in each  $\beta$ -quenched alloy is approximately constant ( $\sim 18\%$  for T134 and  $\sim 22\%$  for T129) over the temperature range 77 to 373K (Fig 2). X-ray diffraction analysis of the  $\beta$ -quenched alloys cold rolled at 77K revealed similar crystallographic changes as observed after deformation at room temperature.

In the T129 alloy the strain-induced  $\alpha''$  plates, stabilized against thinning reversion by precipitation on ageing at 723K for  $7.2 \times 10^3$ s, consisted of bands of two alternating  $\{011\}_{\alpha''}$  twin related variants of alternate arrangements and with a  $\{011\}_{\alpha''}$  interface  $\alpha''$  (Fig 3). The microstructure changes when the  $\alpha''$  plates were converted to a hexagonal structure in the T134 alloy were characterized by (i) initial increase in the surface reliefs exhibited by the acicular  $\alpha''$  plates followed by (ii) the formation of secondary internal plate variants with an unusual  $\{340\}_{\alpha''}$  ( $\equiv \{433\}_{\beta}$ ) type interface rather than a  $\{111\}_{\alpha''}$  twin type (Fig 4a), and (iii) the conversion of the many acicular plate variants into a single plate variant containing lenticular and irregular shaped  $\{111\}_{\alpha''}$  or  $\{10\bar{1}1\}_{\alpha''}$  twins (Fig 4b).

**Discussion.**— The present study shows that the strain induced transformation of  $\beta$  to hexagonal  $\alpha'$  martensite can indeed occur, but only through the intermediate formation of orthorhombic  $\alpha''$ . The progressive change observed in  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio towards unity with increasing strain cannot be attributed to texture ( $\alpha''$ ) and must represent the change in lattice symmetry from  $\alpha''$  to  $\alpha'$ . The transition from  $\alpha''$  to  $\alpha'$  does not involve the nucleation of  $\alpha'$  plates in the  $\alpha''$  matrix but involves the gradual change of  $a_{\alpha''}$  and  $b_{\alpha''}$  and of  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  to 1; this indicates no discontinuous change in free energy and suggests that  $\alpha'' \rightarrow \alpha'$  transformation is a second order reaction. The previous experimental report (14) of the formation of both  $\alpha''$  and  $\alpha'$  in some quenched Ti alloys (Ti-6Al-4V, Ti-8Al-1Mo-1V, Ti-4Al-3Mo-1V) has a similarity to the present strain-induced transformations. The greater effect of quenching strains on the first set of orthorhombic  $\alpha''$  plates to be formed could create some plates with  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio of unity, equivalent to a hexagonal  $\alpha'$  structure. It has been found in this work (15) that the reversion of the martensite on heating is increasingly inhibited as the  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio approaches that of  $\alpha'$ . This contrasts with that reported (10) for  $\alpha''$  which has undergone strain induced transformation to  $\tau$  where the deformation reduced the reversion temperature.

The formation of bands of two alternating  $\{011\}_{\alpha''}$  twin related  $\alpha''$  plate variants during the strain induced  $\beta \rightarrow \alpha''$  transformation in T129 is consistent with the class B type of martensite in the Mackenzie and Bowles theory (16). The transformation is probably both autocatalytic and self accommodating when the shear strains of the two variants are opposite. The strain induced transformation is associated with a very low yield stress  $\sim 200 \text{ MN/m}^2$  (Fig 2b) at room temperature and contrasts with the much higher yield stress of the  $\alpha''$  T134. The increase in the yield strength above room temperature was due to the thermal decomposition of the  $\beta$  to a  $\beta + w$  structure which does not occur in T134. Below room temperature the yield stress increased, presumably because the mobility of the interface dislocations is reduced.

The microstructural changes involved in the conversion of  $\alpha''$  to  $\alpha'$  are quite unusual. The initial increase in surface relief due to the acicular  $\alpha''$  is probably due to the accommodation of the increased elastic strain-energy as deformation proceeds. The subsequent formation of internal plate variants with a  $\{433\}_{\beta}$  type interface rather than the  $\{111\}_{\alpha''}$  internal twin is unusual and at present difficult to explain. The reorientation of several acicular  $\alpha''$  plate variants into one single plate variant shows the great similarity between the behaviour of the  $\alpha''$  Ti alloys to that of pseudoelastic alloys such as Au-Cd, In-Tl (17) where twin related variants could be converted into a single plate by the application or relaxation of stress. The conversion of the many plate variants into a single one may proceed through the glissile motion of the initially created  $\{340\}_{\alpha''}$  or  $\{433\}_{\beta}$  interfaces. The later nucleation of lenticular  $\{111\}_{\alpha''}$  or  $\{10\bar{1}1\}_{\alpha''}$  type twins would be enhanced as the transformation strains, especially the  $\alpha''$  principal strain  $\epsilon_3 = c_{\alpha''}/a_{\alpha''}\sqrt{2} - 1$  increased from 0.8% to 1.4%. Work on Ti-Ta alloys (7) indicates that the  $\{10\bar{1}1\}_{\alpha''}$  twinning occurs when  $\epsilon_3 > 1\%$ . The stunted growth of the lenticular  $\{111\}_{\alpha''}$  twins resulting from obstacles such as impurities in the Ti34 alloy would lead to the development of the irregular shaped  $\{111\}_{\alpha''}$  or  $\{10\bar{1}1\}_{\alpha''}$  twins.

Conclusions: 1. The  $\beta$ -quenched Ti34 alloy showed complete  $\beta \rightarrow$  orthorhombic  $\alpha''$  transformation while that of Ti29 alloy shows only partial transformation to  $\alpha''$  martensite of smaller  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio.  
 2. On deforming the  $\beta$ -quenched Ti29 alloy the transformation of the remaining  $\beta$ -phase to the  $\alpha''$  occurred before the transformation of the  $\alpha''$  to hexagonal  $\alpha'$  occurred. For Ti34 alloy the strain-induced  $\alpha'' \rightarrow \alpha'$  transformation also occurred. For both alloys the strain-induced transformations occurred between 77 and 373K and the ductility associated with the transformation was unchanged within this range.  
 3. The strain-induced  $\beta \rightarrow \alpha''$  transformation in Ti29 alloy produced bands of two  $(011)_{\alpha''}$  twin related variants of alternate arrangement consistent with Class B Bowles and Mackenzie theory of martensitic transformation.  
 4. The strain-induced  $\alpha'' \rightarrow \alpha'$  transformation involved the continuous change of the  $b_{\alpha''}/a_{\alpha''}\sqrt{3}$  ratio towards unity, possibly by a second order reaction and in the Ti34 alloy the transformation involved the conversion of the acicular  $\alpha''$  morphology in the  $\beta$ -quenched material to a single  $\alpha'$  plate variant containing lenticular and irregular shaped  $\{10\bar{1}1\}$  twins.

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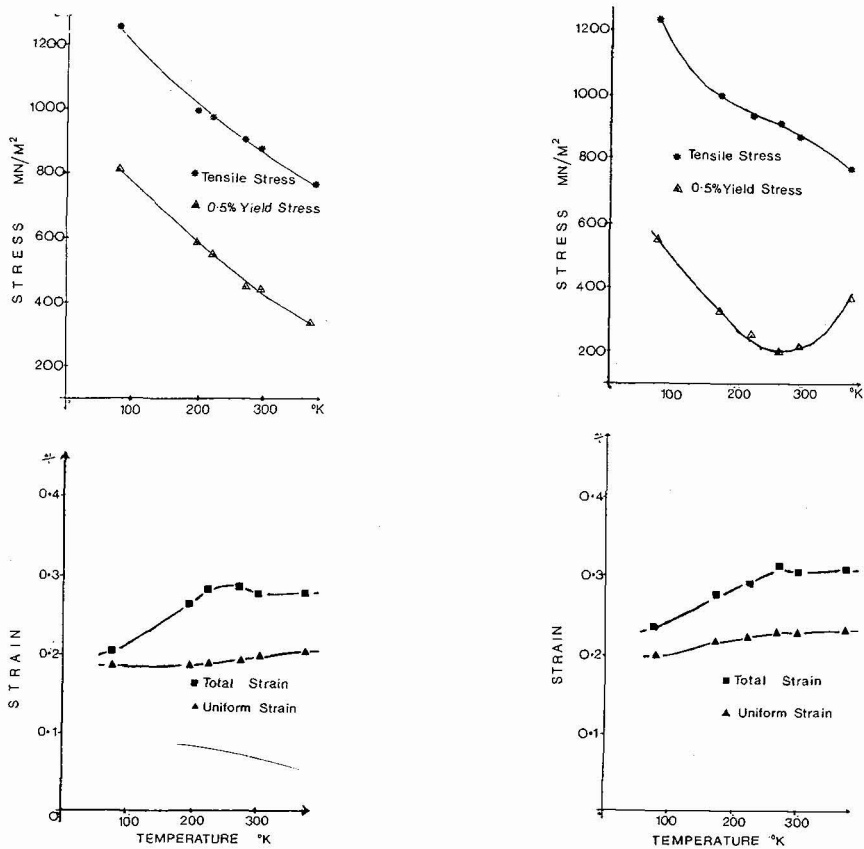


Fig. 2. The temperature dependence of stress and strain for materials deformed in tension between 77 and 373K (a) T134 and (b) T129.

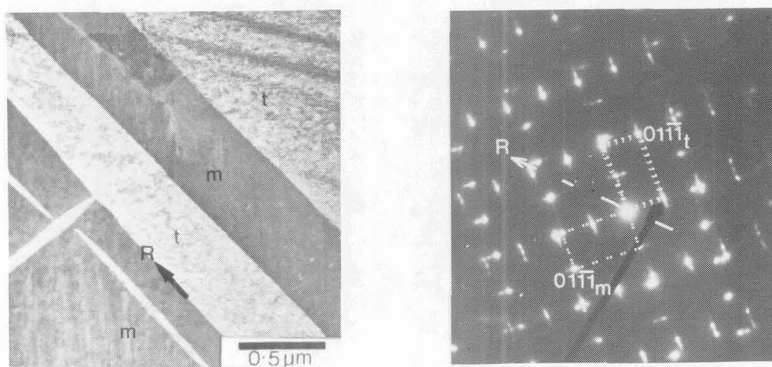


Fig. 3. Electron micrograph and corresponding diffraction pattern showing  $(01\bar{1}2)_{\alpha}$ , or  $(01\bar{1})_{\alpha}$ , twin bands. m and t indicate matrix and twin. R is the trace of the twin plane.

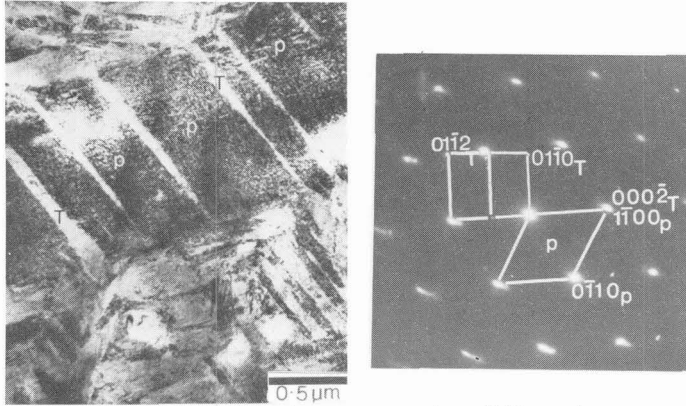


Fig. 4a. Electron micrograph and corresponding diffraction pattern of T134 deformed 10% showing a large martensite plate which has broken into two variants p and T on deformation and which have a relationship equivalent to that between two martensite variants formed from a single  $\beta$  grain rather than that of parent and twin.

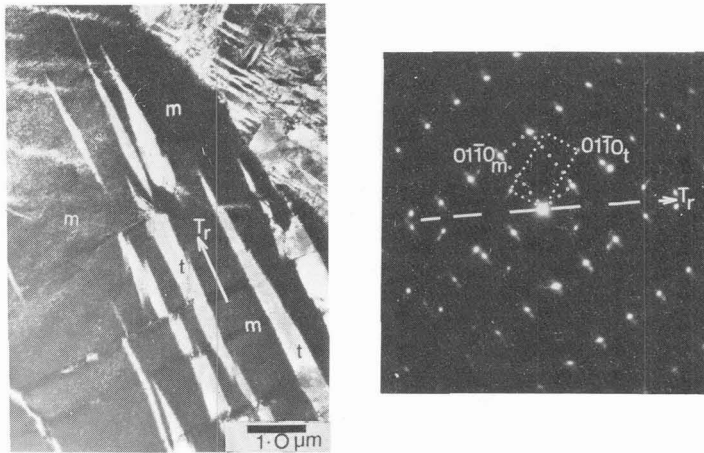


Fig. 4b. Electron micrograph and corresponding diffraction pattern of T134 deformed 15% showing a grain converted into a single variant (m) which contains small  $(111)_{\alpha}$  or  $(10\bar{1}1)_{\alpha}$  twins.