Chinese Journal of Aeronautics, (2016), 29(1): 30–40

CSAA

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Chinese Journal of Aeronautics

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REVIEW ARTICLE

Microstructure control techniques in primary hot working of titanium alloy bars: A review

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Received 20 April 2015; revised 2 June 2015; accepted 12 June 2015
Available online 30 August 2015

KEYWORDS

Hot working;
Mechanisms;
Microstructure;
Simulation;
Titanium alloy

Abstract How to control the microstructure of titanium alloy bars is important to fabricating high-performance aerial forgings. This paper gives a thorough survey of the manufacturing methods and microstructure control techniques for titanium alloy bars. It summarizes the effects of processing parameters on the mechanisms and laws of microstructure evolution during β working and (α + β) working, including the kinetics and grains size of dynamic recrystallization (DRX) during β deformation and the kinetics and grains size of spheroidization during (α + β) deformation. The trends in microstructure control techniques are presented for fabricating titanium alloy bars with high efficiency, low cost, and high quality by means of β/(α + β) working, and the puzzles and challenges in the future are also pointed out.

1. Introduction

Titanium alloys have been widely applied to aviation, chemical processing, and pharmaceutical due to high specific strength, good mesothermal performance, good corrosion resistance, low Young's modulus, and non-toxicity. Especially, titanium alloys are applied in the aerospace industry largely. They are used in advanced airplanes to 30%–50% weight of the total structure, for instance, 41% in F-22 fighters. Titanium alloys have become one of the indispensable structure materials of airplanes.[1–3] Forging is the most applicable forming route of titanium alloy parts. Generally, these forgings are fabricated by primary hot working which transforms ingots to semi-products, followed by secondary hot working which transforms semi-products to final products. Bars are important semi-products, as a large fraction of aerial titanium alloy forgings, such as cartridge receivers manufactured by a ring rolling process, blades, integral blade disks, and bulkheads, are fabricated from bars. The microstructure of bars greatly influences the performance of final products. Thus, rigorous control on microstructure is performed in primary hot working. With increasing of the forging projected area, the diameters of bars for fabricating forgings increase from tens of millimeters to hundreds of millimeters. This requires a more advanced microstructure control technique, for the purpose of meeting the microstructural requirements of bars.

Typical primary processing for titanium alloy bars involves forging in both the β phase field (β forging or β working) and

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.07.011
1000-9361

the (α + β) phase field ((α + β) forging or (α + β) working). Taking the advantages of good workability and low working loads at high temperature[4–6], β working is employed to break the coarse as-cast structure so as to obtain fine and homogeneous beta grains. In despite of lower workability and higher working loads,[7] (α + β) forging is necessary to break the lamellar structure formed in β forging. A more refined bimodal alpha + beta microstructure is achieved after (α + β) working, of which the various mechanical properties are well matched. In order to achieve a fine and homogeneous bimodal microstructure, β working and (α + β) working should be reasonably matched for titanium alloy bars fabrication. To this end, microstructure evolution and control during β working and (α + β) working are researched actively.

This paper summarizes recent research work on microstructure evolution and microstructure control techniques for fabricating titanium alloy bars. The trends in microstructure control techniques are presented for the fabrication of titanium alloy bars with high efficiency, low cost, and high quality by means of β/(α + β) working. For this purpose, the puzzles and challenges in the future are pointed out. The progresses can instruct the fabrication of large-size titanium alloy bars.

2. Microstructure evolution during β working

2.1. Microstructure evolution mechanisms during β working

Dynamic recovery (DRV) is an important softening mechanism in high temperature deformation of beta phases. This is often associated with the bcc structure and high stacking fault energy of beta phases, in which dislocation climb and cross-slip are favored. DRV results in a clear substructure within the original beta grains. This has been confirmed by experimental studies in different kinds of titanium alloys. Wang et al.[8] found that DRV was the dominant microstructure evolution mechanism in β working of the near beta Ti53311S titanium alloy. Han et al.[9,10]also confirmed that DRV occurred in beta grains during β working of the near alpha Ti600 titanium alloy. The apparent activation energy (Q) ranges from 170 kJ/mol to 220 kJ/mol, which is similar to that of self-diffusion in the beta phase (153 kJ/mol),[11] as shown in Table 1.[12–19] The similarity of apparent activation energy to that of self-diffusion in the beta phase indicates that DRV dominates the microstructure evolution during β working.

Besides DRV, some research works also indicate that partial dynamic recrystallization (DRX) occurs.[17,18,20] Generally, the proportion of DRX to the total microstructure evolution is small.[15,21–25] Wanjara et al.[26] reported that an average recrystallized fraction was attained to be 2.3% when the IMI834 titanium alloy was deformed at 1050 °C with a strain rate of 1 s^{-1} to a true strain of 0.2, which reached to 50% with increasing of a true strain of 1.2. Research by Ding et al.[27] reported an average recrystallized fraction of less than 30% in deformation of the Ti–6Al–4V titanium alloy at 1050 °C with a strain rate of 0.05 s^{-1} to a true strain of 0.7. These works show that microstructure evolution is mainly DRV for titanium alloys during β working.

Table 1 Apparent activation energy of titanium alloys in the β phase field.[12–19]

Alloy	Q (kJ/mol)
TA15[12]	215
IMI834[13]	153
IMI685[14]	193
Ti6Al4V[15]	210
TC11[16]	172
TC21[17]	185
Ti3Al5V5Mo[18]	133
TB8[19]	227

The prior beta grains become elongated in the plane perpendicular to the compress axial direction, and exhibit a tridimensional pancake-shape structure due to the strong DRV in β working.[20,28–31] Recrystallized beta grains are often observed at the prior beta grain boundaries, where the nucleation of DRX grains is initiated. This gives a necklace-appearance of fine equiaxed beta grains around the deformed and elongated prior beta phase.[26,32,33] The morphology of beta grains for titanium alloys during β working is illustrated in Fig. 1.[34]

2.2. Effect of process parameters on microstructure evolution during β working

The microstructure of a deformed material is closely related to process parameters, such as temperature, strain rate, strain, and their interactions. Detailed work has been carried out by many researchers on the regulations of microstructure evolution in β working of titanium alloys.

The microstructure evolution during β working is sensitive to strain rate. Excessive high strain rate is disadvantageous to nucleation of DRX.[35,36] Zhu et al.[37] studied microstructure morphology with strain rates of 0.01–10 s^{-1} for the TC21 titanium alloy during β working. The results indicated that only DRV was observed at strain rates greater than 1 s^{-1}. A lower strain rate avails to occurrence of DRX as it provides more time for nucleation and growth of new recrystallizing grains.[38,39] Balasubrahmanyam and Prasad[40] studied the microstructure evolution at strain rates between 0.001 and 100 s^{-1} for the Ti–10V–4.5Fe–1.5Al titanium alloy at high-temperature upset forging and observed DRX at strain rates ranged from 0.001 s^{-1} to 0.1 s^{-1}. Generally, the extent of DRX grows firstly and then decreases with decreasing strain rate. Excessive low strain rate gives enough time for DRV and suppresses DRX.[41] Wang et al.[42] studied the microstructure evolution for the Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy during β working. Their work indicated that only DRV was observed at 1035–1080 °C at strain rates lower than 0.01 s^{-1}.

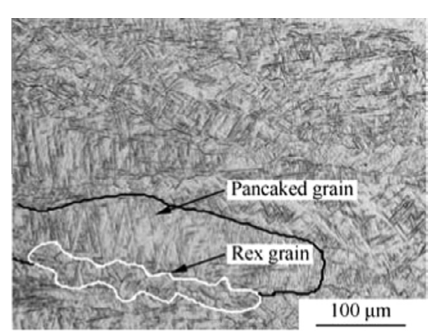

Fig. 1 Microstructure of IMI834 titanium alloy deformed in the β phase field.[34]