Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September-October
2006

Dynamic recrystallization in commercially pure titanium

M.J. Tan*, X.J. Zhu
School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore 639798, Singapore
* Corresponding author: E-mail address: mmjtan@ntu.edu.sg

Received 15.03.2006; accepted in revised form 30.04.2006

Materials

ABSTRACT

Purpose: A study was conducted to investigate the dynamic recrystallization of commercially pure Titanium alloy during high temperature deformation in order to understand it further and enable expansion of its usage.
Design/methodology/approach: Uniaxial tensile tests were carried out at 600, 750 and 800°C with different initial strain rates. Microstructure evolution during high temperature tensile testing was studied by using optical microscope and Electron Back Scattered Diffraction.
Findings: It is found that this titanium alloys do not show good superplasticity at 600-800°C due to the rapid grain growth. Studies also show that the dynamic recrystallization took place at high temperatures. This process not only decreases the average grain size of the alloy but also increase the misorientation angle of the grain boundary.
Practical implications: The investigations of dynamic recrystallization of commercially pure titanium alloy as well as related phenomena are important for achieving desired mechanical behavior of the material.
Originality/value: The dynamic recrystallization phenomenon of commercially pure titanium alloy as well as related mechanism is investigated.

Keywords: Superplastic materials; Titanium; Dynamic recrystallization; Electron back scattered diffraction

1. Introduction

Due to its high strength, high strength-to-weight ratio, excellent corrosion resistance and biocompatibility, commercially pure (CP) titanium (Ti) alloy is one of the most important titanium alloys and widely used in many areas such as the chemical, nuclear and especially biomedical industries [1-4]. Superplastic forming (SPF) is a cost-effective process for manufacturing complex shaped structural components [5-12] and SPF of commercially pure titanium alloy is very attractive in many areas due to the inert nature of this alloy. To date, the amount of research and publications concerning the superplasticity of CP alloys are limited [12]. Consequently, only little basic know-how on the superplasticity of CP Ti alloy is available. The investigations of its potential for Superplasticity, mechanisms, related phenomena and microstructure evolution are important for achieving desired mechanical behavior of the material. In the present study, the evolution of the microstructure of the CP titanium alloy during high temperature deformation is studied in order to understand it further and enable expansion of its usage.

2. Experimental

Commercially pure titanium sheets were used in this study. The average grain size of the as-received CP titanium alloy is 12.9µm. Tensile specimens with a gauge of 11mm length, 4mm width and 1.5mm thickness were machined with the tensile axis oriented parallel to the final rolling direction. The specimens were deformed at 600°C, 750°C and 800°C with different initial strain rates. After testing, the deformed specimens were cooled rapidly to room temperature by forced cooling in order to preserve the microstructure. Specimens were sectioned along the gauge and grip parts of the deformed sample. The samples were then polished by silica paste and etched using $10\%HF + 5\%HNO_3 + 85\%H_2O$ for 5 second. The EBSD measurements were carried out with SEM (JEOL 360) equipped with a TSL EBSD system. The SEM was operated at an accelerating voltage of 20kV and EBSD measurements were performed with a step size of 1.0μm. The production of grain maps based on the orientation measurements was accomplished by assigning points (pixel) to a grain in regions with neighboring orientations differing by less than 4°.

3. Results and discussion

The tensile test results are shown in Figure 1, where it can be observed that the optimum condition for deformation of this alloy is at 600°C with an initial strain rate of 0.001/s. A maximum of elongation of 188% can be obtained under this condition.

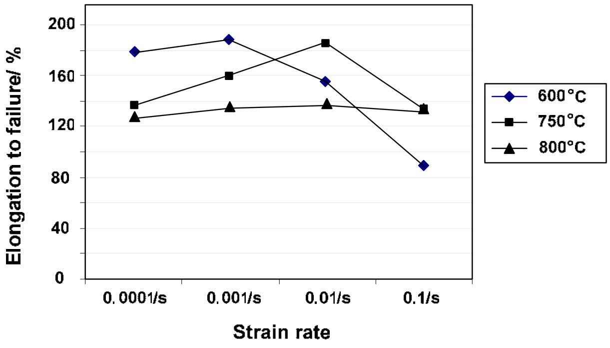

Fig. 1. Tensile test result of CP titanium alloy

Figure 2 shows typical microstructures of the gauge part as well as of grip part of deformed sample. The micro structure of the as-received sample is also presented in this figure for comparison. It is noted form from Figure 2 that the grain size of the deformed sample is much larger than that of the as-received sample.

It is well accepted that the grain size plays a very important role during the superplastic forming. A fine and stable microstructure is a basic requirement for materials to exhibit structure superplasticity. Large grain sizes are not suitable for grain boundary sliding (GBS), in view of the fact that only grains with an average size of less than 10μm can deform by GBS [12,13]. This explains why the alloy does not show good superplasticity under the above-mentioned condition.

Upon closer analysis of the Figure 2, it can be seen that the average grain size of the gauge section is smaller than that of the grip section. Many fine grains were found at the gauge region. These fine grains observed at the gauge region can be presumed as new grains that have been dynamically recrystallized (DRX) under the influence of stress and elevated temperature. This assumption is valid since the isochronous grains at the grip section of the specimen that were not under the influence of stress coarsened.

To further investigate the DRX phenomenon, specimens were tested using the optimum deformation conditions i.e. at 600°C with an initial strain rate of 0.001/s. During the tests, specimens were strained to different strain levels, unloaded and immediately cooled by forced air. Specimens were sectioned from the gauge section. Figure 3 shows the evolution of recrystallized microstructures.

At the beginning of the deformation, i.e. ε=0%, the microstructure consists of equiaxed grains. Because of static grain growth during the heating-up process, the as-received microstructure had transformed into a coarse-grained structure whose average size was 18.9 μm as shown in Figure 3(a).

At ε=10%, the coarser grain boundaries started to appear jagged as a result of the applied stress, as shown in Figure 3(b). Careful examination of the microstructure shows some equiaxed fine grains appear along the grain boundaries and triple points. Figure 3 (c) depicts the microstructure at ε=40%. Comparing with Figure 3 (b), more fine grains can be observed in this figure. However, the distribution of these fine grains is not homogeneous. When ε=80%, the average grain size decrease to 9.7 μm. At this strain level, the average grain size is smaller than that of the as-received sample and the distribution of fine grains is relatively homogeneous. However, many coarse grains with grain size larger than 10 μm can still be found in Figure 3 (d). It also showed that beyond 80% strain, the average grain size increase with increasing strain due to grain growth at this temperature.

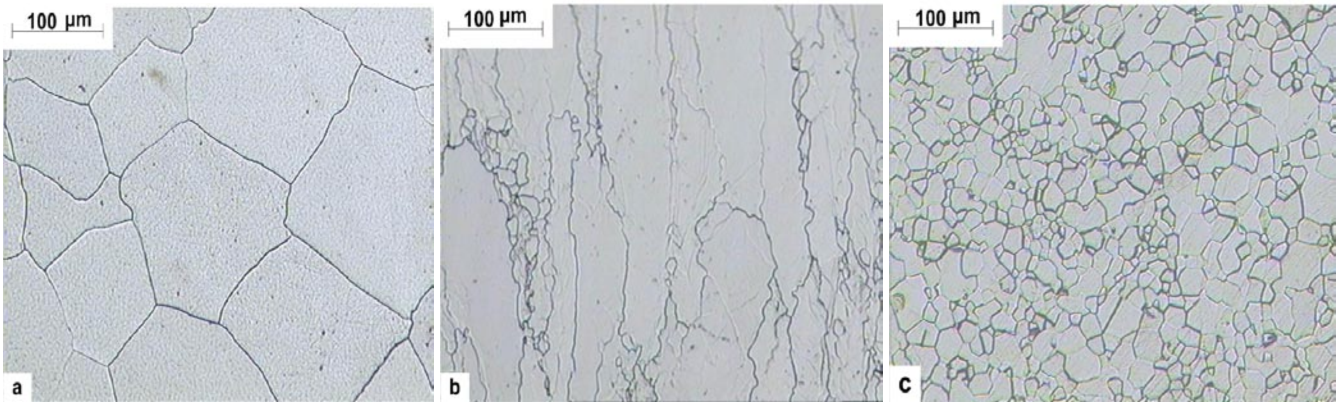

Fig. 2. Optical micrograph of the (a) grip part, (b) gauge part of the sample deformed at 750°C with an initial strain rate of 0.001/s and (c) as-received sample

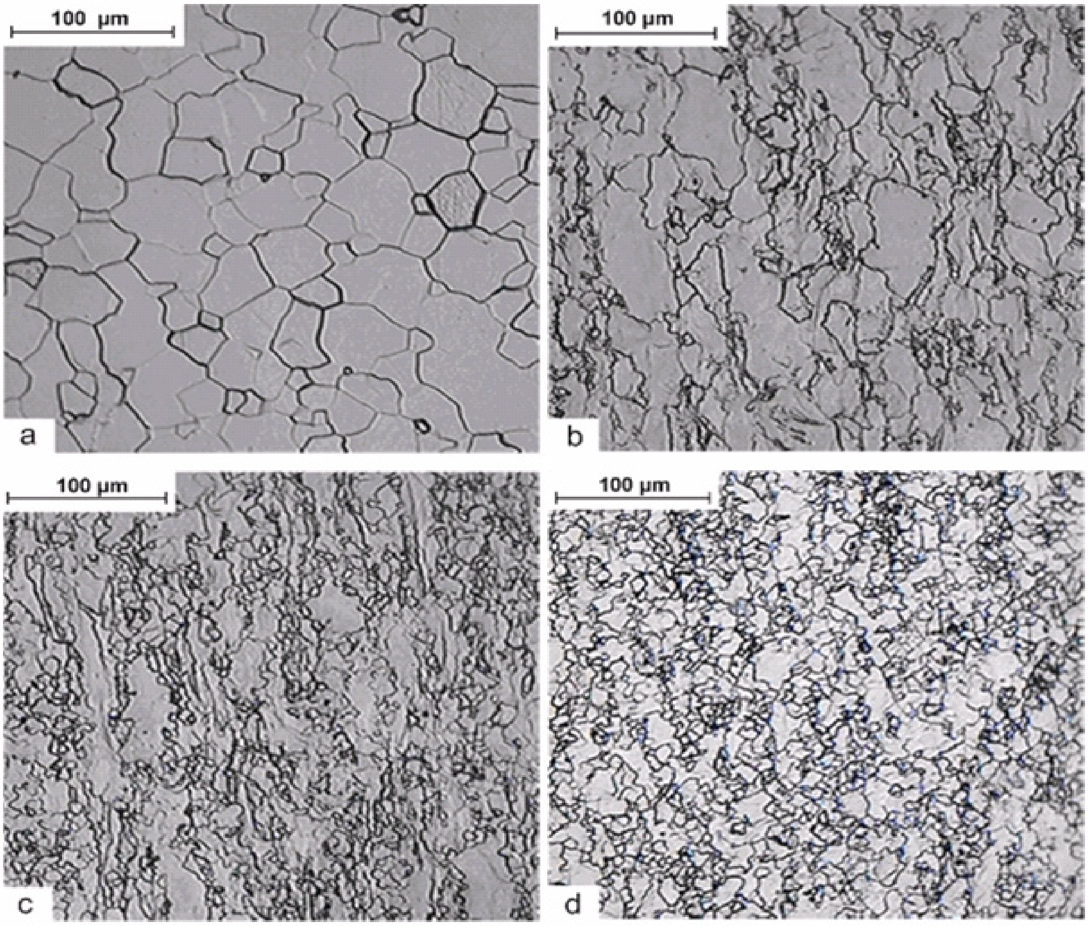

Fig. 3. Optical microstructure of samples strained to: (a) 0%; (b) 10%; (c) 40% and (d) 80% at 600 °C with 0.001/s

In this work, the effect of DRX on the distribution of the grain boundary misorientation was characterized by using electron back scattered diffraction (EBSD) technique. Several EBSD relative maps from the samples strained to 10%, 40% and 80% are presented in Figure 4. Dark lines in these maps refer to misorientation angles higher than 60°. It can be seen from these maps that the density of high angle increased with increasing strain and further studies showed that the average misorientation angles were 48°, 51° and 56° for samples strained to 10%, 40% and 80%, respectively.

A possible mechanism responsible for this phenomenon is localized grain boundary sliding (GBS) [14,15]. As discussed earlier, the average grain size is relatively large (18.9 μm) at the beginning of deformation. Only grains with an average size of less than 10 μm can deform by grain boundary sliding (GBS) [12,13], so GBS is not the predominant mechanism here during deformation. On the other hand, many very high angle boundaries exist in the as-received material and this is confirmed by EBSD. These high angle boundaries can provide the starting sites for localized GBS. However, because the extent of GBS is very limited, its contribution to the total strain is not significant. However, it can lead to accelerated dynamic recrystallization by the following processes [14,15]: (a) as GBS takes place, dislocations are introduced to accommodate the strain incompatibility and the absorption of these dislocations into boundary will increase misorientations between adjacent subgrains; (b) the GBS causes rotation of the adjoining subgrains, thereby introducing additional high angle boundaries which are also able to slide. Repetition of this process rapidly transforms low angle boundaries into high angle grain boundaries. As a result, more and more fine grains with very high angle boundaries are formed as the strain increase.

4. Conclusions

Based on the above mention discussion, the following conclusions can be made from this work:

- Due to the rapid grain growth, CP titanium alloys do not show good superplasticity at 600-800°C. The maximum elongation-to-failure value can be obtained is 188% at 600°C with an initial strain rate of 0.001/s.
- Dynamic resrystallization happens when the alloy deformed between 600 and 800°C.

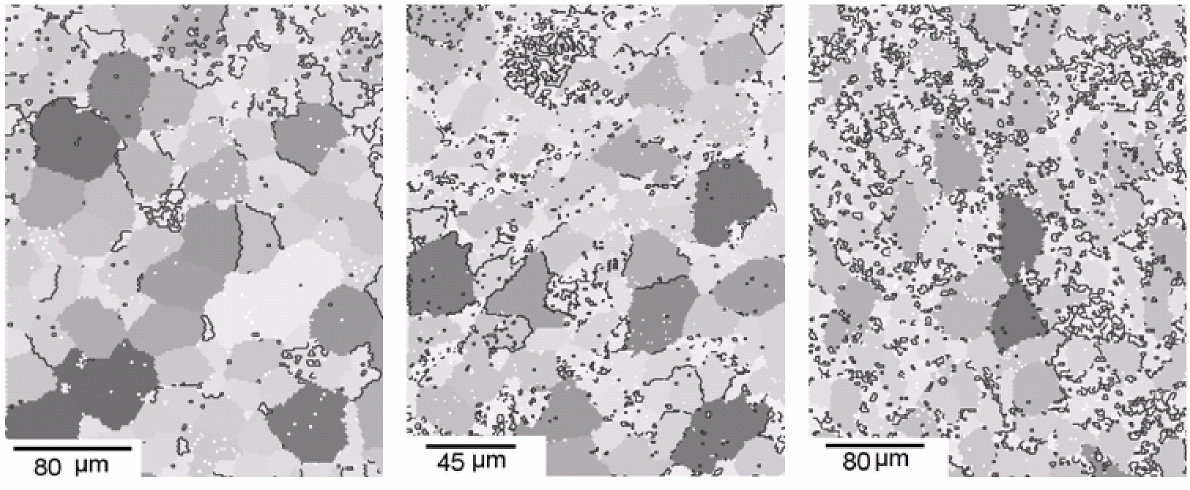

Fig. 4. EBSD relative maps of samples strained to: 10% (left); 40% (middle); and 80% (right) at 600 °C with 0.001/s

References

[1] F.J. Campideli, H.E.P. Sobrinho, L. Correr; D. Goes, M. Fernando: Stress-relieving and porcelain firing cycle influence on marginal fit of commercially pure titanium and titanium-aluminum-vanadium copings, Dental Materials 19 (2003), 686-691.

[2] C.R.F. Azevedo, A.P.D. Santos: Environmental effects during fatigue testing: fractographic observation of commercially pure titanium plate for cranio-facial fixation, Engineering Failure Analysis 10 (2003) 431-442.

[3] S. Kundu, M. Ghosh, A. Laik, K. Bhanumurthy, G.B. Kale, S. Chatterjee: Diffusion bonding of commercially pure titanium to 304 stainless steel using copper interlayer, Materials Science & Engineering: A407 (2005) 154-161.

[4] Jaan-Ming Liu, Sheh-Shon Chou: Study on the microstructure and formability of commercially pure titanium in two-temperature deep drawing, Journal of Materials Processing Technology 95 (1999) 65-70.

[5] C.Y. Gao, P. Lours, G. Bernhart: Thermomechanical stress analysis of superplastic forming tools, Journal of Materials Processing Technology 169 (2005) 281-289.

[6] H. L. Xing, K. F. Zhang, Z. R. Wang: A preform design method for sheet superplastic bulging with finite element modeling, Journal of Materials Processing Technology 151 (2004) 284-288.

[7] K. F. Zhang, G. F. Wang, D. Z. Wu, Z. R. Wang: Research on the controlling of the thickness distribution in superplastic forming, Journal of Materials Processing Technology 151 (2004) 54-57.

[8] Z. Y. Ma, R. S. Mishra: Cavitation in superplastic 7075Al alloys prepared via friction stir processing, Acta Materialia 51 (2003) 3551-3569.

[9] A. H. Chokshi, T. G. Langdon: The influence of rolling direction on the mechanical behavior and formation of cavity stringers in the superplastic Zn-22% Al alloy, Acta Metallurgy 37 (1989), 715-723.

[10] S. N. Patankar, Yeo Thye Kwang, Tan Ming Jen: Alpha casing and superplastic behavior of Ti–6Al–4V, Journal of Materials Processing Technology 112 (2001)24-28.

[11] Y. M. Hwang, H. S. Lay: Study on superplastic blow-forming in a rectangular closed-die, Journal of Materials Processing Technology, 140 (2003) 426-431.

[12] X.J. Zhu, M.J. Tan W. Zhou: Enhanced superplasticity in commercially pure titanium alloy, Scripta Materialia 52 (2005) 651-655.

[13] T.G. Nieh, J. Wadsworth, O.D. Sherby: Superplasticity in Metals and Ceramics, Cambridge: Cambridge University Press, (1996).

[14] K. Tsuzaki, X. Huang, T. Maki: Mechanism of dynamic continuous recrystallization during superplastic deformation in a microduplex stainless steel, Acta Materialia 44 (1996) 4491-4499.

[15] Y. Xun, M.J.Tan, T.G. Nieh: Grain boundary characterisation in superplastic deformation of Al-Li alloy using electron backscatter diffraction, Materials Science and Technology 20 (2004) 173-180.