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On flow stress anisotropy in Ti-6Al-4V alloy sheet during superplastic deformation

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Abstract The anisotropy of flow stress in a cold rolled sheet of Ti-6Al-4V alloy has been observed during superplastic deformation at 850 °C. At this temperature, the alloy has duplex microstructure with almost equiaxed grains of the alpha and beta phases. The maximum value of flow stress has been established for the rolling direction and minimum—for the transverse one. Also, the anisotropy of crystallographic texture weakening in the alpha phase has been observed. However, it has been demonstrated that texture in the alpha phase cannot be responsible for the observed anisotropic behavior. Texture in the beta phase is the suggested reason for the flow-stress anisotropy during superplastic deformation.

Introduction

The anisotropy of mechanical properties during superplastic deformation is an important feature of many polycrystalline materials [1–13]. In general, the reasons for anisotropic behavior are the presence of preferential orientations of grains, i.e., crystallographic texture, and/or non-ideal, aligned and banded microstructure. The origin of anisotropic behavior, however, is not always clear for a specific material. In the case of multiphase commercial alloys these different structural factors often coexist and their separation can be difficult. McDarmaid and coworkers [7–11] and Benay et al. [12] observed the anisotropy of flow stress and plasticity in Ti-6Al-4V alloy with a strong texture and microstructure aligned in the rolling direction (RD). The authors of [8–12] ascribed such behavior to the influence of aligned and banded microstructure. Also, Bai et al. [13] ascribed the change from circular to elliptical cross-section in Ti-6Al-4V alloy during superplastic deformation to the influence of microstructure (grain size, shape and distribution). Kaibyshev and coworkers [6] have shown that texture-free Ti-6.5Al-5.1V alloy has no anisotropy of mechanical properties. After hot rolling the same material becomes anisotropic. Therefore, it has been suggested that the flow stress anisotropy during superplastic deformation is the result of the presence of texture in the α-phase. This paper is devoted to investigation of superplastic behavior of Ti-6Al-4V alloy sheet having cold rolling texture in the α-phase and random distribution of equiaxed grains of α- and β-phases.

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Experimental details

The material in as-received condition was a cold rolled sheet of Ti-6Al-4V alloy with a thickness of 1 mm. Its composition (wt%) was: 6.38Al; 4.26V; 0.15Fe; 0.072Si, 0.006H and the balance titanium. Superplastic deformation was carried out in air using Instron tensile machine at a constant cross-head velocity. The range of initial true strain rates was 8.3×10^{-5}–8.3×10^{-2} s^{-1}. The samples were heated up to 900 °C with subsequent annealing during 5 min; then they were cooled with furnace up to 850 °C and annealed for 10 min before mechanical testing. The constant temperature of 850 °C was maintained with accuracy of 5° over a 100 mm length of a triple-zone furnace. This temperature is in the region of β-phase stability. It is shown by Cope and Ridley [14] that the excessive grain growth reducing superplasticity in Ti-6Al-4V alloy occurs at temperatures higher than 880 °C. Specimens with gauge section of 40 mm × 9 mm × 1 mm were cut from the sheet in different directions: in the RD, in the transverse direction (TD) and at 45° with respect to the rolling direction (RD–TD). Before gripping the gage of specimens were covered by the layer of glass powder EVT-24 to reduce the oxidation and alpha casing. This glass coating works in the melting state within the temperature range of about 850–1050°C. The 0002 pole figures for the α-phase were measured using CuK_α radiation. To avoid any effect of alpha case, the direct pole figures were measured from the mid-layer of the sheet. The inverse pole figures were measured and built using methods of Harris [15] and Morris [16] for the three different directions of straining. The data were obtained by reflecting X-rays from the surfaces exposed by sectioning stacks of the sheet. The average Schmid's factors for three slip system were calculated on the basis of the inverse pole figures. The mean linear intercept length for the α- and β- grains was assessed in the rolling and TDs in the mid-layer of the sheet.

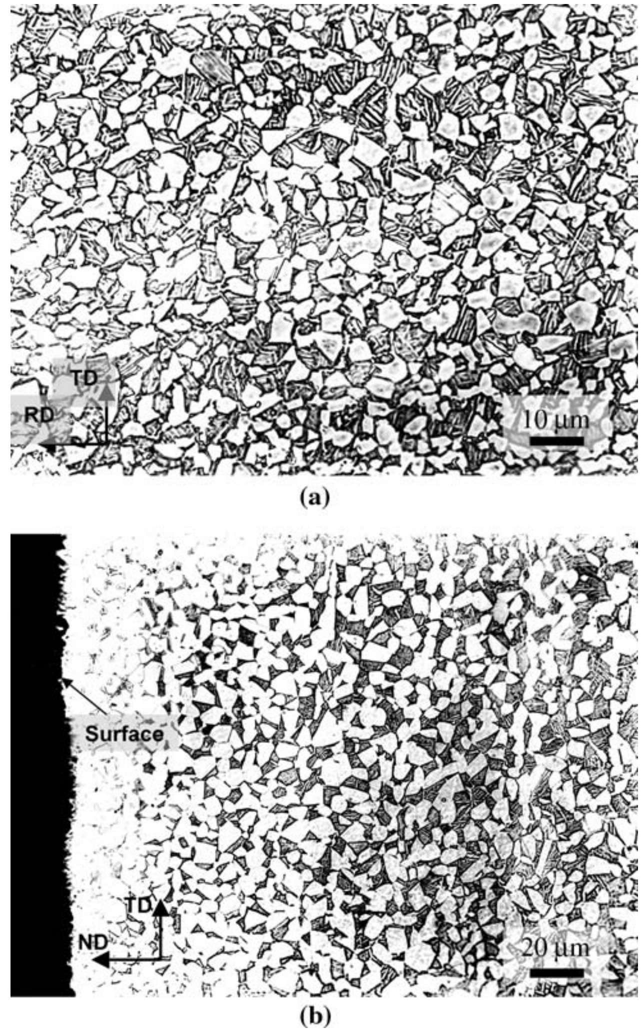

Fig. 1 Microstructure of Ti-6Al-4V sheet after heating at 900 °C during (**a**) 5 min and (**b**) 160 min, cooling in air. (**a**) Rolling plane and (**b**) ND–TD plane

Results

Figure 1 shows initial microstructure in the sheet plane (Fig. 1a) and sheet cross section after heating at 900 °C during 5 min and 160 min, respectively with subsequent cooling in air. It is clearly seen that the structure consists of randomly distributed equiaxed fine grains of the α- and β-phases. Mean linear intercept grain size of the α-phase in the rolling plane is 2.35 µm, and the β-phase –1.35 µm. The dimensions of grains in the RD and TD are the following: for the α-phase, d^{α}_{RD} = 2.40 µm and d^{α}_{TD} = 2.31 µm; for the β-phase, d^{β}_{RD} = 1.40 µm and d^{β}_{TD} = 1.29 µm. As shown in Fig. 1b, after 160 min annealing the layer of alpha case was less than 50 µm.

The effect of initial strain rate on flow stress at 850°C for the three directions is shown in Fig. 2. In the range of strain rates of 4.2×10^{-5}–8.3×10^{-3} s^{-1}, marked flow stress anisotropy was observed: $\sigma_{RD} > \sigma_{RD-TD} > \sigma_{TD}$. With increasing strain rate from 4.2×10^{-3} to 8.3×10^{-2} s^{-1} the difference in flow stress decreases significantly. Figure 3 shows the strain rate sensitivity coefficient, m, for different directions. The maximums of these curves ($m > 0.5$) correspond approximately to the strain-rate of 10^{-3} s^{-1}.

As-received material is characterized by a strong texture in the α-phase having two basal poles tilted at ~20–30° about the RD (Fig. 4a) which is typical for cold rolled titanium. Texture changes in the α-phase at the rate of deformation of 4.2×10^{-4} s^{-1} are shown in Fig. 4(b–d). For all straining directions, the intensity of texture is reduced significantly, whereas the texture type remains unchanged. It is worth noting that in the TD the reduction of the intensity is lesser than in the other directions. The inverse pole figures for the as-received state illustrate a high density of the (1010) and (0001) poles parallel to the RD and TD, respectively (Fig. 5). The average Schmid's factors for different directions of deformation are shown in Table 1. It is

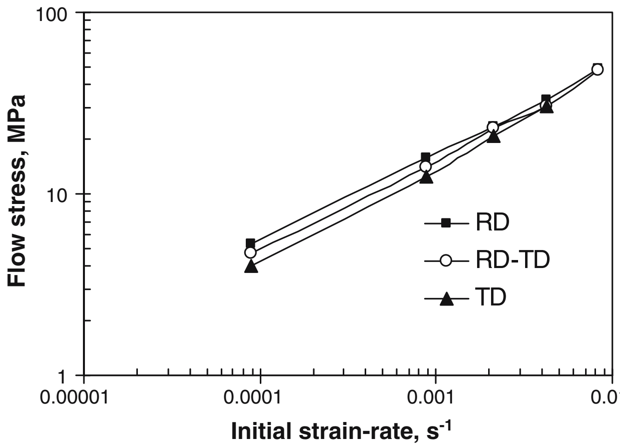

Fig. 2 The effect of straining direction on flow stress versus initial strain-rate curve at 850 °C

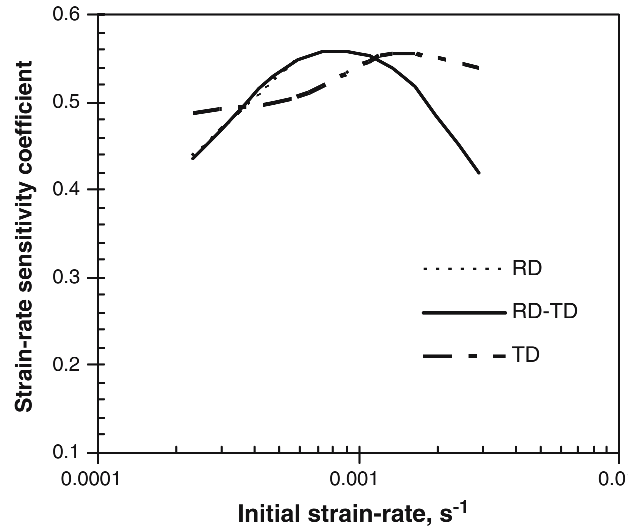

Fig. 3 Strain rate sensitivity coefficient as a function of strain-rate

seen that for prismatic and pyramidal slip the maximum values are reached in the RD whereas for basal slip—in the TD; the intermediate values for all slip systems are obtained in the RD–TD.

Discussion

The results show that Ti-6Al-4V alloy sheet having fine grained microstructure manifests superplastic behavior at 850 °C ($m > 0.5$). It is seen that alpha case layer is really thin due to the effective protection of the surface by the glass coating (Fig. 1b). Therefore, the anisotropy of flow stress observed in the optimum superplastic region and at low strain rates can be related to the two-phase ($\alpha + \beta$) duplex microstructure. Although the stress anisotropy in Ti-6Al-4V has been established in previous investigations [6–12] it is difficult to compare those results with ours due to the differences in microstructure and texture. One of the reasons of anisotropic behavior of titanium alloys can be banded and aligned microstructure [7–13]. This explanation, however, cannot be used in our case due to the absence of such microstructure. In contrast to materials investigated in [7–13], the original microstructure of our alloy contains almost equiaxed and randomly distributed grains of the α- and β-phase. A thorough measurement of grain size revealed a slight elongation of grains in the RD of the annealed material, which was, however, within the accuracy of measurements. Although one assumes that such elongated grains result in the anisotropy of flow stress, a different character of the anisotropy can be expected. It has been demonstrated [17] that the effect of elongated grains on the anisotropy of flow stress can be isolated in the case of Zn-22wt%Al alloy. Normally, this alloy with equiaxed grains does not show a noticeable anisotropy of flow stress during superplastic deformation despite a strong crystallographic texture [5]. However, the same alloy manifests marked anisotropy of flow stress in the case of the elongated grains; the minimum value of flow stress is observed for the specimens cut at 45° with respect to the RD [17]. It is well-known that at usual plastic deformation the main reason for the anisotropy of mechanical properties of many polycrystalline materials (including Ti-6Al-4V alloy [6, 7]) is the presence of crystallographic texture. Such explanation can be also extended to superplastic deformation due to significant contribution of intragranular slip (IS) to total strain (see, e.g., [18]). Actually, crystallographic slip should change positions of texture peaks [18]. However, in this investigation the positions of the 0002 texture poles do not change; only their intensity decrease (Fig. 4). The absence of relationship between average Schmid's factors for prismatic (and pyramidal) slip (Table 1) and the anisotropy of flow stress is an additional evidence for inactivity of IS in the α-phase. Although some correlation between Schmid's factor for basal slip and the character of the stress anisotropy is observed, it cannot be considered as a proof for operation of basal slip. The critical resolved shear stress for basal slip in Ti-6Al-4V alloy is expected to be always higher than that for the prismatic slip. Therefore, it is difficult to expect that basal slip can operate in the absence of prismatic slip. In the case of the β-phase, a large changes in the positions of texture peaks and their intensities have been observed by Bowen et al. [11] for superplastic

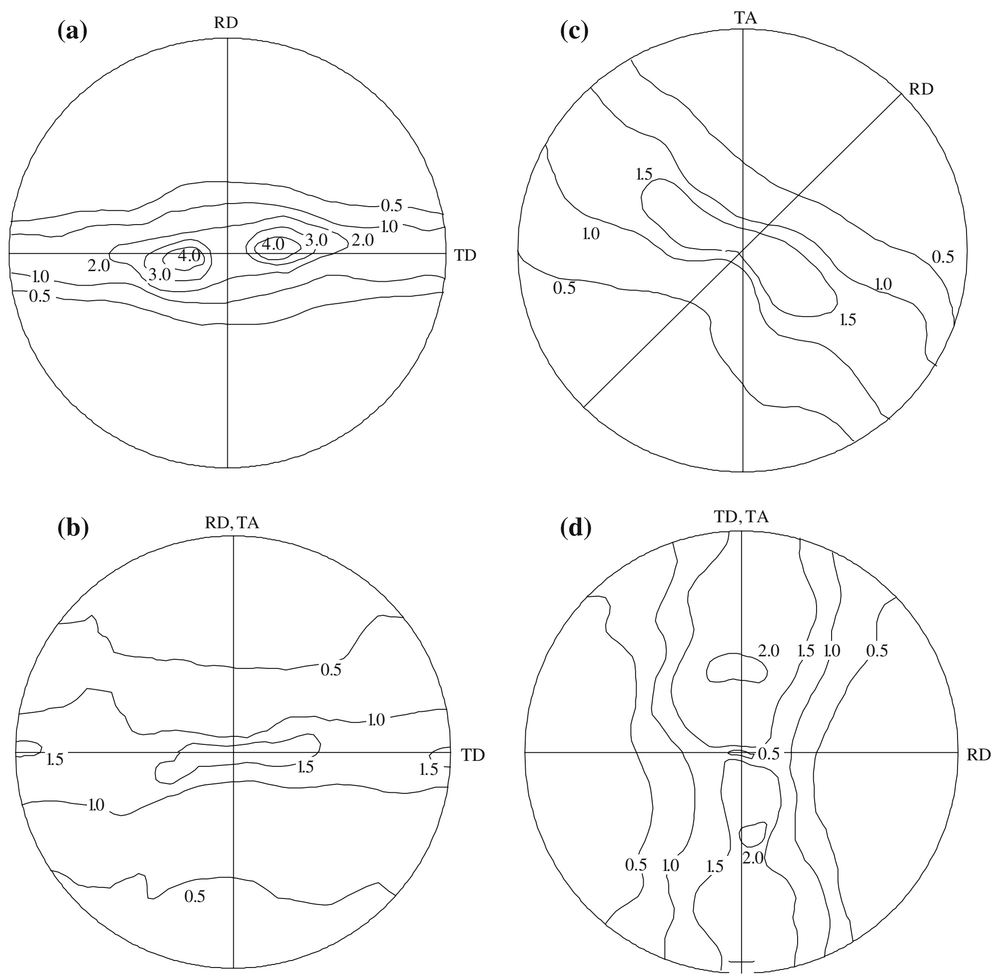

Fig. 4 Effect of 200% superplastic strain on 0002 pole figures for Ti-6Al-4V sheet. (**a**) As-received, (**b**) deformation in RD, (**c**) RD–TD, (**d**) TD; $\dot{\varepsilon} = 4.2 \times 10^{-4}$ s^{-1}, 850 °C

deformation. Actually, regarding phase concentration in superplastic ($\alpha + \beta$)-titanium alloys, the two phases are notably different in their high-temperature deformation-related characteristics. The α-phase has a fewer slip systems than the β-phase, and self-diffusivity in the α-phase is about two orders of magnitude slower. Both of these features would suggest that α is the harder phase and β is the softer one at temperatures of superplasticity. Leader et al. [19] showed the evidence for plastic deformation in the β-phase with little or no deformation in the α-phase at 900 °C. As shown by Salischev and Lutfullin [20] the decrease in flow stress with increasing temperature is more pronounced in ($\alpha + \beta$)-region than in α-region. It is reasonable to suppose, therefore, that the observed anisotropy of flow stress during superplastic deformation is related to the presence of texture in the β-phase. For cubic lattice materials the magnitude of anisotropic effects should be smaller in comparison with materials having lower symmetry. These effects, however, can be still significant. The flow stress anisotropy during superplasticity has been reported to occur in some cubic lattice alloys [2–4] such as copper–bronze [2] and aluminum based alloys [3, 4] for which the anisotropy of texture changes has been also observed. Matsuki and coworkers [4] have demonstrated a relationship between anisotropic behavior of aluminum alloy sheet and Schmid's factors. Unfortunately, measurements of texture in the β-phase of Ti-6Al-4V is a challenging problem: only ~10% β-phase is presented at room temperature [11]. In this paper, we consider the possible influence of β-phase texture on the flow stress anisotropy without information on the Schmid's factors. Our observations indicate that texture peaks in the α-phase weaken without

Table 1 Average Schmid's factors for different slip systems in α-phase and different directions of deformation

	Prismatic slip	Basal slip	Pyramidal slip
RD	0.38	0.22	0.41
RD–TD	0.34	0.29	0.4
TD	0.29	0.3	0.37

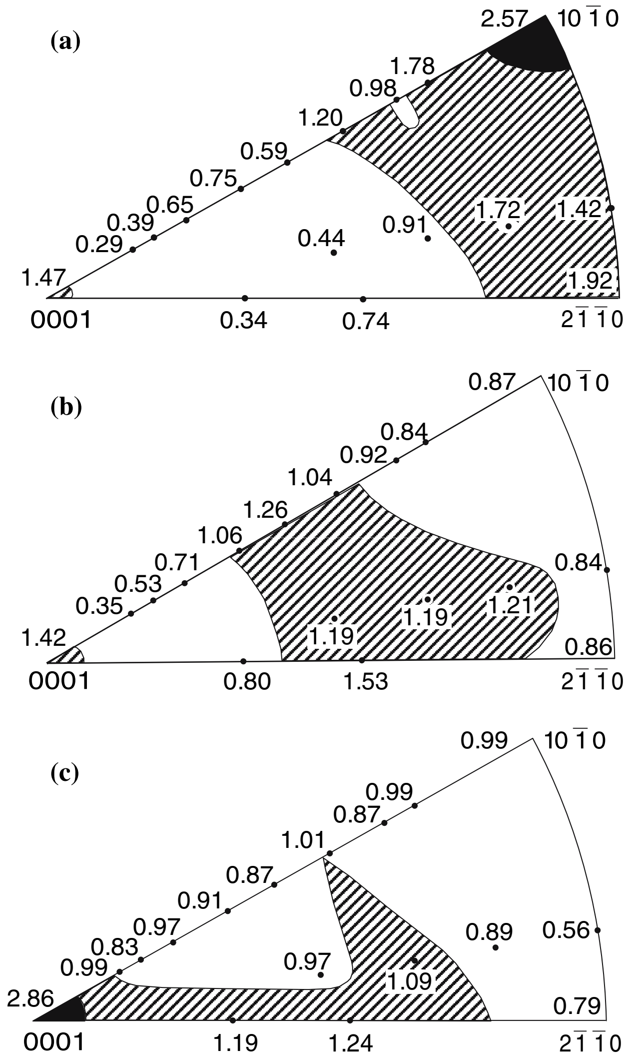

Fig. 5 Inverse pole figures for three directions of deformation: (**a**) RD, (**b**) RD–TD and (**c**) TD

changing their positions. For different straining directions the degree of texture reduction is different. Texture weakening during superplastic deformation is related to non-crystallographic grain rotations. The resistance to grain boundary sliding (GBS) depends on boundary atomistic structure and topology. Consequently, the rate of sliding along different boundaries of the same grain can be different and the grain rotates. In the case of Ti-6Al-4V there is a big difference in sliding resistance between interphase and grain boundaries [21]. Thus, the angle of grain rotation should be related to the value of GBS. It means that with increasing the contribution of sliding to total strain, the intensity of texture decreases. After deformation in the TD the intensity of texture remains higher than that for the other directions. These results suggest that the magnitude of GBS is lower in the TD. In this direction, orientations of grains of the β-phase appears to be more favorable for IS in comparison with the rest directions. Assume that GBS and IS are independent and concurrent processes [22, 23], i.e., $\varepsilon = \varepsilon_{\mathrm{GBS}} + \varepsilon_{\mathrm{IS}}$, and GBS is slower than IS. Consequently, at a constant cross-head velocity the increase in contribution of IS to total strain, γ_{IS}, should reduce the contribution of GBS, γ_{GBS}, according to the formula $\gamma_{\mathrm{GBS}} = 1 - \gamma_{\mathrm{IS}}$. It has been established [21] that the sliding resistance of different boundaries in Ti-6Al-4V increases in the order of $\alpha/\beta \ll \alpha/\alpha \approx \beta/\beta$. Therefore, in the optimal region of superplasticity, GBS along α/β-boundaries and IS in the β-phase are concurrent processes which make the highest contributions to total strain. The presence of texture in the β-phase appears to be the reason for the anisotropy of contributions of GBS and IS to total strain, and, hence, results in the flow-stress anisotropy during superplastic deformation.

Summary

The flow stress anisotropy during superplastic deformation has been observed in Ti-6Al-4V alloy sheet. The sheet contains randomly distributed grains of the α- and β-phases. In the rolling plane, the grains of both phases are found to be almost equiaxed. The anisotropy of reduction of crystallographic texture in the α-phase has been established. However, no evidence found that texture in the α-phase is the reason for anisotropic behavior of the alloy during superplastic deformation. It is suggested that texture in the β-phase is responsible for the flow-stress anisotropy.

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