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THERMOMECHANICAL PROCESSING OF NEAR BETA TITANIUM ALLOYS

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Abstract: Near beta titanium alloys are promising materials for structural applications due to their high specific strength, good hardenability and fatigue resistance. The high performance of these alloys mainly depends on the type of microstructure, which can be engineered through thermomechanical processing. Based on the assumption that the beta stabilising elements affect the phase transformation and plastic deformation, this work aims to describe the deformation behaviour and subsequent microstructural changes by thermal activation in titanium alloys with different Mo equivalent. Hot compression tests of selected near beta titanium alloys (Ti-55531, Ti17 and Ti-xMo) were carried out in the beta and alpha+beta fields over a wide range of temperature, strain, and strain rate. The characterisation of the microstructural features after hot deformation was carried out by scanning electron microscopy images and electron backscatter diffraction measurements. This contributes to the analysis of the effect of deformation on the dynamic recovery followed by continuous dynamic recrystallisation in the beta field, and on the globularisation of the alpha phase in the alpha+beta field. The development and improvement of microstructure-based mesoscale models for near beta titanium alloys describe the behaviour of the material under plastic deformation, restoration, and phase transformation.

Keywords: Titanium alloys, hot deformation, metallography, modelling, restoration mechanisms

1. INTRODUCTION

The evolution of engineering materials is giving us opportunities for innovation in the mechanical design and the substitution of conventional materials in different application fields. Titanium alloys are highly attractive

materials for various applications, including aerospace, process engineering, automotive, medical, and sports industries, due to their high specific strength, stiffness, good corrosion, and creep resistance [1,2]. The use of β and near β titanium alloys has become increasingly common for structural components, particularly in aerospace and biomedical applications. These alloys (metastable β , and β -rich alloys) by high ductility due to their body-

centered cubic structure, superior fatigue resistance, and a wide range of strength-to-weight ratios. Near β alloys also exhibit relatively good workability due to their lower beta-transus temperature (T_β) compared to typical $\alpha + \beta$ alloys.

Thermomechanical processing is essential for these materials, as it enables the production of near-net shapes and the optimization of mechanical properties through microstructure control. The microstructural evolution of titanium alloys during processing depends on the deformation window. Parameters such as the initial microstructure, deformation temperature, soaking time before deformation, strain rate, and total strain influence both the material's flow behavior and the morphology of the phases present. Subsequent annealing and ageing treatments can further improve toughness [1,3]

The hot deformation of near β alloys titanium alloys has been widely studied. The restoration mechanisms that occur during deformation are influenced by temperature, strain rate, and phase volume fraction,[3] as well as by the distribution of the α phase and the stacking fault energy of both phases. In titanium alloys, dynamic recovery of the beta phase is the dominant mechanism during deformation near the T_β , as shown for different alloys through metallographic observations [4,5] and flow stress analysis [6]. As in other high-stacking-fault-energy materials, such as α -iron[7] and aluminum alloys,[8] continuous dynamic recrystallization (cDRX)[8] and geometric dynamic recrystallization (gDRX) are expected to occur at large strains.[9]. cDRX involves the progressive and continuous development of misorientation within low-angle grain boundaries (LAGBs) through lattice rotation, transforming them into high-angle grain boundaries (HAGBs), while gDRX takes place at low strain rates and large strains. This mechanism occurs by the pinching off of prior β HAGBs, forming new grains that are similar in size to the subgrains. The identification of this mechanism can be challenging and the use of in-situ water quenching immediately after the

deformation can help to suppress static recrystallization (SRX) or avoid a misinterpretation of the microstructure [10].

Accurate microstructural characterization and a clear understanding of the active mechanisms and kinetics during deformation are essential for developing robust models to predict microstructure evolution during industrial processing.

This work summarizes the authors' findings on the hot deformation behavior of near- β titanium alloys and the resulting microstructures. Further details can be found in references [11-18].

2. METHODOLOGY

This work comprises the study of different near β alloys, as described in the Table 1. The alloys present different beta-transus temperature (T_β).

Table 1. Studied alloys by thermomechanical process.

Alloy	T_β
Ti-10V-2Fe-3Al	810 °C
Ti-5Al-5Mo-5V-3Cr-1Zr	803 °C [11]
Ti-5Al-5Mo-5V-3Cr	850°C [16]
Ti-17	865°C [15]
Ti-15 Mo	730°C [18]
Ti-18 Mo	712 °C

Hot compression tests were carried out using a Gleeble®3800 servo hydraulic system machine (Figure 1) at constant strain rates up to 10 s^{-1} at temperatures in the range of $T_\beta \pm 100^\circ\text{C}$, and true strain up to 0.7. The specimens were heated to the compression temperature at a heating rate of 5K/s and were held at the deformation temperature to reach the equilibrium of α phase below the T_β , and a full β transformation into the β field above T_β . Immediately after hot compression, the samples were in-situ water-quenched to room temperature, keeping the microstructure for further microscopic analyses. All the

experiments were carried out in an Argon atmosphere to prevent oxidation and formation of alpha case of the specimens.

For metallographic observations, samples were hot mounted in PolyFast (Struers) resin, followed by sequential grinding with SiC papers and final polishing using a 5:1 mixture of colloidal silica (OP-S, Struers) and hydrogen peroxide.

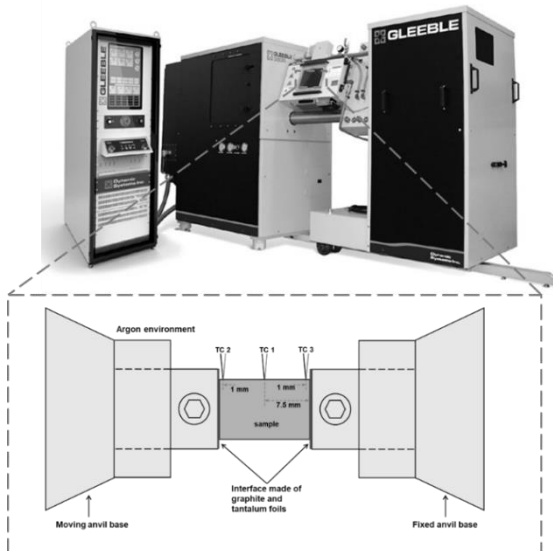


Figure 1. Testing machine Gleeble® 3800 and a scheme of the sample positioned for compression tests.

Electron backscatter diffraction (EBSD) measurements and scanning electron microscopy (SEM) images were used to characterise the microstructure of the deformed samples in the β phase and $\alpha+\beta$ phase regions, respectively. A TESCAN Mira3 field emission gun scanning electron microscope (FEG-SEM) equipped with an EDAX-Ametek Hikari EBSD camera and APEX V2.5.1001 software was used for the measurements. EBSD measurements were conducted with different step sizes depending on the initial beta grain size.

3. RESULTS AND DISCUSSION

3.1 Flow behaviour

The flow stress is strongly influenced by both temperature and strain rate. In the β region, deformation behavior varies with chemical composition. Alloys such as Ti-10-2-3

and Ti-5-5-5-3-1 exhibit an initial sharp peak—indicative of discontinuous yielding—followed by a steady-state regime, whereas Ti-xMo alloys show strain hardening before reaching steady state (Figure 2). Ti-17 alloys predominantly display steady-state behavior. In the $\alpha + \beta$ region, deformation typically results in flow softening as strain increases. The rate of softening is affected by the strain rate and the initial morphology of the α phase. For example, in Ti-17 with an initial lamellar microstructure, increased strain rates lead to more pronounced softening, as shown in Figure 3 [15].

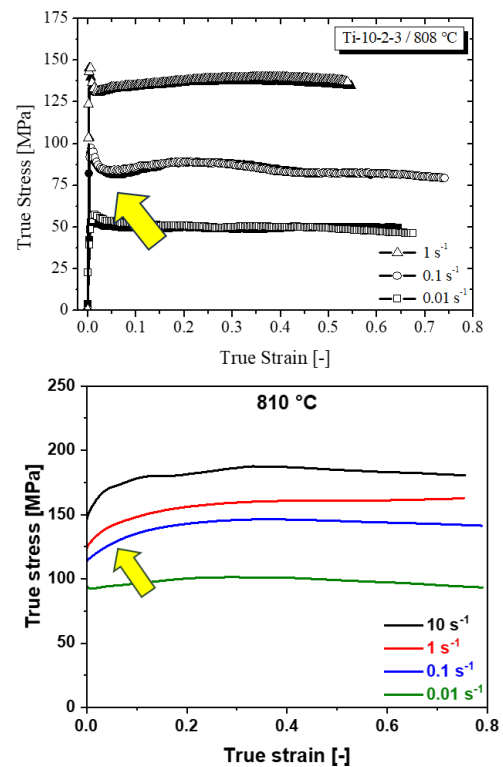


Figure 2. Example of flow curves of Ti-10-2-3 (above) and Ti-15Mo [18] (below) in the β -phase region at various strain rates. Arrows indicate the discontinuous yielding and the strain hardening.

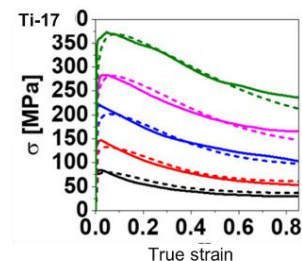


Figure 3. Example of flow curves of Ti-17 in the $\alpha+\beta$ -phase region at various strain rates [15].

3.2 Deformation in the β region

Figures 4 and 5 show an example of the microstructure of Ti-18Mo deformed in the β region. During deformation of near- β alloys, changes in the misorientation are observed alongside the development of substructures. Dynamic recovery (DRV) is the dominant restoration mechanism, but its activity varies among grains due to differences in initial crystallographic orientations, leading to heterogeneous subgrain formation. In addition to DRV, fine new grains form via continuous (cDRX) and geometric dynamic recrystallization (gDRX), particularly near prior grain boundaries in all the studied materials.

With increasing temperature at a constant strain rate, subgrain size increases, as illustrated in Figure 4. At higher strain rates, deformation bands appear, and both the fraction of DRV and the subgrain size decrease (Figure 5) [18]. Quantification of DRV and DRX in Ti-xMo alloys shows that both fractions decrease with increasing strain rate and decreasing temperature. Only very small amounts of DRX were observed—up to approximately 2% at the highest temperature and lowest strain rate for Ti-15Mo [18]

3.3 Deformation in the $\alpha+\beta$ region

The final microstructure obtained during deformation in the $\alpha+\beta$ region is influenced by both the initial microstructure and the strain rate, as illustrated in Figures 6 and 7 for Ti-10Al-2Fe-3Al and Ti-15Mo, respectively.

For partially fragmented starting microstructures (Figure 6), deformation primarily causes rotation of the α grains perpendicular to the applied load. As strain increases, the elongated α grains begin to fragment and gradually transform into a globularized microstructure. At higher strain rates, the α grains become thinner and the volume fraction of globular α grains decreases.

When the initial microstructure is lamellar (Figure 7), the transition toward a globular morphology proceeds through several stages [15], including diffusion-controlled processes, kinking, and fragmentation of the α lamellae. This mechanism is more evident at low strain rates and higher α -phase fractions. Near the T_β temperature, globularization of the α phase occurs more rapidly and additionally promotes continuous dynamic recrystallization (cDRX) at higher strains.

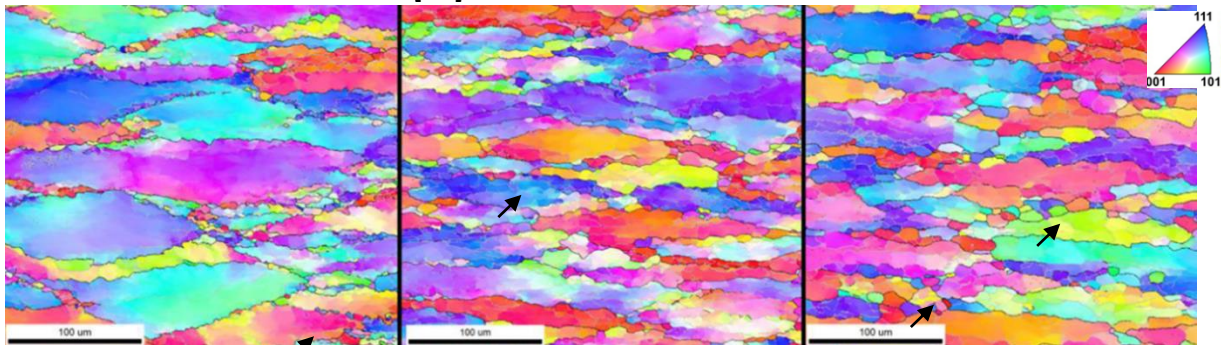


Figure 4. Example of deformation of Ti 18Mo alloy in the β field. EBSD measurements (IPF Maps) of samples deformed at 0.01s^{-1} and 0.7 of true strain at 810°C (left), 860°C (center) and 910°C (right). Black arrows show the formation of new grains. Deformation axis is vertical.

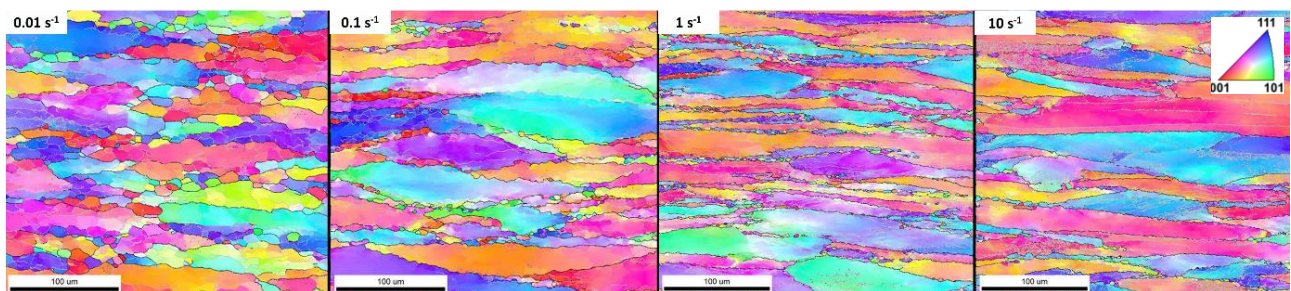


Figure 5. Example of deformation of Ti 18Mo alloy in the β field. EBSD measurements (IPF Maps) of samples deformed at 910°C at different strain rates. Deformation axis is vertical.

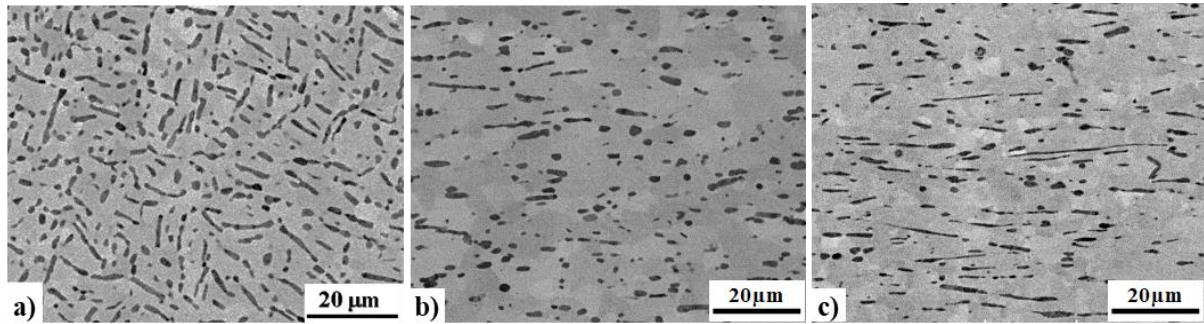


Figure 6. Example of deformation at 768°C of a partial globularized initial microstructure in Ti-10V-2Fe-3Al alloy: a) Initial microstructure without deformation, b) Deformed at 0.01s⁻¹ and 0.7 true strain, and c) Deformed at 1s⁻¹ and 0.7 true strain. Deformation axis is vertical.

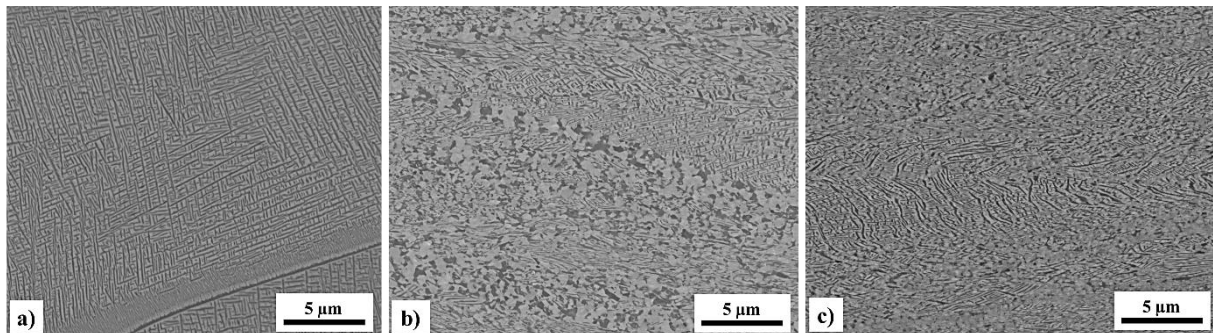


Figure 7. Example of deformation at 610°C of a fine lamellae initial microstructure in Ti-15Mo alloy: a) Initial microstructure without deformation, b) Deformed at 0.01s⁻¹ and 0.7 true strain, and c) Deformed at 1s⁻¹ and 0.7 true strain. Deformation axis is vertical.

3.4 Strategy for modelling and simulation of the microstructure

Physically based models are developed for predicting the microstructure evolution and the flow stress of near beta titanium alloys. The models are able to predict microstructural features such as grain size, subgrain size, boundary misorientation and dislocation densities evolution during deformation. For that, the models require a broad array of parameters that fall generally into three categories: initial microstructure inputs, fixed material constants (often derived from literature), and fitted parameters that govern the kinetics of the various deformation and restoration mechanisms (DRV, CDRX, globularization, etc.). SEM and EBSD analyses are typically used to quantify and provide the initial microstructural inputs. Constitutive equations are commonly applied to fit the flow stress as a function of processing parameters such as temperature, strain, and strain rate (see Figures 2 and 3). Examples of model predictions

and experimental validation can be found in the works of Miller et al. and Buzolin et al. for the titanium alloys Ti-5-5-5-3 and Ti-17 [14–17], as well as for the $\alpha+\beta$ alloy Ti-6Al-4V [19].

4. CONCLUSION

Thermomechanical processes can be simulated and characterized by combining Gleeble testing machine—which provides flow stresses and a frozen microstructure—with scanning electron microscopy equipped with an EBSD detector. EBSD analysis is particularly valuable for identifying the dominant restoration mechanisms and quantifying subgrain size, grain size, and the fractions of recovered and recrystallized microstructures.

In this work, we summarized results for near- β titanium alloys. The main conclusions are as follows:

- Temperature and strain rate significantly influence the heterogeneity of the microstructure during deformation.

- During deformation in the β region, the flow stress depends on temperature, strain rate, and the content of β -stabilizing elements. Alloying elements can lead to either discontinuous yielding or strain hardening before the steady-state regime is reached. Dynamic recovery (DRV) is the primary restoration mechanism, followed by continuous dynamic recrystallization (cDRX) and geometric dynamic recrystallization (gDRX).

- In the $\alpha + \beta$ region, deformation generally leads to flow softening, with the softening rate affected by strain rate and the initial α -phase morphology. Dynamic globularization is observed in initial lamellae microstructure.

- Modelling and simulation are essential for optimizing thermomechanical processing of titanium alloys to achieve tailored microstructures and mechanical properties.

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