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Substructure of high temperature compressed titanium alloy IMI 834

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Abstract

The substructure of IMI 834 was studied by transmission electron microscopy (TEM). The samples were compressed at 1050 °C at two different strain rates, 0.01 and 0.1 s^{-1} to a total strain of 0.2. Compared to the as-received microstructure, coarsening of α platelets was found after the compression at both strain rates. Recovery of the compression microstructure was observed in the high strain rate compression sample. A majority of the dislocations was identified as $\langle a \rangle$ type, although some $\langle a+c \rangle$ type dislocations were also found. Retained β phase and silicides show strong resistance to the glide of dislocations. This results in the pileup of dislocations at the vicinity of retained β phase and the formation of low angle subgrain boundaries. Interactions of $\langle a \rangle$ and $\langle a+c \rangle$ type dislocations on the pyramidal planes $\{1\,\bar{1}\,0\,2\}$ were observed to form hexagonal dislocation networks. The observed substructure differences resulting from different strain rates indicate that forging speed will influence microstructure development of the IMI 834 alloy.

Keywords: IMI 834; Titanium alloy; TEM; Compression; Dislocation; Forging

1. Introduction

Near-α titanium alloys have been used as compressor discs and blades in jet engines due to their excellent specific properties and high temperature capabilities [1]. These parts are subjected to cyclic loading during take-off and landing stages and high stress at the cruising stage of each flight. This loading and unloading pattern, which is called dwell cycling, has drawn a lot of attention due to its differences in failure characteristics in comparison with low cycle fatigue (LCF) [2]. The superimposition of dwell periods on a LCF pattern at temperatures that may reach 600 °C at a cruise stage also requires good creep resistance of the alloy. A combination of good resistance against fatigue and creep is, therefore, required. A bimodal microstructure that consists of different volume fractions of equiaxed primary α grains and α platelets in transformed β grains via an α + β processing route is currently adopted to meet the requirement [3]. However the equiaxed primary α grains within the bimodal microstructure offer weak dwell fatigue resistance, which is a serious problem for jet engine components [4,5]. Large prior β grain size is also a negative factor with respect to the dwell sensitivity of near α titanium alloys [6].

Generally speaking, α phase has high creep resistance than β phase due to the slower self diffusivity of Ti in the α phase at a given temperature [7]. Therefore, to improve the creep resistance of titanium alloys, a high percentage of α phase is desired. For fatigue resistance, β processed lamellar structures offer poor resistance to the nucleation of cracks, whilst equiaxed α grains show the highest crack growth rates [8–10]. In near α titanium alloys, the β phase is distributed at the α platelet boundaries as thin layers inside transformed β grains. The boundary β phase layers may play beneficial roles in diverting cracks during fatigue according to the orientations of their neighboring α platelets [11]. Boundary β phase layers that meet the Burgers orientation relationship with its neighboring α platelets show no effects on the deviation of cracks. The bimodal microstructure is, therefore, chosen as a compromise to give an optimum combination of creep and fatigue resistances.

Such microstructures are produced by choosing suitable processing routes, which consist of forging at super- and/or sub-β-transus temperatures and subsequent heat treatment. Processing at temperatures close to or above the β transus normally results in a lamellar microstructure, which is characterized by α platelets with inter-platelet β phase layers. The thickness of the α platelets

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is largely affected by the processing parameters, specifically annealing temperature and cooling rate [7,12]. The thickness generally decreases with an increase in cooling rate, varying from plate-like to basketwave and to martensitic microstructures. Forging in the α + β region, results in a microstructure consisting of primary α grains and α platelets in transformed β grains that have smaller grain sizes than the prior β grains due to the deformation of prior β grains and their subsequent recovery and recrystallization [12,13]. The forged alloys contain large quantities of crystal defects and recovery substructures, which may alter the heat treatment responses and eventually the properties of the materials in applications. However, very little has been reported on the effects of thermomechanical processing parameters on substructure evolution.

The current paper reports on substructures in the near α titanium alloy IMI 834 after compression at different strain rates at 1050 °C in order to get an insight into the microstructure evolution during forging. The observed substructures are discussed in terms of phase transformation and dislocation movement in relation to the crystallography of titanium.

2. Experimental procedures

Cylindrical specimens of a near-α titanium alloy IMI 834 were compressed in the upper part of the α + β field at 1050 °C to a total strain of 0.2, followed by cooling in air to room temperature. The cylindrical specimens were cut from a forged bar to the dimension of 11.4 mm in height and 7.6 mm diameter. The compression tests were performed on a computerized materials testing system (MTS 810) adapted for elevated temperature compression test. The testing device consisted of a load frame rated for a maximum load of 100 kN, a hydraulic power supply and closed loop servohydraulic and computerized outer loop systems. A research incorporated radiant furnace, which was interfaced with a Micristar digital programmer and controller, was used for heating up the samples. The strain rate was chosen as 0.01 and 0.1 s^{-1}, which are denoted as low and high strain rate compression, respectively. The compression consists of two identical steps with 20 s interval between them. The processing is shown in Fig. 1 schematically. First the samples were heated up to 1050 °C at a rate of 50 °C per minute. The samples were then held at the same temperature for 10 min before the first compression, in order to stabilize the microstructure and temperature. After the second compression, the samples were removed from the furnace and cooled to room temperature in air.

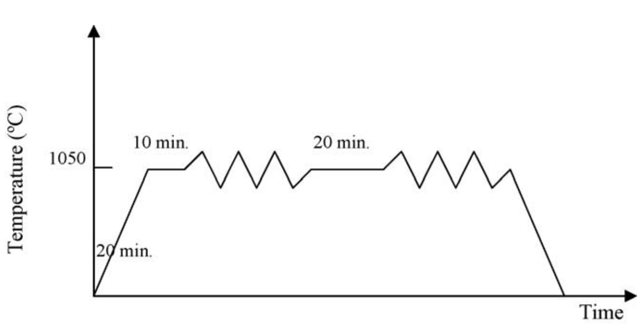

Fig. 1. Schematic representation of the hot compression tests.

After compression, the samples were transversely sectioned for optical and transmission electron microscopic analyses. Samples for optical microscopy were mounted into bakelite and ground by SiC paper to a 1200 mesh grade followed by polishing using alumina suspensions up to 0.3 μm. None crystalline silica, in the size range of 0.01 μm, was used to finish the polishing. For TEM analysis, samples were first cut into 0.5 mm thick discs using a diamond saw, followed by grinding to a thickness between 60 and 100 μm. The discs were then punched into 3 mm diameter discs for thinning to less than 20 μm using a Tenupol-2 electropolisher. The solution that was used for the electropolishing consists of 20 ml perchloric acid, 10 ml hydrochloric acid, 180 ml butyl alcohol, and 300 ml methanol. The electropolishing was carried out at −35 °C and 70 V. TEM analysis was performed using a JEOL EM2011 FastTEM operated at 200 keV. Images were recorded using a Gatan CCD camera.

3. Results and discussions

Fig. 2(b) and (c) show typical optical microstructures of the IMI 834 alloy after low and high strain rate compression in comparison with their as-received microstructure, Fig. 2(a). The effects of high temperature compression on the microstructure can be seen clearly from these optical micrographs. The as-received microstructure is characterized by a basketwave microstructure with fine α platelets. Microstructures after high temperature compression show coarse α platelets as a result of the moderate cooling rate used in this investigation. Compared to the as-received microstructure in Fig. 2(a), both the length and width of the α platelets are increased. An increase in the α colony size is also observed. The effects of cooling rate on the thickness of α platelet in transformed β grains are well documented [12]. Low cooling rates, such as furnace cooling, result in a microstructure with thick aligned α platelets. Quenching in oil or water results in the formation of martensitic platelets. Intermediate cooling rate, such as air cooling, leads to a microstructure consisting of thin α platelets. In the current investigation, identical cooling rates resulted in α platelets of similar thickness for low and high strain rates compression samples as shown in Fig. 2(b) and (c).

A major effect of high temperature compression is the grain refinement of the prior β grains. An average β grain size of the as-received alloy was measured as 760 μm. After the compression, the average transformed β grain sizes were measured as 306 and 280 μm for the high (0.1 s^{-1}) and low (0.01 s^{-1}) strain rate compressions, respectively.

It is evident from Fig. 2(b) and (c), that the α platelets are more aligned and form large colonies after low strain rate compression, while the colonies have smaller sizes and the α platelets are less aligned after high strain rate compression. This is possibly related to the generation of a larger number of crystal defects in prior β grains under high strain rate compression testing. These defects possibly offer more nucleation sites for α platelets during phase transformation, resulting in finer α platelets in less aligned orientations.