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Thermo-mechanical processing window for β phase recrystallization inTi-5Al-5Mo-5V-3Cr alloy

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ABSTRACT

Ti-5Al-5Mo-5V-3Cr (Ti-5553) is a high strength β titanium alloy. It is now commonly used in thick section aerospace components. In general, the thermo-mechanical processing (TMP) of β titanium alloys done at high temperature to obtain uniformly recrystallized fine grain structure is one of the major challenges. Through this work, a TMP window for Ti-5553 (through systematic variation in % reduction and post deformation annealing temperature) has been developed to obtain fine uniformly recrystallized β grains. Grain size has been quantified on EBSD generated orientation maps, by applying stereological methods, image processing and automated reconstruction. Effects of % deformation and post deformation annealing temperature, as well as that of initial ingot size prior to deformation and the capacity of the forge on the static and dynamic recrystallization behavior, which eventually determine the final grain size distribution, have been illustrated.

1. Introduction

Conventional titanium alloys are classified into different categories: α alloys (CP Ti), near α alloys (IMI 834), α + β alloys (Ti-6Al-4V) and β alloys. The β alloys are characterized by sufficient β stabilizer (Mo, V, W, Nb, Ta, Fe, Cr, Cu, Ni, Co, Mn and Si) concentration to ensure retention of bcc β phase at room temperature on rapid cooling. Within the class of β alloys, a distinction can be made between so-called "high strength" β alloys which are located with their chemical composition close to the phase boundary between β and α + β regions in the phase diagram and therefore contain a high volume fraction of α phase and so-called "heavily stabilized" β alloys which are located more to the right in the pseudo-binary phase diagram. These latter alloys contain a much lower volume fraction of α phase and the maximum achievable strength is therefore lower as compared to the high strength group of β alloys. Strengthening of these alloys is achieved during aging process by precipitation of fine α phase [1]. The applications of Ti-10V-2Fe-3Al (Ti-10-2-3) and Ti-5Al-5V-5Mo-3Cr (Ti5553), which are high strength β alloys, are usually in airframe components like landing gear and flap/slat tracks.

Ti-5553 is a newly developed alloy and based on Russian alloy VT-22 (Ti-5.7Al-5.1V-4.8Mo-1Cr-1Fe). Ti-5553 is a deep hardenable alloy due to presence of Mo which is a slowly diffusing element. Precipitation of α phase in Ti-5553 is sluggish in comparison to that in Ti-10V-2Fe-3Al and therefore it exhibits excellent hardenability and can be used for manufacturing structural components which are thicker than 100 mm. In addition, Fanning et al. [2] have also reported that the thermo-mechanical process-ability of Ti-5553 is more robust.

Mechanical properties of an alloy depend on its thermo-mechanical processing (TMP) history and heat treatment. Mechanical working like forging and rolling introduce strain energy into the material that acts as a driving force for recrystallization. Recrystallization, if occurs during the hot deformation itself, it is termed as dynamic recrystalliazation (DRx), whereas if the recrystallization phenomenon occurs during the post deformation annealing treatment, then it is termed as static recrystallization (SRx) [3,4]. Contieri et al. [5] investigated the SRx in cold worked CP titanium during annealing and found that SRx is followed by grain growth with increasing annealing time. Chun et al. [6] studied the effect of deformation temperature on SRx kinetics in warm rolled CP titanium and found that recrystallization rate increased with increasing rolling temperature. Several researchers also investigated the hot working of β titanium alloys and found that Drx is predominant during hot deformation [7,8].

Ti-5553, just like other β alloys, is worked in the β phase field and then final processing is done in the α + β phase region in order to control the β grain size. The alloy is usually solution treated in either β

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or α + β phase field to vary the amount and morphology of primary α phase and then aged at lower temperatures in the α + β phase field to obtain precipitates of fine secondary α phase.

To a large extent, mechanical properties and behavior of an alloy depends on the structure, the size and the orientation of grains (texture). Mechanical properties also depend on the extent and type of deformation during processing. Further heat treatment is carried out to obtain desirable mechanical properties. The first step of the post deformation heat treatment schedule is given to cause recovery and recrystallization, of which grain growth is also a subsequent phenomenon.

The β transus temperatures of the β titanium alloys are comparatively lower and therefore they have a narrower processing window. Although the secondary α laths are constituents with maximal strength however some mechanical properties such as ductility and fatigue properties are dependent on size of prior β grains. It is a major challenge to obtain uniformly recrystallized fine β grain structure in these alloys. Therefore, it is imperative that recrystallization study of this new β titanium alloy be carried out in a systematic manner so that an effective guideline for thermo-mechanical process parameters can be recommended to obtain fine β grains through recrystallization.

This article presents the results of a systematic investigation done on the recrystallization behavior of Ti-5553 in the β phase field. TMP variables that affect final recrystallized grain size are amount of deformation and post deformation annealing temperature and time. These variables affect both dynamic and static recrystallization (SRx) phenomena, which together determine the final grain size distribution. One of the factors that affect dynamic recrystallization (DRx) is capacity of the forging and rolling equipments; which along with the material characteristics determine the number of passes and number of presoaking required for a particular % reduction. This is one of the pivotal factors, which is often ignored by many investigators. Amount of deformation and corresponding stored strain energy would vary if the initial thickness of the ingot prior to deformation is different for the same % reduction to achieve. As the main driving force for recrystallization is the amount of stored strain energy, hence the initial ingot size and % deformation both should be considered for interpreting the effects of factors on recrystallization behavior. Through our work we have also observed the effect of forge/roll capacity and initial ingot size on recrystallization behavior along with the effects of % deformation and post deformation recrystallization temperature. In this study, a TMP window (through systematic variation in % reduction and post deformation annealing temperature) has been identified to obtain fine uniformly recrystallized β grains. The recrystallization behavior has been studied using electron back scatter diffraction (EBSD) and quantifications have been made using stereological methods as well as using MIPAR™ software.

2. Experimental

2.1. Material

Ti-5553 alloy was cast by double vacuum arc remelting (VAR) process. Ingot was then homogenized at 1050 °C for 1.5 h before deformation. The compositions of as cast Ti-5553 (at the top and bottom of the ingot) are shown in Table 1.

2.2. Deformation

VAR ingot was subsequently deformed. Based on the final deformation step, the set of deformed samples can be broadly categorized into two different groups; for one group, the final deformation step was in the β phase field and for the other the final deformation was done in the α + β phase field.

2.2.1. Starting Thickness of Ingot Prior to Deformation

Samples from VAR (as cast) ingot had different starting thicknesses before deformation, details of which are given below and also in Table 2. While starting thickness of the ingot sections which were to be deformed in the β phase field were small (25–65 mm), the starting thickness of the ingot for samples whose final deformation step was to be in the α + β phase field were significantly higher (140 mm).

2.2.2. Details of Deformation Steps

2.2.2.1. Deformation (26%, 42%, 60% and 80%) in the β Phase Field. This group of samples were first forged and then subsequently rolled, both at 950 °C (in the β phase field) to achieve different total % reductions (26%, 42%, 60% and 80%). The schematic for these deformations is shown in Fig. 1(a). Forging was done using a hydraulic double acting hammer of capacity 60 tons and rolling was done with rollers of 120 mm diameter and 120 mm length.

2.2.2.2. Final Deformation Step in the α ± β Phase Field (Total 90% Reduction). VAR ingot of 140 mm diameter was deformed by 90% reduction in total to achieve 15 mm thick deformed plate. Schematic of the deformation steps is shown in Fig. 1(b). The detailed deformation steps were as follows. This was first deformed from 140 mm to 65 mm (55% reduction) by forging after pre-soaking at 1050 °C (in the β phase field) and then forged from 65 mm to 30 mm (further 54% reduction) at 780 °C (in the α + β phase field), and finally it was rolled from 30 mm to 15 mm (further 50% reduction) at 780 °C (in the α + β phase field). The forging was carried out using a pneumatic hammer of 1 ton capacity and the rolling was carried out with rollers of 300 mm diameter and 750 mm length.

Detailed deformation histories (details of number of hammering/passes and number of presoaking, presoaking time and temperature, % reductions etc.) for all deformations are given in Table 2. Samples were coated with Deltaglaze® before forging and rolling to protect and lubricate specimens during forging/rolling.

2.3. Post Deformation Annealing (Recrystallization Annealing Treatment)

Post deformation, all samples were annealed at different temperatures of 925 °C, 950 °C, and 975 °C for 30 min to study the combined effect of % deformation and post deformation recrystallization annealing temperature on resulting grain size. Henceforth in this paper, samples undergone these heat treatments will be termed as post recrystallization-annealed samples.

Annealing was carried out on samples of size 5 mm × 6 mm × 5 mm in a conventional muffle furnace. Chromel–Alumel thermocouple was used for measuring sample temperature during heat treatment.

2.4. Microstructural Characterization

After the final heat treatment step, specimens were machined to

Table 1
Compositional analysis of Ti-5553 alloy.

Elements	Al (wt%)	V (wt%)	Mo (wt%)	Cr (wt%)	Fe (wt%)	O (ppm)	H (ppm)	N (ppm)
Top	5.48	5.10	5.06	3.22	0.1	500	38	60
Bottom	5.17	5.33	5.34	3.10	0.09	1100	34	50