JOURNAL OF MATERIALS SCIENCE LETTERS 12 (1993) 697–699

Structure of martensite in titanium alloy Ti–6Al–1.6Zr–3.3Mo–0.3Si

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The alloy Ti–6Al–1.6Zr–3.3Mo–0.30Si (VT9) is a creep-resistant alloy of $\alpha + \beta$ type, designed for application in the compressor stage of jet engines. Its β transus temperature is 1243 K [1]. It develops a wide variety of microstructures depending on the solution-treatment temperature and the subsequent rate of cooling [1, 2]. Whereas rapid cooling from the β-range leads to transformation of the β-phase to a single-phase martensitic structure, slow cooling results in a two-phase structure with Widmanstätten α and β retained between the α-plates. Two types of martensite, one with h c p crystal structure (α') [1–6] and the other with orthorhombic structure (α'') [4–10] occur in titanium alloys. There have been different reports [2, 3, 11] concerning the crystal structure of martensite in the alloy VT9. Dyakova *et al.* [11] reported the structure of martensite to be orthorhombic in the $\alpha + \beta$ solution-treated and water-quenched condition, whereas Trenogina and Lerinman [3] reported it as h c p with a small amount of retained β in the β treated and quenched condition. In the same VT9 alloy Banerjee *et al.* [1] reported single-phase h c p martensite with no β present at the α'-plate interfaces even in the stabilized condition (803 K for 6 h), following β treatment and water-quenching. The structure of the martensite and its decomposition upon ageing are known to influence predominantly the tensile ductility of these titanium alloys [1, 12]. The aim of the present investigation was therefore concerned with studying the structure of the martensite in VT9 titanium alloy in unaged and aged conditions, following β treatment and water-quenching.

The VT9 alloy was obtained from Midhani (Hyderabad, India) in the form of a rod 20 mm in diameter in mill-annealed condition, following forging and rolling in the β-phase field. It contained (in wt %) 5.47 Al, 2.90 Mo, 1.90 Zr, 0.22 Si and balance titanium. Small specimens were sealed in silica tubes with titanium getter at a vacuum level of 0.08 Pa. The sealed specimens were solution-treated at 1323 K in the β range and quenched in water (WQ), using the technique described in [13] to ensure efficient quenching. A few specimens were again sealed in silica tubes separately as described above, and aged at 823 K (WQ-A) for 24 h. The specimens were heated in a resistance heating furnace with temperature control of ±3 K. X-ray diffraction analysis was carried out using Philips X-ray diffractometer. Thin foils for transmission electron microscopy were prepared by a Fischione twin jet electropolisher using electrolyte containing (in vol %) 59 methanol, 35 n-butanol and 6 perchloric acid, cooled at 230 K, at 12.5 V. The foils were examined at 120 kV in a Jeol 200 CX transmission electron microscope.

X-ray diffraction data for the WQ and WQ-A specimens are given in Tables I and II, respectively. Analysis of the diffraction data showed single-phase orthorhombic and h c p crystal structures in the WQ and WQ-A conditions, respectively. The lattice parameters of the orthorhombic martensite (α'') were determined as $a = 0.3106$, $b = 0.4915$ and $c = 0.4659$ nm, and those of the h c p martensite as $a = 0.294\,02$ and $c = 0.468\,28$ nm.

Figs 1 and 2 are transmission electron micrographs showing single-phase martensitic platelets in the WQ and WQ-A specimens, respectively. It may be noted that in contrast to the orthorhombic structure in the WQ condition using X-ray diffraction, selected-area electron diffraction confirmed it to be h c p martensite. No evidence for β-phase at the platelet interfaces or the Ti_3Al phase could be obtained even in the WQ-A condition.

TABLE I Observed and calculated interplanar spacings for VT9 in the WQ condition indexed on the basis of an orthorhombic cell with $a = 0.3106$, $b = 0.4915$ and $c = 0.4659$ nm

$h\,k\,l$	2θ (degrees)	d_{obs} (nm)	d_{cal} (nm)
100	28.746	0.3105	0.3106
101	35.546	0.2525	0.2584
020	36.600	0.2455	0.2457
002	38.650	0.2329	0.2329
111	39.188	0.2298	0.2287
021	40.527	0.2225	0.2173
022	53.600	0.1709	0.1690
130	63.801	0.1459	0.1449
132	77.000	0.1238	0.1230
040	78.200	0.1222	0.1228
004	82.640	0.1167	0.1164
222	84.140	0.1150	0.1143
033	86.820	0.1121	0.1127
141	87.700	0.1112	0.1109
150	110.770	0.0936	0.0937

TABLE II Observed and calculated interplanar spacing for VT9 in the WQ-A condition indexed on the basis of a hexagonal cell with $a = 0.294\,02$ and $c = 0.468\,28$ nm

$h\,k\,l$	2θ (degrees)	d_{obs} (nm)	d_{cal} (nm)
$0\,1\,\bar{1}\,0$	35.247	0.254 62	0.254 65
$0\,0\,0\,2$	38.446	0.234 14	0.234 14
$0\,1\,\bar{1}\,1$	40.348	0.223 53	0.223 71
$0\,1\,\bar{1}\,2$	53.321	0.171 81	0.172 36
$0\,1\,\bar{1}\,3$	71.082	0.132 62	0.133 08
$0\,2\,\bar{2}\,1$	78.243	0.122 18	0.122 86

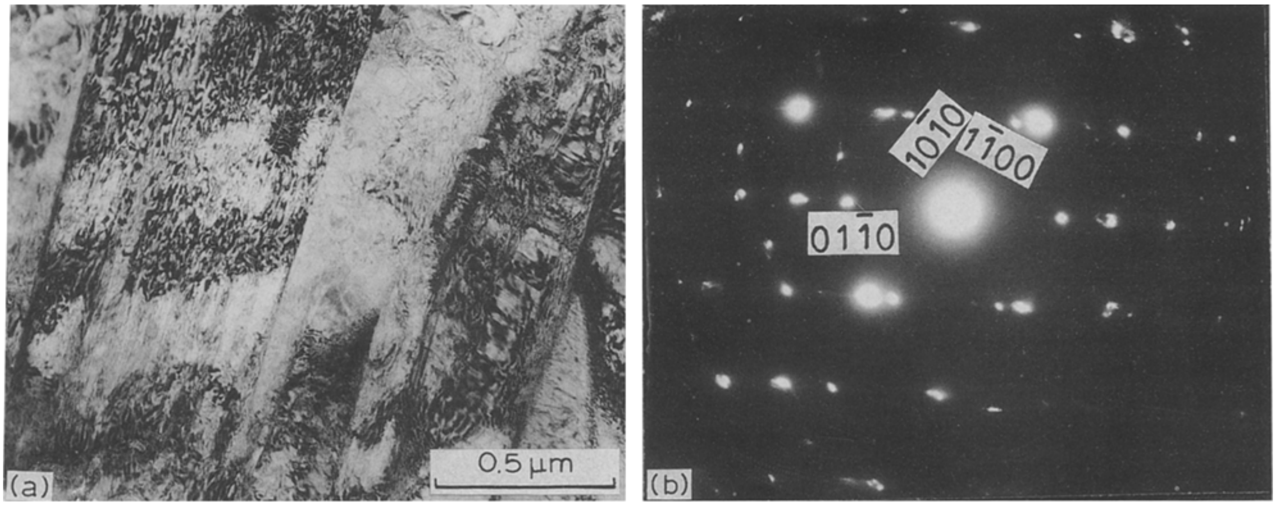

Figure 1 (a) Transmission electron micrograph of martensitic (α') platelets in as-quenched (WQ) condition showing a high density of dislocations. (b) Selected-area diffraction pattern taken from the region shown in (a). The pattern shows two zones: $B = Z = [0001]$ and $\beta = Z = [01\bar{1}1]$. The indices belong to the [0001] beam direction.

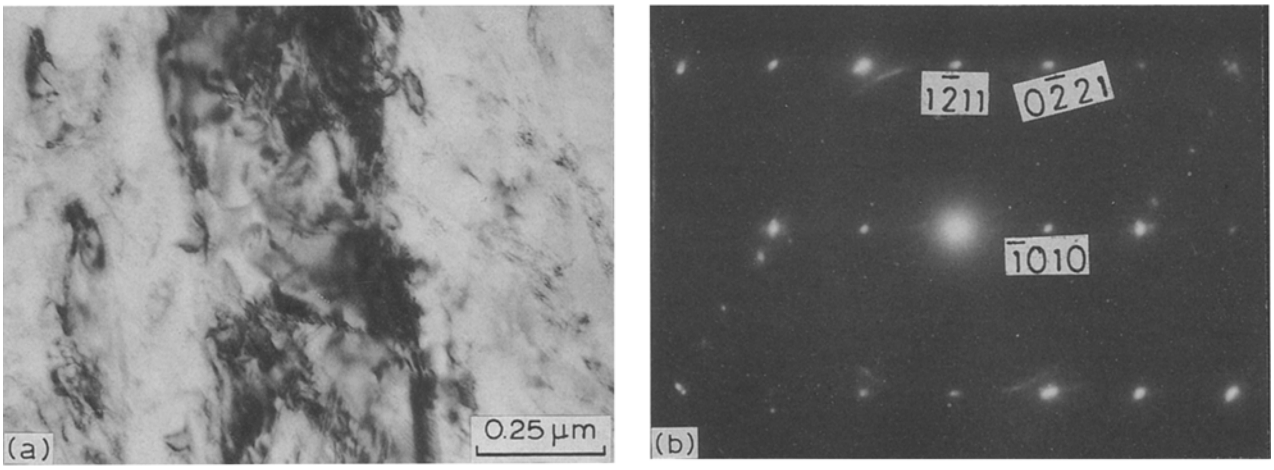

Figure 2 (a) Transmission electron micrograph showing single-phase martensitic platelets of α'. Platelets show a low density of dislocations. (b) Selected-area diffraction pattern taken from the region shown in (a) with the zone axis $B = Z = [\bar{1}2\bar{1}6]$ in the WQ-A condition.

It is obvious from the X-ray diffraction data that the β-phase transformed to a single-phase orthorhombic martensitic (α'') structure when solution-treated in the β range and quenched in water at room temperature. The values of the lattice parameters of this phase determined in the present investigation are in good agreement with those reported in [7, 8, 12, 14] for the orthorhombic phase in other titanium alloys. However, electron diffraction analysis showed the structure to be hcp and is in agreement with a similar report [3] on the same VT9 alloy. Such differences were also observed previously [8, 15] in other titanium alloys. These differences are attributed to relaxation of the orthorhombic (α'') to hcp (α') during electrothinning [8, 15]. Thus, it may be inferred that the orthorhombic phase as determined using X-ray diffraction represents the true structure of the material in the WQ condition.

The formation of the orthorhombic phase upon quenching is observed to occur over a limited composition range and over a a small temperature interval of solutionizing. Sugimoto *et al.* [16] confirmed the formation of α'' in simulated commercial titanium alloys of the type Ti–Al–Sn–Zr–Mo with Mo content in the range 4–6 wt% and quenched from a temperature range of 1173–1323 K. Dyakova *et al.* [11] observed, in VT9 alloy (comparable to the alloy of Sugimoto *et al.* but with lower Mo content), that the β-phase transforms to α'' upon water-quenching following solution-treatment in the ($\alpha + \beta$)-phase field. This could be attributed to the higher Mo partitioning to β-phase during the $\alpha + \beta$ treatment to the critical amount of approximately 4%. The formation of the orthorhombic α''-phase in VT9 alloy in the present investigation, even in the β solutionized and water-quenched condition (which results in the overall Mo content of 2.9 wt% instead of the required critical amount of 4 wt%), could probably be attributed to the role of silicon in stabilizing the orthorhombic α'' structure [14].

Ageing of the WQ specimen at 823 K resulted in the transformation of the orthorhombic α'' martensite to the hcp α' martensite structure. This is in accordance with the observation of the transformation of α'' through precipitation of α needles [14] rather than through the precipitation of β particles [12], as no β particles could be observed in the present investigation. It is important to note that the stabilizing treatment (803 K for 6 h) of the as-quenched specimen [1] did not result in the precipitation of β in VT9 alloy. Also, in [17] it was found that only ageing the as-quenched specimen at the high temperature of 973 K for 4 h gave thin films of β at the interplatelet boundaries of the martensite.

On the basis of the above analysis, it may be concluded that the crystal structure of the martensite in VT9 alloy resulting from β treatment and water-quenching is orthorhombic. A small amount of silicon seems to stabilize the orthorhombic martensite even when the overall β stabilizing element is only about 2.9 wt% compared with the approximately 4 wt% found by Sugimoto *et al.* [16]. However, it transforms to h c p upon ageing at 823 K for 24 h.

Acknowledgement

The authors thank Professor S. Lele, Department of Metallurgical Engineering, Banaras Hindu University, Varanasi, for his encouragement and suggestions.

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*Received 13 May
and accepted 16 November 1992*