Understanding the β-phase texture development in Ti-6Al-4V during compression in the α+β regimes

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Abstract

The β-phase texture development during α+β compression of Ti-6Al-4V was investigated at two temperatures in the α+β regime at strain rates of 0.005, 0.05 and $0.5s^{-1}$. It was found that the β-phase develops a strong {001}<100> (called 001β cube) texture and a weaker {111}<110> fibre (called 111β). The 001β texture is strengthened when increasing strain rates and temperature. The strong 001β is also found in single β-compression, due to recrystallization or high-strain rate sensitivity from literature. However, the strain-rate effect in the α+β regime cannot be explained by the two mechanisms. Simple crystal plasticity simulations were used to compare the disorientation between the undeformed and deformed β orientations in single or two-phase model and then in different relative strength of the α and β phase, which simulates the strain rate effects. There is significantly higher frequency of low-angle disorientation in the simulated samples having 001β cube and α-orientations or with the lower relative strength. Thus, the presence of suitably aligned α-orientations and the decrease in the strength ratio when increasing strain rates help stabilize the 001β orientation under α+β compression. These findings support the development of processing parameters to minimize the 001β texture and its deleterious effect on the strength of components.

1. Introduction

Ti-6Al-4V alloy is used for many airframe and engine parts in aircraft thanks to its good balance of characteristics like strength, ductility, creep characteristics, weldability and formability [1]. Airframe Ti-6Al-4V components are often manufactured by forging in the α+β regime and following by heat treatment in the β-regime [1]. Thermo-mechanical processing leads to significant changes in microstructure and texture of both phases (hcp α-phase and bcc β-phase) which in turn affect overall mechanical properties of products [2].

The bcc β-texture development during compression in the two-phase α+β regime is not well known, although texture development in single-phase bcc metals has been studied extensively. It is reported that a strong 111 fibre develops along the compressive direction, together with a weaker 001 fibre, when compressed at room temperature [3,4]. At high temperatures in the β-regime, a stronger rotated 001β cube develops together with a weaker 111β fibre [5]. Hot forging in large components may lead to changes in temperature and strain rates through their thickness, resulting in the formation of different deformed β-texture via two-phase interaction deformation, recovery, recrystallization or phase transformation. Following a heat treatment in the β-regime, the deformed texture of the β-phase will grow to dominate the high-temperature β-phase texture during phase transformation and β-grain growth [6]. This then affects the texture of the transformed α-phase on cooling and ultimately the overall mechanical strength. For example, on cooling, the 001β cube texture in the high-temperature β-phase will transform to the α-phase texture having few the 'hard' 0002 poles along the three principal directions following the Burgers orientation relationship, causing probably the lower yield stresses when pulling along these directions. The aim of the present paper is to investigate the β-texture development under uniaxial compression in the relatively high α+β phase regime to improve the forging route of Ti-6Al-4V for an appropriate texture and resultant mechanical strengths.

2. Material and experimetal method

The billet of Ti-6Al-4V supplied by Otto-Fuchs was cut directly for dilatometer samples in cylinder with 5mm diameter and 10mm length. The samples were cut in 2 principal directions of X0 and Y0 in the same plane as described in Fig. 1a. The microstructure of the billet contains both primary and secondary α-grains, with the β-phase between α laths at a volume fraction of about 6-8%, as shown in Fig. 1b. The texture is very weak in both the α-phase and the β-phases, as shown by the pole figures in Fig. 1c-d. The texture of the α-phase shows a 0002 fibre along the drawing (tensile) direction Z0 and a $10\bar{1}0$ fibre along Z0. The texture of the β-phase has a 110 fibre along Z0 and 111 fibre along the two compressive directions X0 and Y0. Although the starting billet has a circular cross-section, the β-texture shows orthorhombic sample symmetry, indicative of square section forging at some point during the process.

The Ti-6Al-4V samples were compressed on a dilatometer at two different temperatures in the α+β regime: a high temperature (50-100ºC below the β-transus) and a low temperature (150-200ºC below the β transus), and under strain rates of 0.005, 0.05 and $0.5s^{-1}$. The microstructure and texture of each phase in the compressed samples were then mapped using electron backscatter diffraction (EBSD). The indexed secondary α-phase was used to calculate the high-temperature β-phase texture after compression thanks to the β reconstruction algorithm [7] based on analysis α-variant misorientation with its neighbours and the Burgers relationship. A crystal plasticity finite element model (CPFEM) was used to understand the stability of the β-texture under α+β compression.

3. Results

3.1 Macroscopic stress-strain curves

The stress-strain curves recorded at the two temperatures in the α+β regime both show slight hardening in early stage of plastic deformation followed by softening. The stress-strain curves measured by dilatometer are in good agreement with those performed at Otto Fuchs at the two temperatures, especially in the early stages, Fig 2. This would suggest that the temperature and applied strain rates are well controlled in the compression tests on the dilatometer.

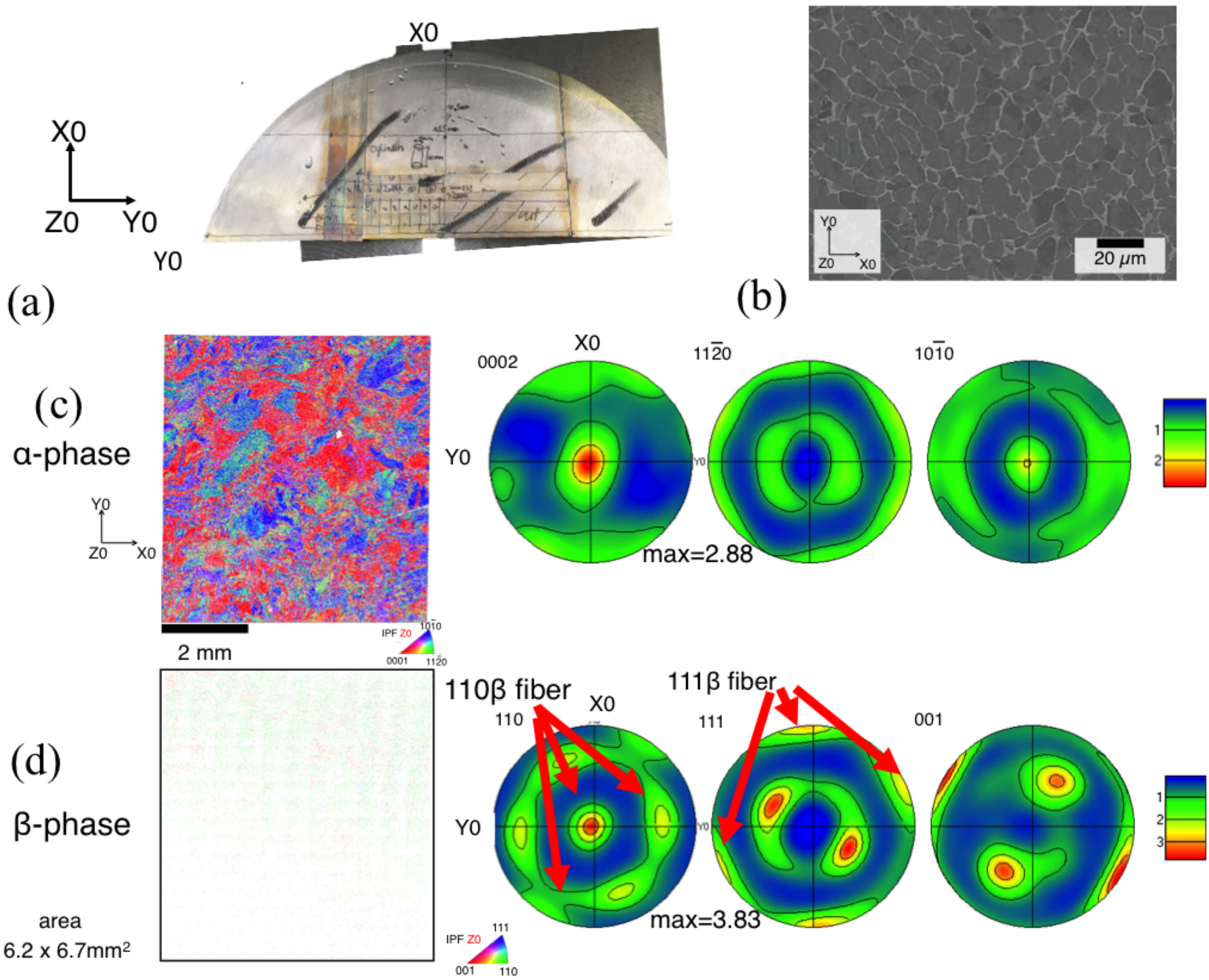


Fig. 1: Ti-6Al-4V in billet condition (a); Backscatter electron image of the billet condition (b); inverse pole figure (IPF) maps and pole figures (PF) of the α and β phase at room temperature (c and d).

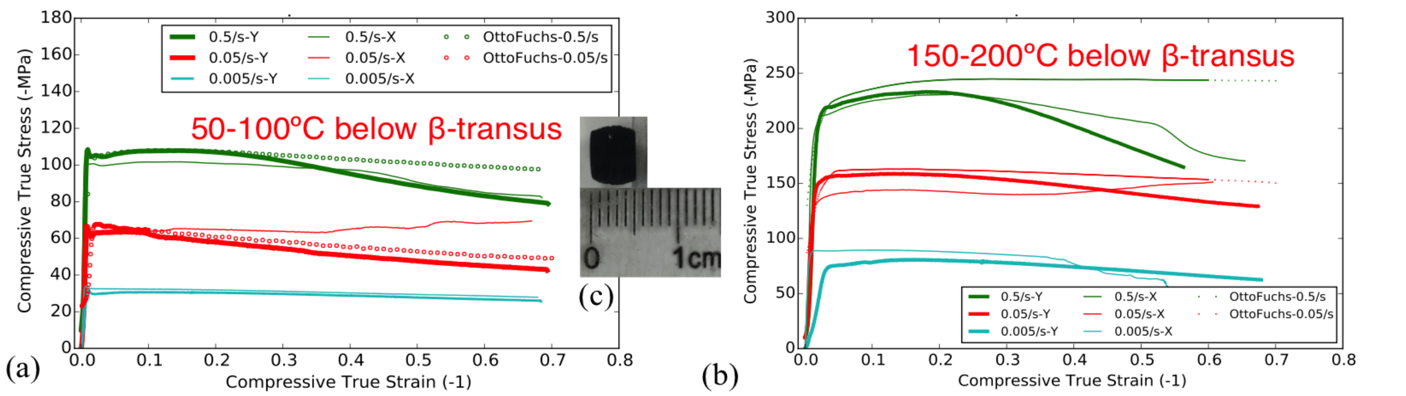


Fig. 2: True stress-strain curves of Ti-6Al-4V under compression at different strain rates at 50-100ºC below the β-transus (a) and 150-200ºC below the β-transus (b). The shape of compressed samples (c) shows less barrelling effect.

3.2. Texture and microstructure of compressed samples at room temperature

After compression, the deformed α-texture is characterised by maxima of the basal poles along the transverse direction, as shown in Fig. 3 and 4. The deformed α-texture is thus in agreement with reports in literature [8]. More importantly, and regardless of the compression direction, there is a strong cube 001-fibre along the loading direction in the β-phase texture as shown from direct EBSD indexing in Fig. 3 and 4 and β reconstruction in Fig. 5.

In the temperature and strain rate range studied, the 001 alignment with the compressive direction strengthens with increasing strain rate and temperature, Fig. 3 and 4. Interestingly, although uniaxial compression should produce a fibre texture, there is a tendency to form a cube texture component, especially at higher strain rates and temperatures.

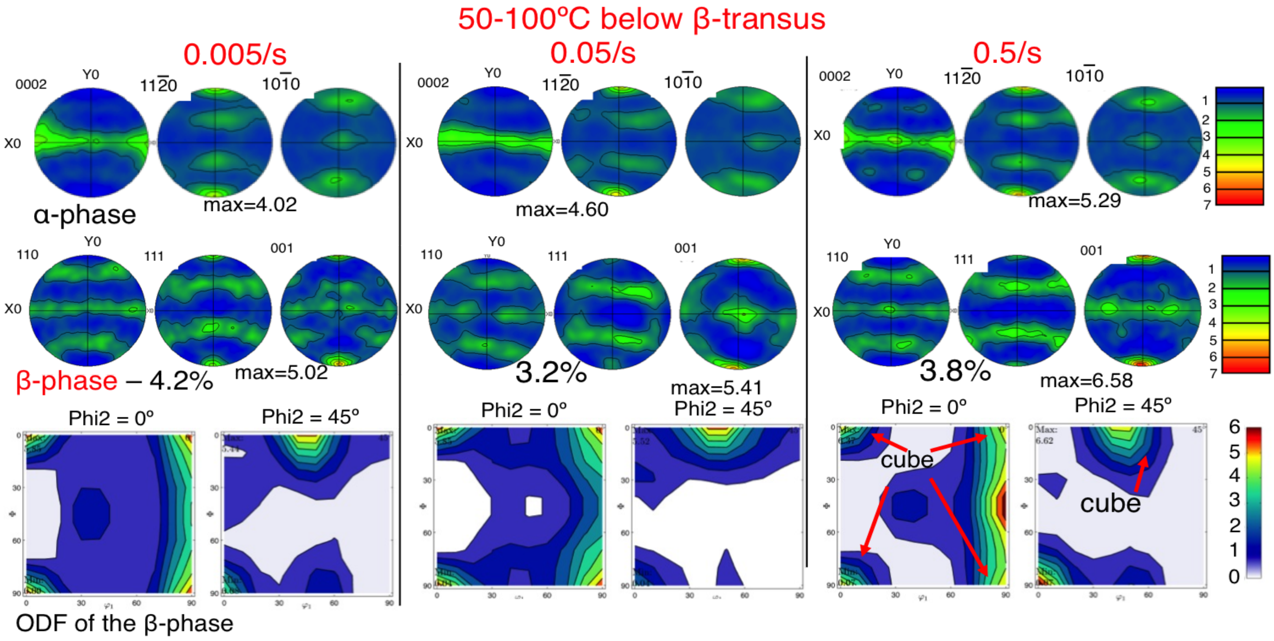


Fig. 3: PF of the α and β phase at room temperature after compressing along Y0 at different strain rates at 50-100ºC below the β-transus. ODF of the β phase shows a strong 001β cube and no 111β fibre.

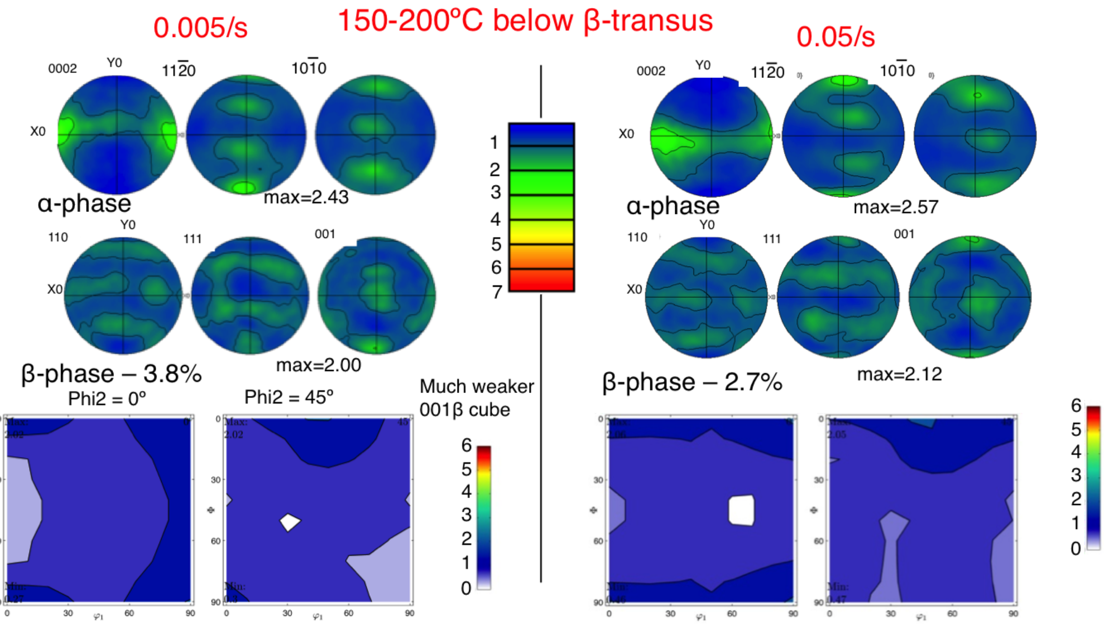
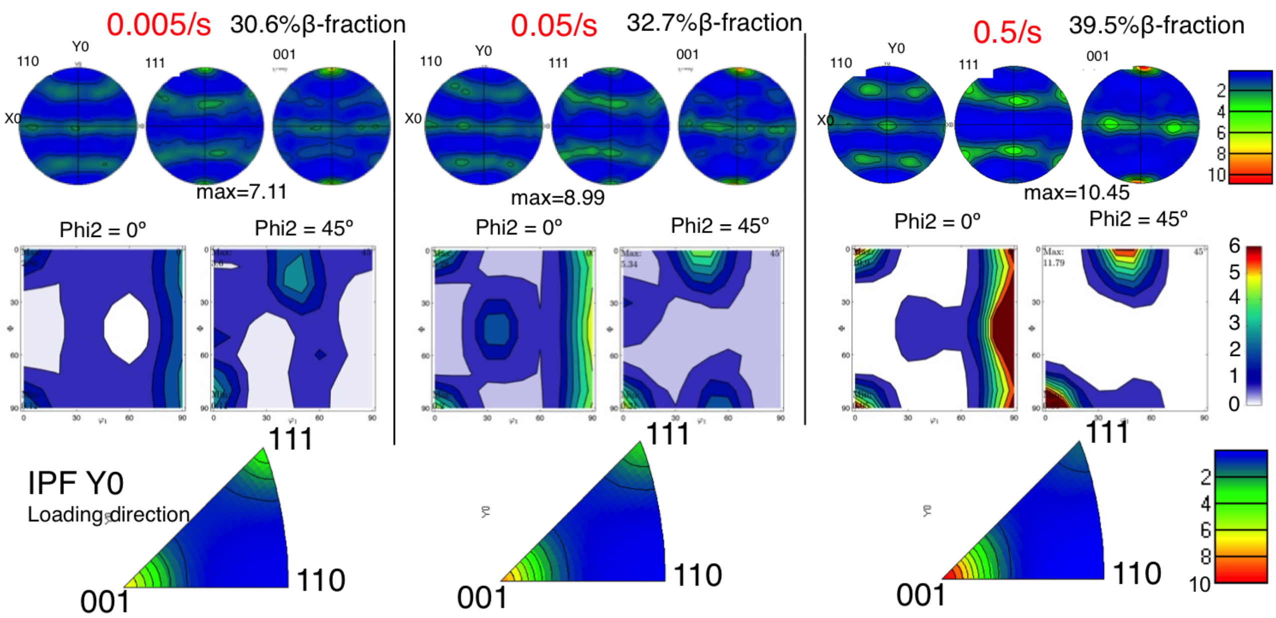


Fig. 4: PF of the α and β phase at room temperature after compressing at different strain rates at 150-200ºC below the β-transus. ODF of the β phase shows a much weaker 001β cube.



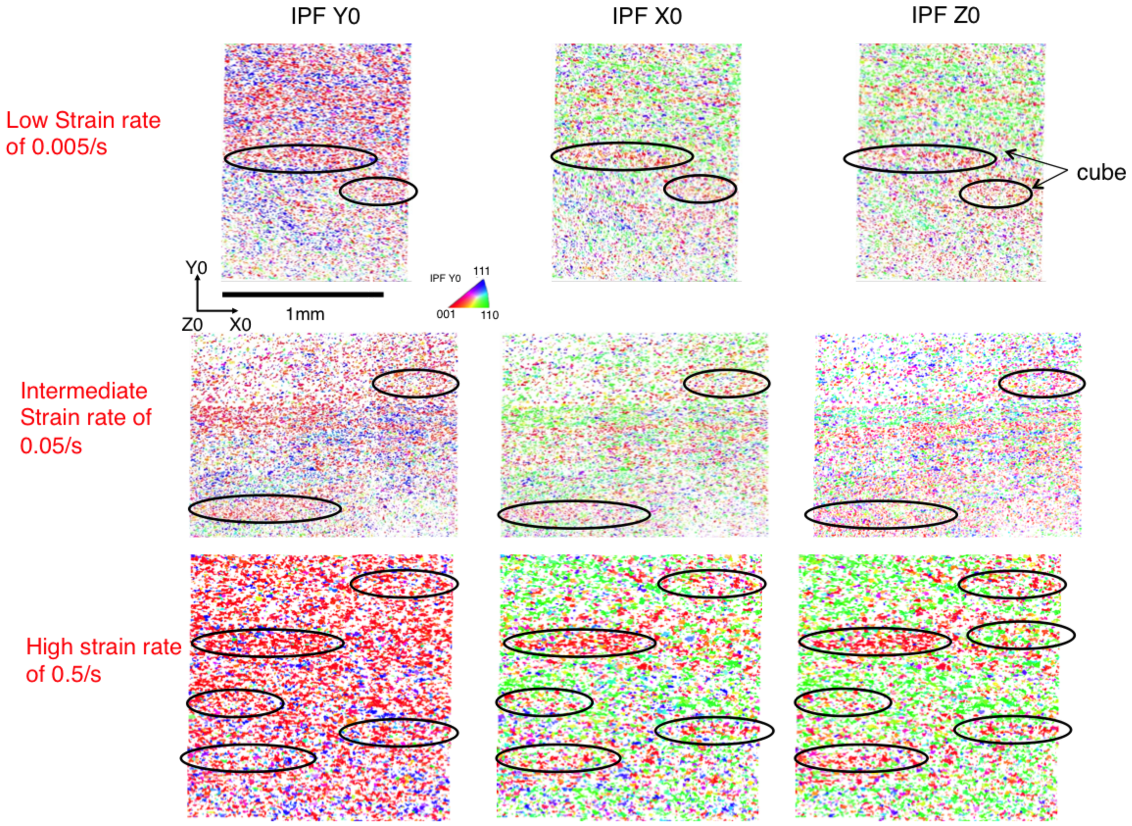


Fig. 5: PF, ODF, IPF and IPF maps along compressive direction of high-temperature reconstructed β-phase after compressing at different strain rates at 150-200ºC below the β-transus.

4. Discussion

We found that uniaxial compressing Ti-6Al-4V at α+β temperatures results in a strong 001β (cube) fibre, the strength of which increases with increasing strain rates and increasing temperature. This is different from the β-texture after compression at low temperatures in single-phase bcc metals, where a strong 111β fibre texture usually develops along the compressive direction [3,4].

Compressing in the α+β regime (shown here) and in a high-temperature β-regime [5,9] develops a stronger 001β cube than the 111β fibre. In addition, the strain rate effect on the strength of the 001β cube is opposite to that when compressing in the α+β and β-regime. In fact, our results show that when compressing in the β-domain (not shown here due to the length constraint) , the 001β (cube) fibre strengthens with decreasing the strain rates, in agreement with the results in [9]. This strong 001β cube texture in β-compression is in part explained by recrystallization [9]. However, even without recrystallization, the strong 001β fibre can also be predicted using a Taylor deformation model with high-strain rate sensitivity and relaxed constraints [5], which is related to the elongated β-grains at very high applied strains.

We also used a crystal plasticity model to predict the β-texture after compression in β-domain with the high strain-rate sensitivity and elongated β-grains. Our simulations show that both these characteristics act to increase the strength of the 001β, however the model still predicts that the 111β texture dominates for the strain-rate sensitivity value of 0.2 to 0.3 as reported in [5]. Thus, it seems that recrystallization could be a reasonable explanation for the 001β strengthening in the β-regime [9] and also in the α+β regime when increasing temperature as shown in the present study (Fig. 3 and 4). However, in the α+β regime, only recrystallization cannot explain the 001β strengthening when increasing strain rates, where less recrystallization would be expected. Therefore, there must be a different mechanism responsible for the strengthening of the 001β cube during α+β deformation. Using CPFE modelling, we investigated the possible effects of α-orientations and the relative strength between the α and β-phase on the stability of the different texture components.

A two-phase crystal plasticity finite element (CPFE) model was used to investigate the role of the α-phase in compressing Ti-6Al-4V in the α+β regime when increasing the strain rates. The simulation study aimed to investigate two issues: the relative orientation of the α and β and the effect of strain rate. Simulations were carried out to investigate the stability of the single 001β 'orientation' {001}<100> in comparison to the single 111β 'orientation' (the γ-fibre of {111}<110> or {111}<112>) under compression in two cases: single β-phase and two-phase α+β models to illustrate the role of suitable α orientations, which helps to stabilize the 001β orientation. The differences between the two-phase models of single 001β 'orientation' and 111β 'orientation' are both the different β-orientation itself and the different relationship between the embedded α-orientations with respect to the two β-orientations despite having the same embedded α-orientations. In other words, by assuming the primary α-orientations at hot-compression temperature is similar to that measured at room temperature in Fig. 1c, the simulation was to investigate the α-orientation effects on the 001β and 111β orientation. The single 001β and 111β orientations in undeformed condition are shown in Fig. 6. A second set of simulations was carried out to help explain the strengthening of the 001β fibre with increasing strain rates, which is captured by reducing the relative strength between the α and β phase.

Only a simple configuration of the single 001β orientation and the single 111β orientation was studied using crystal plasticity modelling [10] instead of the overall β-texture from the billet condition due to computational limitations limitation and the complexity required to capture the exact texture and microstructure of the α and β phase. In the model, each element represents one grain/orientation while the input orientations are distributed randomly. The model is used to show which one of the stable β fibres develops less misorientation between undeformed and deformed conditions, indicating it to be a more stable orientation.

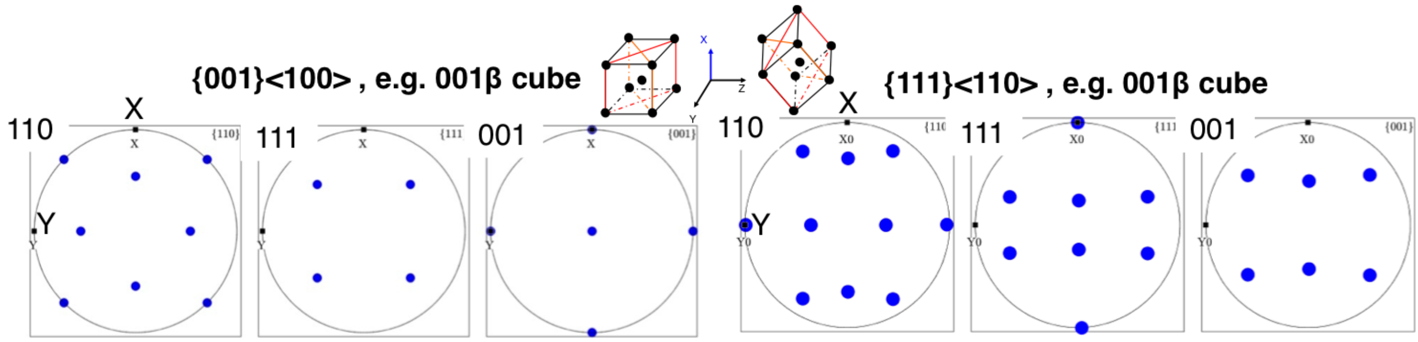


Fig. 6: Input of single β orientations of either (a) {001}<100> or (b) {111}<110> (b) for simulating in single-phase or two-phase model.

Slip Systems	CRSS (MPa) strain rate of 0.005/s	CRSS (MPa) strain rate of 0.05/s	CRSS (MPa) strain rate of 0.5/s
α-phase Prismatic	60	100	100
α-phase Basal	60	100	100
α-phase Pyramidal <c+a>	420	700	700
β-phase {110}<111>, {112}<111>, {123}<111>	6	12.5	33.3
CRSS ratio of α-prismatic and β-slip	10	8	3

Table 1: Calibrated CRSS based on matching experimental and simulated stress-strain curves.

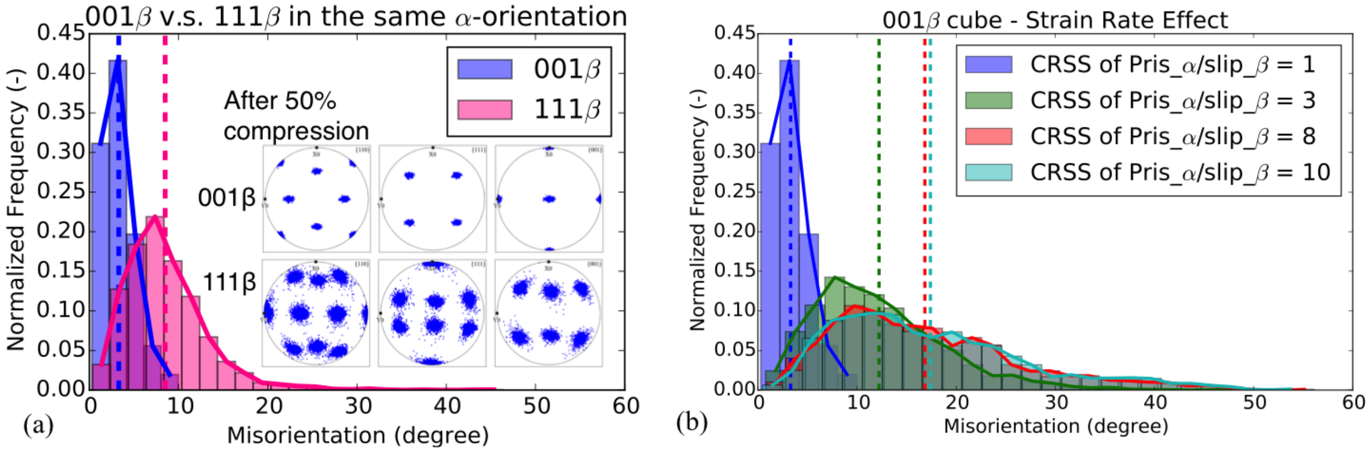


Fig. 7: (a) Quantitative disorientations for the 001β or 111β orientation between before and after compression in the 30% α and 70% β simulation and (b) for the 001β under different strength ratio between the α-and β-phase. The dash lines are the mean disorientations.

4.1. Stability of the {001}<100> and the {111}<110> component

It was found that the disorientation (e.g. the spread of the β-orientation) between the undeformed β-orientations and its deformed ones are different between the two simulations of the single-phase β model and the two-phase α+β model, as shown in Fig. 7a. In the model having only the single β-phase, the disorientation is very low and similar for the two starting β-orientations of {001}<100> and the {111}<110>. However, in the two-phase model, the disorientation of the 001β orientation is lower than that of the 111β-orientation, as quantified in Fig 7a. This suggests the presence of suitably aligned α-orientations can help stabilizing the 001 orientation under α+β compression.

4.2. Strengthening of {001}<100> component with increasing strain rates

The increase in strain rates was represented by a change in the critical resolved shear stress (CRSS) in slip of each phase by matching between the simulated and experimental stress-strain curve up to 10%, as shown in Table 1. The fitting CRSS is based on the assumption that the α-phase is stronger than the β-phase as shown in [11]. It was found that the disorientation between the 001β orientation after compression shows much higher frequency of low-angle misorientation in the simulated samples with the lower strength differential between phases, which corresponds to higher strain rates, Fig. 7b. This suggests the presence of suitably aligned α-orientations and the decrease in the ratio strength of the α and β-phase when increasing strain rates can help stabilize the 001β orientation under compression. It is worth noting that different sets of CRSS ratios from those reported in Table 1 are still possible to produce a good agreement in the macroscopic stress-strain curves. Thus, a further study by in-situ synchrotron X-ray diffraction is needed to verify the assumption on the relative strength of the two phases and the fitting CRSS ratios for different strain rates.

Another explanation of the effects of strain rates on increasing the strength of the 001β cube is due to the possible dynamic phase transformation while compressing at α+β temperature, as shown in [12,13]. The deformed α-phase can transform into the new β-phase having 001 fibre texture. Higher strain rates provide more external driving force for the α-phase to transform to the β-phase. This can be investigated further by in-situ synchrotron x-ray diffraction.

5. Conclusions

When deformed in uniaxial compression in the α+β-regime, the β-phase develops a strong 001β fibre texture and weaker 111β fibre texture. The 001β fibre strength increases with increasing temperature and strain rate. Two-phase crystal plasticity CPFEM confirmed the stability of the single 001β orientations during α+β compression due to the presence of suitable aligned α-orientations and the decrease in the ratio strength of the α and β-phase when increasing strain rates. This new understanding will help develop processing parameters that can minimize the development of the 001 cube in α+β forging and eliminate its deleterious effects on the strength of components.

References

[1] R.R. Boyer, Mater. Sci. Eng. A. 213 (1996) 103–114.

[2] G. Lütjering, J.C. Williams, Titanium, 2nd Editio, Springer, Berlin, 2003.

[3] L. a. I. Kestens, H. Pirgazi, Mater. Sci. Technol. 32 (2016) 1303–1315.

[4] M. Hölscher, D. Raabe, K. Lücke, Steel Res. 62 (1991) 567–575.

[5] N. Gey, M. Humbert, M.J. Philippe, Y. Combres, Mater. Sci. Eng. A. 219 (1996) 80–88.

[6] G.C. Obasi, R.J. Moat, D.G. Leo Prakash, W. Kockelmann, J. Quinta da Fonseca, M. Preuss, Acta Mater. 60 (2012) 7169–7182.

[7] P.S. Davies, Thesis at The University of Sheffield, 2009.

[8] G. Lütjering, Mater. Sci. Eng. A. 243 (1998) 32–45.

[9] K. Li, P. Yang, Metals (Basel). 7 (2017) 412.

[10] P. Bate, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 357 (1999) 1589–1601.

[11] D. Canelo-Yubero, G. Requena, F. Sket, C. Poletti, F. Warchomicka, J. Daniels, et al., Mater. Sci. Eng. A. 657 (2016) 244–258.

[12] B. Guo, S.L. Semiatin, J.J. Jonas, S. Yue, J. Mater. Sci. 53 (2018) 9305–9315.

[13] C. Aranas, B. Guo, S. Rodrigues, J. Choi, S. Kim, B. Sun, et al., Mater. Lett. 220 (2018) 229–233.