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Unique texture transition during sub β-transus annealing of warm-rolled Ti-6Al-4V alloy: Role of orientation dependent spheroidization

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ABSTRACT

We report here, interrelation between orientation dependent spheroidization [1] and bulk texture evolution during static annealing of warm-rolled Ti-6Al-4V alloy. Weakening of basal fibre (ND$\parallel\langle 0001\rangle$) and complementary strengthening of prism fibre (RD$\parallel\langle 10\bar{1}0\rangle$) occur on annealing, which is unique and contrary to previous reports. Texture transition is conjugated with two counteracting processes, both being α-colony orientation dependent: spheroidization of α_p-phase increasing spread of the fibres, and variant selection during $\alpha_p \rightarrow \beta \rightarrow \alpha_s$ transformation strengthening **only** the prism fibre. Basal fibre weakens from orientation dependent spheroidization on annealing, while prism fibre intensity is maintained or increased from α_s-variant selection depending on annealing durations.

Conversion from lamellar to equiaxed morphology for the α-phase in a β-transformed Ti-6Al-4V alloy is accomplished by sub β-transus secondary thermo-mechanical processing (TMP) [2–5]. TMP most often comprises warm-rolling, followed by static annealing, both below the β-transus, and inducts spheroidization of α-lamellae. Equiaxed microstructure is required for final shaping by superplastic forming [6–8], and favours superior strength and ductility combination for fracture critical applications [9]. Room temperature microstructure after TMP contains starting α-phase that either remains stable (lamellar) or spheroidize (equiaxed) at high temperature (primary, α_p-phase), and transformed α-phase derived from high temperature β-phase on cooling, forming lamellar morphology (secondary, α_s-phase) [10]. Equilibrium β-phase (~6 vol%) is retained as thin layer between α_s-lamellae, thus producing (α_s + β)-colonies within transformed β-regions.

Spheroidization response of α-colonies in (α + β)-rolled microstructure differ markedly during subsequent (α + β)-static annealing; certain α-colonies spheroidize almost immediately, while certain others retain lamellar morphology for prolonged durations [11–15]. Recently, we have shed light, for the first time, on this difference in spheroidization response of α-colonies from an orientation perspective [1]. We have divided the α-colonies from starting warm-rolled microstructure into six orientation types depending on their c-axis alignment with respect to the principal straining directions, which translates to different slip system activation during prior-rolling. Spheroidization response then becomes different for individual α-colony, because various spheroidization mechanisms (boundary splitting and thermal grooving, termination migration etc.) are sensitive to dislocation generation and boundary formation. These six orientations types are explained in Table 1, along with corresponding slip system activation on prior-rolling and their spheroidization response on subsequent annealing. Objective of the present study is to evaluate the interrelation between this micro-scale ***orientation dependent spheroidization*** and bulk α-phase texture evolution on static annealing.

Basis for this quest is the discrepancy reported previously about α-phase texture evolution after static annealing as a function of TMP schedule. A close proximity exists, in most cases, between prior-rolling and (α + β)-annealing textures, when prior-rolling and annealing temperatures were close [3]. On the contrary, warm-rolling at low temperature, followed by static annealing close to the β-transus led to the formation of additional texture components [16], and/or significant modification in the prior-rolling texture [15,17]. Exact mechanism of this modification in warm-rolling texture on high temperature annealing was, however, not well-explained, neither by Bowen [16], nor by Zheng and Bieler [17]. Roy et al. [15] also have reported modification in prior warm-rolling texture on higher temperature static annealing, and hinted that perhaps, orientation dependent spheroidization is responsible, but could not adequately coupled the two per se. Need is thus felt for an in-depth apprehension on this ***apriori-obvious*** correlation between orientation dependant spheroidization and bulk α-phase texture evolution on static annealing of Ti-6Al-4V alloy. For this part, bulk texture is measured at different annealing durations, and a

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Table 1
Orientations of α-colonies with respect to the prior-rolling specimen (orthotropic) symmetry, corresponding slip system activation during prior-rolling, their spheroidization response and role in texture evolution upon static annealing.

Type	Orientation		Slip activation	Spheroidization response		Contribution to texture fibre
	c-axis, ⟨0001⟩	$\langle 10\bar{1}0\rangle/\langle 11\bar{2}0\rangle$		*Boundary splitting and thermal grooving*	*Termination migration or cylinderization*	
I	‖TD	‖ND/RD	No basal ⟨a⟩ slip, only prism ⟨a⟩ slip	No stable boundary formation; almost always resistant	Sluggish due to inter-lamellar α/β boundaries even up to long term annealing	Prism fibre
II-a	‖ND	TD‖$\langle 10\bar{1}0\rangle$, RD‖$\langle 11\bar{2}0\rangle$	No basal ⟨a⟩ slip, prism ⟨a⟩ slip in tension, pyramidal ⟨c + a⟩ slip in compression	Rapid	Not much effective	Basal fibre
II-b	‖ND	TD‖$\langle 11\bar{2}0\rangle$, RD‖$\langle 10\bar{1}0\rangle$	No basal ⟨a⟩ slip, prism ⟨a⟩ slip in tension, pyramidal ⟨c + a⟩ slip	Limited up to longer duration	Effective under long term annealing	Both basal and prism fibre
III	‖RD	‖ND/TD	Neither basal nor prism ⟨a⟩ slip	No boundary formation; Limited β-phase penetration through micro-shear bands	Extremely sluggish	Not applicable
IV	Aligned within 45° to the straining directions (ND/RD)	Aligned beyond 45° to the straining directions (ND/RD)	Basal ⟨a⟩ slip; restricted prism ⟨a⟩ slip due to plain strain constraint	Sluggish initially, effective at longer durations	Not much effective	Both basal and prism fibre (only when c-axis is close to ND)
V	Aligned within 45° to TD	Aligned within 45° to the straining directions (ND/RD)	Multiple (both basal and prism) ⟨a⟩ slip	Rapid	Not much effective	Prism fibre

annealing time-resolved, micro-mechanistic, phenomenological model for texture evolution is developed.

Cast Ti-6Al-4V alloy, having β-transus 1040 ± 10 °C [18,19], was warm-rolled at 700 °C up to 90% thickness reduction, and isothermally annealed at 900 °C for 15, 30, 45, 60, 75 and 90 min under constant argon gas flow. Specimens were directly kept at the heat treatment temperature to avoid any possible microstructural changes during heating. Detailed microstructures of the prior-rolled and annealed specimens are presented in Refs. [1, 14, 15]. Bulk α-phase textures for prior-rolled and (α + β)-annealed specimens were measured by X-ray texture goniometer using CuK_α radiation from rolling direction (RD)–transverse direction (TD) plane at half-thickness level. From six experimental pole-figures viz. (0001), $(10\bar{1}1)$, $(10\bar{1}2)$, $(11\bar{2}0)$, $(10\bar{1}3)$ and $(20\bar{2}1)$, orientation distribution functions (ODFs) were determined using Arbitrarily Defined Cells (ADC) algorithm by imposing orthotropic specimen symmetry. Micro-texture of 60 min annealed specimen was characterized by Electron back-scatter diffraction (EBSD) from electro-polished RD-ND (normal direction) plane. Orientation data were processed considering 2° minimum boundary misorientation. Separation between α_p and α_s-phases in EBSD data are created using image quality criteria [20]. For EBSD and X-ray texture, crystal coordinate system was chosen such that X = $\langle 2\bar{1}\bar{1}0\rangle$ (Miller-Bravais indices), Y = $\langle 0\bar{1}10\rangle$, and Z = ⟨0001⟩ [1].

Bulk texture of starting warm-rolled alloy (Fig. 1a), and that after static (α + β)-annealing for various durations (Fig. 1b–e) is represented by two dimensional φ_2 ODF-sections with 5° interval. Rolling and/or annealing texture for hexagonal metals (e.g. Ti or Zr) has traditionally been described by two texture fibres, rather than discrete components in the Euler space, viz. basal fibre (ND‖⟨0001⟩) along φ_1-direction and prism fibre (RD‖$\langle 10\bar{1}0\rangle$) along Φ-direction, [21]. Definition of basal or prism fibre is, however, not strictly limited to φ_1 = 0–90°, Φ = 0° or φ_1 = 0°, Φ = 0–90°, respectively, since they generally show larger spread, and often broadened up to 30° in Φ- and φ_1-directions [22,23]. Warm-rolled alloy here likewise represents basal and prism texture fibres in φ_2 ODF-sections (Fig. 1a), with comparatively higher volume fraction recorded for the basal fibre (Table 2).

For low annealing durations (15 and 30 min), no significant changes occur to prior-rolling texture on annealing, hence results are not presented. After 45 min of annealing, basal fibre from warm-rolling texture is somewhat preserved (Fig. 1b), although with reduced volume fraction (Table 2). Basal fibre significantly weakens (volume fraction reduces) after 60 min of annealing, compared to prior-rolling condition (Fig. 1c, Table 2), and nearly vanishes after 75 and 90 min of annealing in the φ_1 ODF-sections (Fig. 1d–e).

Prism fibre shows complementary variation to basal fibre volume fraction with annealing durations; it is preserved up to 45 min of annealing, with similar volume fraction to that present after prior-rolling, but significantly strengthens in Φ-direction (volume fraction increases) after 60 min of annealing (Fig. 1b–c, Table 2). Strength (volume fraction) of prism fibre remains nearly constant up to 75 min; afterwards continuous disappearance of basal fibre leaves only prism fibre present in φ_2 the ODF-section on 90 min of annealing (Fig. 1d–e, Table 2).

Volume fraction ratio, V_{Basal}/V_{Prism} of these two texture fibres (Table 2) depicts this texture transition from prior-rolling ($V_{Basal} \approx V_{Prism}$) on static annealing ($V_{Basal} \ll V_{Prism}$) vividly. This ratio is high (0.79) after warm-rolling, indicating that the basal fibre is comparatively stronger because of 90% thickness reduction [14]. The ratio decreases continuously on static annealing for 45 min (0.53), 60 min (0.33), 75 min (0.23) and 90 min (0.17). Average spreads for basal and prism fibres range within ~20–30° after warm-rolling in Φ- and φ_1-directions, respectively, which is also maintained on annealing for 45 min. As the basal fibre continually vanishes, spread for the prism fibre increases in φ_1-direction up to ~40° on annealing for 60–90 min.

A closer observation of the relevant ODF sections (φ_2 = 0° and 30°) reveal that not the entire prism fibre, rather certain particular orientations with large spreads, are strengthening on continuous annealing. These texture components are calculated to the nearest lowest possible indices assuming a spread of 5° in the Euler space (Table 3). It appears that the prism fibre having two components, $(11\bar{2}2)[1\bar{1}00]$ and $(11\bar{2}3)[1\bar{1}00]$, after prior-rolling, changes to a single component $(11\bar{2}4)[1\bar{1}00]$ on static annealing for 45 min and 60 min. Afterwards, this annealing prism fibre component slightly rotates to another closely spaced component $(11\bar{2}5)[1\bar{1}00]$. The variation in normalized f(g)-intensity (f(g)-Absolute/f(g)-Maximum) of these components also suggests that static annealing initially strengthens $(11\bar{2}4)[1\bar{1}00]$ and $(11\bar{2}5)[1\bar{1}00]$ components in the prism fibre up to 75 min while removes $(11\bar{2}2)[1\bar{1}00]$ and $(11\bar{2}3)[1\bar{1}00]$ components from prior-rolling condition (Fig. 1f). Longer annealing for 90 min, however, increases the spread of all these prism fibre components and reduces their strength in the Euler space.

With reference to Fig. 2a **and** Table 1, in the microstructural level, different α-colonies whose spheroidization response differs as per