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Effect of Processing Parameters on Hot Deformation Behaviour and Microstructural Evolution of PM Ti-5553 Alloy at a Moderate-high Strain Rate

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Isothermal compression tests of Ti-5553 (Ti-5Al-5V-5Mo-3Cr) alloy, produced by a fast consolidation approach from blended elemental powder mixture, were performed on a Gleeble® 3800 thermal-physical simulator to investigate its hot deformation behaviour. The samples were compressed in a wide temperature range from 700 °C to 1150 °C and a moderate-high strain rate of 1 s^{-1}, with the sample deformation degree of 30%, 50% and 70%, respectively. Flow instability occurred when the deformation temperature was less than 900 °C. Dynamic recovery (DRV) accompanied by dynamic recrystallization (DRX) become the dominated mechanisms at the medium temperature range between 900 °C and 1000 °C, while almost only DRV features could be observed at high temperature (1050 °C ~ 1150 °C). Moreover, α phase globalization could be identified in the alloy deformed in (α+β) region. DRV, DRX, α globalization and the transformation of α to β phase were promoted with the increasing deformation degree.

Keywords: *Powder metallurgy, Ti-5553 alloy, Hot deformation behaviour, Microstructural evolution, Deformation mechanism.*

1. Introduction

The alloy of Ti-5553 (Ti-5Al-5V-5Mo-3Cr) has become attractive material extensively for aerospace and marine industry field as it low density, ultra-high strength, good ductility and excellent hardenability [1,2]. The thick forging parts of the alloy have been successfully used in the landing gears and the wings' covering of the Boeing and Airbus aircrafts [3,4]. Although titanium alloys are becoming the ideal choices of the materials for some high-performance applications, the relatively high cost limits their widespread use coming from the melting of the raw material, hot processing and subsequent machining.

Using raw powders to prepare the titanium alloy products instead of conventional melting and casting is proved as a feasible method with the economic benefits. Powder metallurgy (PM) titanium alloys parts can be produced through hot isostatic pressing, vacuum sintering and selective melting with qualified properties and refined microstructures [5,6]. In order to reduce the cost further and shorten the manufacturing period, fast consolidation approaches have been developed by the researchers like power forging and hot pressing [7,8].

Near-beta titanium alloys like Ti-5553 are even more hard to process among the titanium alloys and always need the hot processing for several steps, leading to the significant growth of the producing cost. Moreover, the quality of Ti-5553 alloy products is extremely dependent on the hot working variables which can influence the microstructural evolution significantly [9]. The deformation mechanisms like dynamic recrystallization (DRX) and dynamic recovery (DRV) can refine and homogenize microstructure and they are always regarded as the optimal softening mechanisms. Therefore, it becomes important to study the effect of the hot working parameters on the hot deformation behaviour of the Ti-5553 alloy for the optimization of the microstructures and properties. Some previous researches have been conducted to investigate the effect of the deformation parameters on the behaviour of titanium alloys.

Some previous researches have been conducted to investigate the hot deformation behaviour and the effects of the hot processing parameters on titanium alloys. Warchomicka et al. [10] studied the hot deformation behaviour of Ti-5Al-5Mo-5V-3Cr-1Zr alloy using various deformation parameters. They found β-restoration with elongation and rotation of α grains were obvious in the (α+β) region, DRX processes were mainly observed in the deformation in single β region deformation strain, while DRV was the dominated mechanism at the wide temperature range in both (α+β) and single β regions. Seshacharyulu et al. [11] reported the changing regulation of deformation mechanism with varying deformation parameters of commercial grade Ti-6Al-4V alloy. The material suffered from cracking and adiabatic shear bands at low-temperature deformation lower than 900 °C, phase globalization and lamellae kinking took effects at the intermediate temperature between 900 °C and 1000 °C, and the high-temperature deformation is primarily dominated by DRX. Fan et al. [12] investigated the hot deformation behaviour of Ti-7Mo-3Nb-3Cr-3Al alloy, and revealed the effects of deformation temperature on the flow behaviour and microstructure evolution. The effects of

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deformation parameters on the hot deformation behaviour of Ti-25V-15Cr-0.3Si titanium alloy were reported by Zhu et al. [13] They disclosed that the DRX fraction increased with increasing the deformation temperature.

Whereas, there is still limited works carried out to study the effect of the hot working parameters on the hot deformation behaviour of PM titanium alloys, leading to the insufficient information for the industries to conduct the optimal hot processing of PM titanium alloy. This present work investigated the influence of the deformation parameters including temperature and deformation degree on the hot deformation behaviour of a PM Ti-5553 alloy obtained through fast consolidated techniques at a moderate-high strain rate of 1 s^{-1}, the flow softening and the microstructural evolution during the deformation have been studied and discussed.

2. Experimental Details

The as-consolidated PM Ti-5553 (Ti-4.99Al-4.93V-4.94Mo-2.90Cr-0.05Fe-0.36O) alloy studied in this work is prepared using the raw powders as: hydride-dehydrided (HDH) titanium powder (-200 mesh, purity: 99.6%), Al powder (purity: 99.9%), Al35-V65, Al15-Mo85 and Al30-Cr70 (wt%) master alloy powders (-75μm, commercial purity) supplied by Dalian Rongde Company, PR China. The powder mixture the was warm compressed (400 MPa, 250 °C, in air) into green powder compact (56 mm in diameter and 52 mm in height) after the mixing for 1.5 h at the speed of 60 rpm in a V-shape blender. Afterwards, the green powder compact was heated up rapidly in an induction furnace to 1250 °C ~1300 °C and held for 10 min, followed by uniaxial hot pressing into cylindrical alloy billet (58 mm in diameter and 42 mm high) under 400 MPa pressure and reach the relative density about 98% (The relative density of the alloy was determined by the Archimedes principle, the weight measurement were done in water and air using the standard of ASTM B962). A 100-ton hydraulic press was utilized to perform warm compaction and hot pressing. The rapid heating, hot pressing and cooling processes were operated in a flow argon atmosphere protective chamber had the oxygen content of below 200 ppm to avoid oxidation. The β phase transus temperature is measured as 975 °C according to the metallographic results after heat treatment and quenching. Fig. 1 shows the initial microstructure of the PM Ti-5553 alloy, primary fine β phase matrix with the average grain size of 100 μm, a small number of precipitations (inhomogeneous and agglomerative) and some visible residual pores can be easily identified.

Gleeble® 3800-GTC thermal physical simulator was used to conduct the hot compression tests at the temperature range of 700 °C to 1150 °C at the strain rate of 1 s^{-1}. The cylinder specimens were produced from the alloy billets by wire cut and the following machining to the target size of 10 mm diameter and 15 mm height. The specimens were heated up to the preconcerted temperatures at the rate of 10 °C/s and soak 4 min to ensure the homogeneous temperature distribution in the specimen, after which, the specimens were isothermally compressed to different height reductions in vacuum. After the deformation, the specimens were cooled rapidly in water to retain the deformed microstructure. Graphite foils and Tantalum sheets were used to improve the system conductivity and reduce the friction between the specimens and the die.

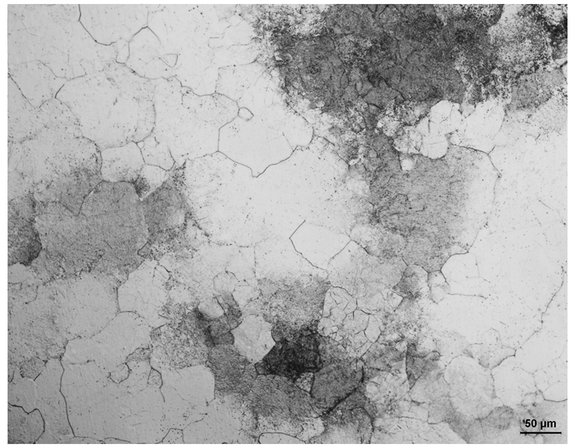

Figure 1. Optical image showing the origin microstructure of as-consolidated PM Ti-5553 alloy

The phase constitutions of the deformed samples were analysed by X-ray diffraction (XRD) with a Bruker D8 Advanced X-ray diffractometer equipped with a Cu Kα radiation source (λ = 0.154157 nm). The microstructure characterizations were performed using optical microscopy (OM, OLYMPUS/PMG3), and scanning electron microscopy (SEM, JSM-6460). The metallographic samples were prepared through grinding, polishing and Kroll's reagent etching (10 ml HF, 20 ml HNO_3 and 70 ml H_2O).

3. Results and Discussion

3.1 True stress-strain curves

Fig. 2 displays some related true stress-strain curves of the PM Ti-5553 alloy deformed at 1 s^{-1} in the temperature range of 700 °C to 1150 °C. It is obvious that all the curves suggest similar trends at the beginning of the deformation with a dramatic increase of the stress to the peak values followed by different flow softening mode to the steady-state stages. For the specimens deformed at the temperatures lower than 800 °C, the constant softening can be seen after the stress peaks, indicating the occurrence of strong flow softening like flow localization and cracking [12-15]. Slight drops after the peak stress and subsequent gradually decreasing of the curves are observed for the condition of 900 °C, 950 °C and 1000 °C, these typical features suggest the flow softening may be controlled by DRX. In terms of the deformation conducted at a high temperature over 1050 °C, the flow stress is kept steady after the peak stress, which means the dominated softening mechanism could be DRV with high possibility. Moreover, it can not be ignored that considerable oscillation of some the curves can be found in some conditions, which can be ascribed to DRX or flow instability and has been observed in some other titanium alloys [12].

Moreover, the flow stress shows a high sensitivity of the deformation temperature, as shown in Fig. 3a. The peak stress is reducing obviously with increasing the temperature, as the deformation becomes easier due to more thermal activation effect and the enhanced diffusion process. In addition, the flow softening values (using the deviation of peak stress and the steady-state stress at the strain of 1.0) also illustrate a constant-reduction trend at the temperature range low than beta transus, while the flow softening keeps at a low and stable stage after the beta transus (Fig. 3b). These means the softening mechanism is different before and after the α→β phase transformation. As it can be realized that it is difficult and to determine the deformation mechanisms only rely on the flow behaviour, so the microstructural evolution characterizations are necessary to be conducted for further discussions.

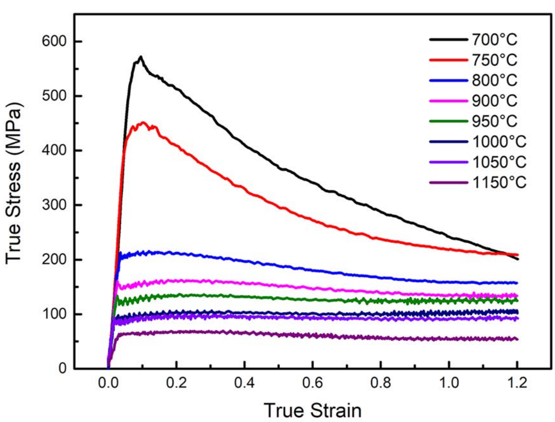

Figure 2. True stress-stain curves of as-consolidated PM Ti-5553 alloy at 1 s^{-1} and various temperatures

3.2 Microstructure evolution at (α+β) region

Fig. 4 displays the optical microstructures and SEM characteristics of deformed PM Ti-5553 alloy subjected to various temperatures and strain at 1 s^{-1} in (α+β) region. As can be identified in Fig. 4a of 700 °C specimen, the microstructure consists with a large amount of α precipitation band β matrix, the grain boundaries are difficult to be observed. Meanwhile, the specimen displays a serious flow localization band with inhomogeneous deformation in a macroscopic view, as seen in Fig. 4b. The microstructure (Fig. 4c) and macroscopic view (Fig. 4d) of 800 °C specimen show the similar characteristics with 700 °C specimen, but less α precipitation bands and slighter flow localization situation. These results indicate that the dominated softening mechanism at 700 °C and 800 °C is flow localization and dynamic α precipitation, and flow localization degree become slighter as increasing the deformation temperature. The flow localization band is generated based on the local temperature rise attribute to the short deformation time and the poor thermal conductivity of titanium alloys [16]. When the temperature increase to the relatively higher value, the degree of the localized flow will reduce as the lower local temperature rise.

When it comes to the deformation of 900 °C and 30% height reduction specimen, the slightly elongated grains with some areas full of α precipitates can be clearly found in Fig. 4e. Whereas, when the deformation degree increase to 70% at 900 °C (Fig. 4f), the grains are obviously elongated along the direction vertical to compression direction with serrate grain boundaries, and the amount and morphology of α precipitates also become less and band-shaped. The phase constitution changes of 900 °C specimens for different deformation degrees can also be confirmed by the XRD tests. As is shown in Fig. 5a and b, the amount and intensity of α peaks of 900 °C/30% specimen are obviously more and higher than 900 °C/70% specimen. It can be deduced from these results that, the deformation is dominated by DRV at 900 °C, and the higher deformation degree can promote DRV, dynamic α precipitation and the α→β phase transformation.

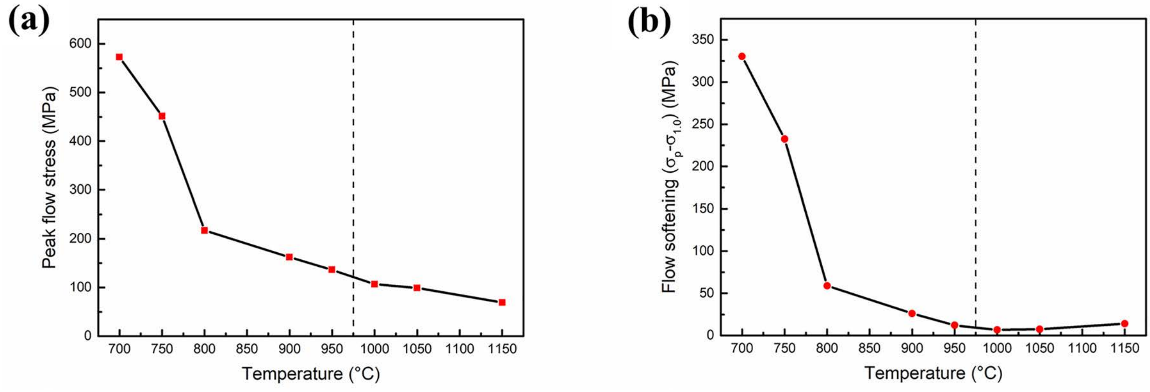

Figure 3. The changing of peak flow stress and flow softening values of as-consolidated PM Ti-5553 alloy with temperature of during hot deformation: (a) peak flow stress; and (b) flow softening (σ_p-$\sigma_{1.0}$) value

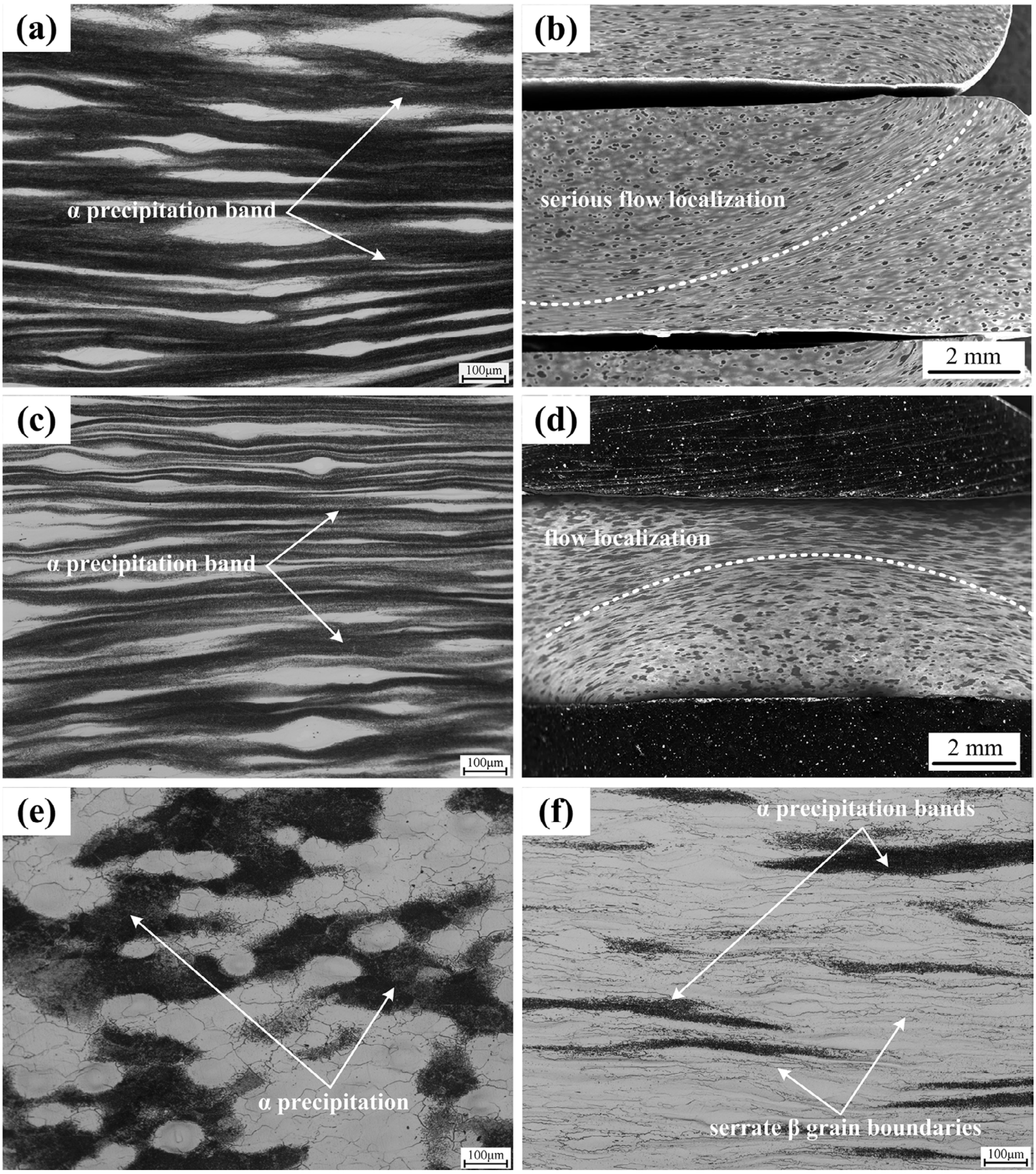

Figure 4. Optical microstructures and SEM characteristics of deformed PM Ti-5553 alloy subjected to various temperatures and deformation strain at 1 s^{-1} in (α+β) region: (a) OM, 700 °C, 70%; (b) SEM, 700 °C, 70%; (c) OM, 800 °C, 70%; (d) SEM, 800 °C, 70%; (e) OM, 900 °C, 30%; and (f) OM, 900 °C, 70%

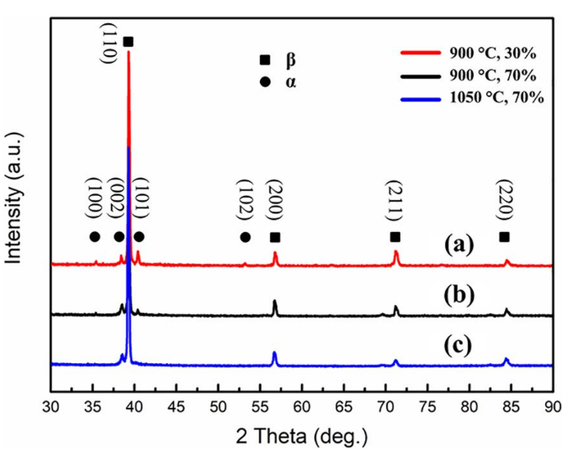

Figure 5. XRD patterns of deformed PM Ti-5553 alloy subjected to various temperatures and deformation degrees at 1 s^{-1}: (a) 900 °C, 30%; (b)900 °C, 70%; and (c) 1050 °C, 70%

3.3 Microstructure evolution near β transus and at β region

Fig. 6 shows the optical microstructures of deformed PM Ti-5553 alloy subjected to various temperatures and strain at 1 s^{-1} from 950 °C to 1100 °C. As can be identified in Fig. 6a of 950 °C specimen, serrate grain boundaries dressed by distinct neck-lace shaped small grains can be easily observed, which reveals the flow softening mechanism is dominated by the combination of DRV and DRX. As the temperature increase to 1000 °C (Fig. 6b), the grain boundaries become more and more irregular and the size of recrystallized uniaxial grains become more and more large, indicating the enhancement of the DRX and DRV processes. When the deformation is processed at 1050 °C (Fig. 6e), fewer DRX grains are found, and the strong DRV process

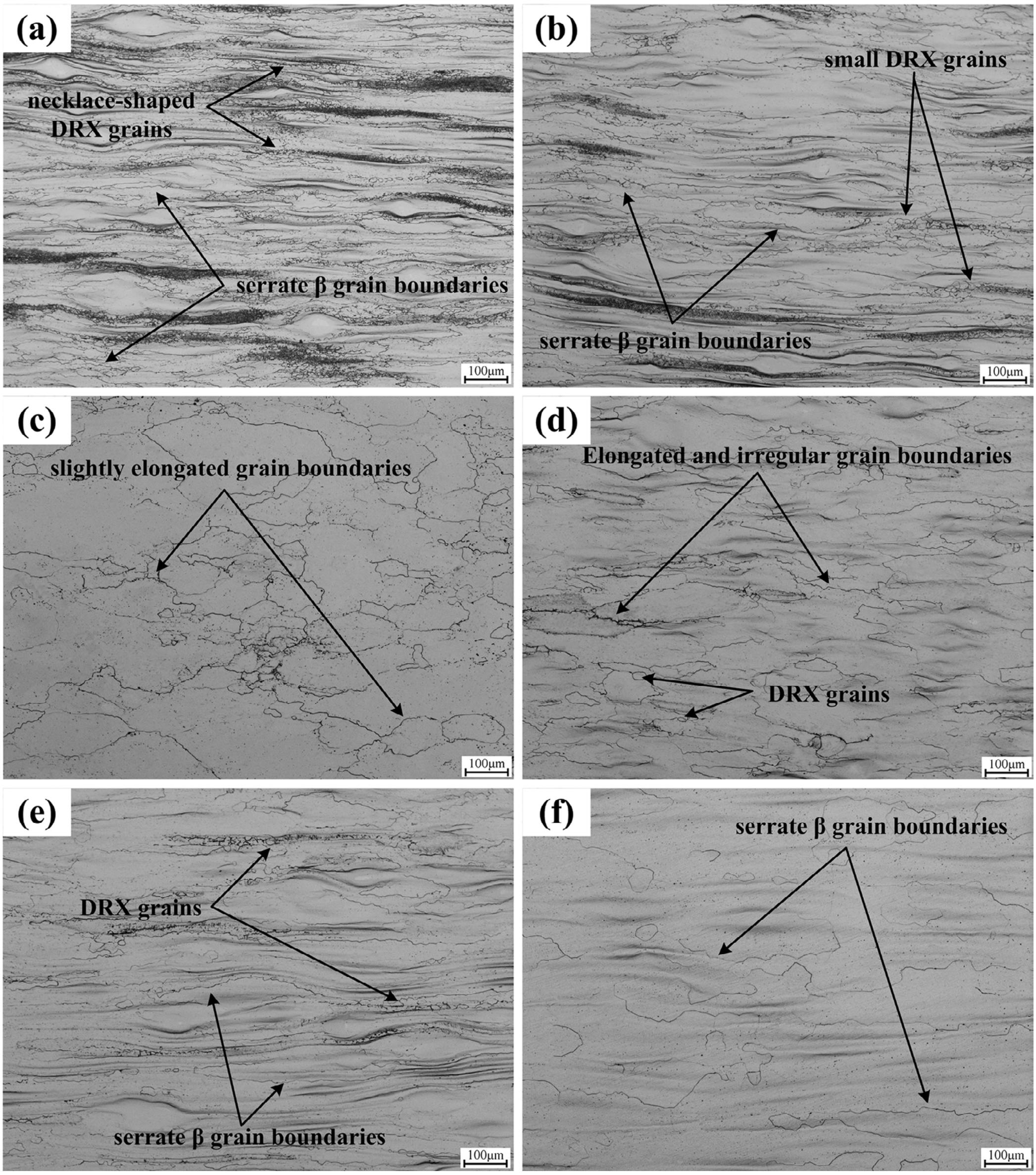

Figure 6. Optical microstructures of deformed PM Ti-5553 alloy subjected to various temperatures and deformation strain at 1 s^{-1} near the β transus and in β region: (a) 950 °C, 70%; (b) 1000 °C, 70%; (c) 1050 °C, 30%; (d) 1050 °C, 50%; (e) 1050 °C, 70%; and (f) 1150 °C, 70%.

is still significant as the coarsening of the serrate grain boundaries. As the deformation temperature further increases to 1150 °C (Fig. 6f), no DRX grains but only the coarsen serrate grain boundary can be identified. Deformation degree also plays a significant role in determining the flow softening mechanisms. Fig. 6c and d show the microstructures of the specimen deformed at 1050 °C for the various deformation degree of 30% and 50%. The grains are slightly elongated and keep straight for 30% height reduction specimen, while the obvious elongated grains with irregular grain boundaries and some small equiaxial DRX grains can be seen for 50% height reduction specimen.

These observation results reveal the DRV process is always remarkable at quite a wide temperature between 900 °C and 1150 °C range and occurrence of DRX process is prominent at the temperature range of 950 °C to 1000 °C at this moderate high strain rate of 1 s^{-1}. DRX is a thermal active process controlled by the elemental diffusion and can be facilitated by the elevated temperature. However, the high stacking fault energy (SFE) of titanium alloys make it easier for the dislocation to climb and gliding, which hinder the proceeding of DRX at high temperature over 1050 °C [12]. Meanwhile, the deformation can encourage DRV and DRX processes as these softening mechanisms are driven by the deformation stored energy and rely on the dislocation movement which can be higher and more active at a high deformation degree.

In terms of the situation of the dynamic α precipitation, as it can be seen in Fig. 6, the amount of α precipitation shows an obvious tendency that it reduces with increasing the temperature, and the precipitate almost disappears at 1050 °C. As shown in Fig. 5c, the XRD pattern of 1050 °C specimen almost shows only β peaks with high intensities, which means most of the α precipitates are dissloved and transformed into β matrix at this condition. These observations indicate that dynamic α precipitation is only prominent during the processing of the PM Ti-5553 in (α+β) region and the region near β transus, attribute to the α→β phase transformation.

4. Conclusions

This work investigated the hot deformation behaviour of the PM Ti-5553 alloy at a moderate-high strain rate of 1 s^{-1} and a wide temperature range from 700 °C to 1150 °C. Flow behaviour and microstructural evolution of during the deformation are studied and characterized clearly. Based on the results, the main conclusions can be obtained as:

1. The flow stress of the PM Ti-5553 alloy decreases with the increasing deformation temperature and flow softening phenomenon is more obvious at low temperature than at high temperature.
2. Flow localization is the dominated softening mechanism in the low-temperature range deformation of 700 °C~800 °C, and the degree of the unstable deformation increases with reducing the temperature.
3. DRX mainly occurs at the temperature range of 950 °C to 1000 °C, while DRV occurs at a wider temperature range from 900 °C to 1150 °C. Higher deformation degree can promote DRX and DRV processes, and obvious DRX and DRV features are observed in the deformation higher than 50% at elevated temperatures.
4. Dynamic α precipitation is prominent during the hot working of the PM Ti-5553 alloy in (α+β) region and the region near β transus, which can also be enhanced by increasing the deformation degree.

5. Acknowledgements

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6. References

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