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Effect of microstructures on hot compression behavior of a Ti-43Al-2Si alloy fabricated by cold crucible continuous casting

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ABSTRACT

To investigate the influence of lamellar orientation and colony boundary on deformation behavior, fully lamellar Ti-43Al-2Si alloys were prepared by cold crucible continuous casting and isothermal compression tests were conducted at different temperatures in the range 1373–1523 K with a strain rate of 0.01 s^{-1}. The as-cast microstructures were elongated colony with lamellae oriented at nearly 45° to the compression direction and equiaxed colony with various lamellae orientations, respectively. The results revealed that serious cracking or sliding traces appeared on the surface of deformed specimens with elongated colony original microstructure and that their peak stresses were lower compared to those of specimens with equiaxed colony original microstructure. The relationship between deformation behaviors and as-cast microstructure was analyzed in detail. It was found that the recrystallization/globularization level is significantly lower than that in specimens with equiaxed colony original microstructure during hot deformation owing to the preferred nucleation sites in colony boundaries. Finally, the lamellae conversion process was characterized to reveal the softening mechanisms of full lamellar TiAl-based alloy during hot compression.

1. Introduction

Titanium aluminide (TiAl) alloys have excellent engineering properties, i.e., high specific strengths, good structural stability, and superior resistance against oxidation, as high-temperature lightweight structural materials in the aviation and aerospace fields [1,2]. Casting is a well-known conventional production technology for TiAl-based alloys and other materials. However, as-casted TiAl alloys often have coarse grains and low room-temperature ductility [3]. Generally, thermo-mechanical processes such as isothermal forging [4], canned extrusion [5], and pack rolling [6] can improve the mechanical properties and expand applications for TiAl-based alloys through microstructure manipulation.

The closed-die forged TiAl alloy blade possesses outstanding specific creep rupture strength, enabling its potential application at temperatures up to 700 °C [7]. A cast Ti–45Al–(8–9)Nb–(W,B,Y) alloy has a poor room-temperature ductility of 0.49%, which can increase to 2.29% via canned forging at the (α + γ) phase region [8]. Xu et al. [9] found that hot extrusion refines as-cast TiAl alloy grain to reduce the resistance of intragranular slip, which results in improved alloy mechanical properties and prevents the occurrence of anomalous yield stress. As mentioned above, the original as-cast microstructure generally is lamellar colonies, forming by complex conversion during thermo-mechanical processing [10,11].

The relationship between lamellar orientation and deformation mechanisms in lamellar TiAl-based alloys has been an important topic at low temperature (< 700 °C). For deformation of polycrystalline full lamellar microstructure, the strain distribution between lamellae colonies is heterogeneous because of the anisotropic yield stress of lamellae [12]. The main deformation mechanism is mechanical twinning at a small strain (5.4%) and turns to dislocation glide at a higher strain (8.3%) when the loading is parallel to lamellae of polysynthetically twinned TiAl crystal at room temperature [13]. The increased ease of deformation twinning for polycrystalline TiAl alloys as temperature increases to 700 °C is attributed to the reduced constraint by neighboring domains and lamellae, because the twin shear energy for lamellae increases monotonically with increasing temperature [14]. To the best of our knowledge, little attention has been paid to the high-temperature deformation mechanisms of lamellar microstructure. Therefore, it is necessary to investigate the effect of lamellar microstructure on deformation behaviors at elevated temperatures.

In the present work, Ti–43Al–2Si alloys with different starting

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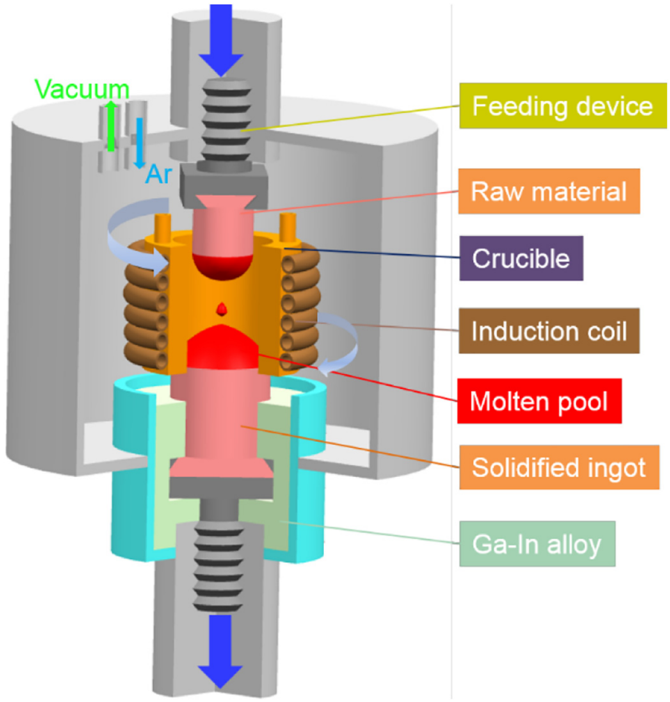

Fig. 1. Schematic of cold crucible continuous casting.

microstructures were fabricated by cold crucible continuous casting. The influence of lamellar orientation and colony boundary on the deformation mechanisms was investigated at elevated temperatures. The results can provide references for process design and microstructure control during hot forging of as-cast TiAl-based alloys.

2. Materials and Experiments

2.1. Materials

A billet of Ti–43Al–2Si (at.%) was prepared by melting pure titanium (99.98 wt%), high-purity aluminum (99.99 wt%), and silicon (99.99 wt%) in a vacuum cold crucible induction melting furnace. Two cylindrical bars of 20 mm in diameter and 200 mm in length were cut from the billet as raw materials in the subsequent solidification process, and the procedure was performed using an electromagnetic cold crucible apparatus as indicated in Fig. 1. The raw material was placed in a feeding device and then melted by the induction coil under a high-frequency input power of 55 kW. The melt dropped onto a pulling mechanism, forming a molten pool. Finally, two square ingots with cross-sectioned dimensions of 25 mm × 26 mm were quenched into liquid Ga-In alloy at different pulling velocities of 5 and 10 μm/s.

2.2. Compression Procedure

Several cylindrical specimens of 6 mm in diameter and 9 mm in height were machined from the two square ingots with their axes parallel to the solidification direction. Hot compression tests were conducted with a Gleeble 1500D instrument and the temperatures were monitored by Pt-Rh thermocouples. The specimens were heated to compression temperatures at a heating rate of 10 K/s and the hold time was 1 min to ensure thermal homogeneity throughout the entire specimen before compression. The compression temperatures were chosen in the range 1373–1523 K ($\alpha + \gamma$ phase region) in intervals of 50 K under a strain of 55% reduction from the original height of the specimens. The loading direction was parallel to the growth direction of the solidified ingots. The strain rate in the present work was 0.01 s^{-1}, which was proved to be suitable for hot deformation of Ti–43Al–2Si alloy based on our previous study [15]. After compression, the specimens were water-quenched from the deformation temperatures.

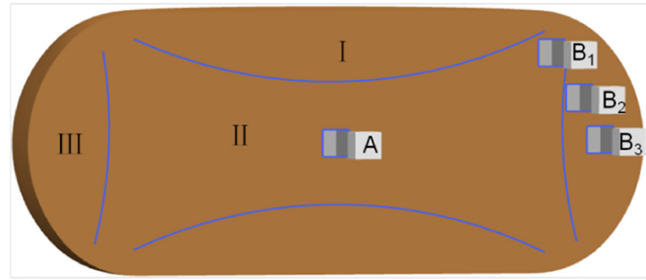

Fig. 2. Schematic of sampling positions for observation.

2.3. Microstructure Characterization

The solidification ingots obtained from cold crucible continuous casting were split into two equal parts along the growth direction. After mechanically grinding, polishing, and etching, the as-cast microstructures were separately photographed with a Nikon D7100 digital single lens reflex camera and a Leica DMI5000 M optical microscope. According to our previous research [15], the compression specimens exhibited three deformation regions, with maximum strain located at the center (II region), as shown in Fig. 2. In addition, failures were often generated from the bulging (III region) owing to circumferential tensile stress. Therefore, the samples (A, B_1, B_2, and B_3) for microstructure observation were taken from these special positions in Fig. 2. For scanning electron microscope (SEM) examinations, these specimens were prepared by electrochemical polishing using a solution of 34% butyl alcohol, 6% perchloric acid, and 60% methanol. A Quanta 200FEG SEM equipped with an electron backscatter diffraction (EBSD) detector was used for the observations. The EBSD data were acquired at an accelerating voltage of 30 kV with a step size of 0.2 μm and analyzed via TSL OIM Analysis 6 software.

3. Results and Discussion

3.1. Original Microstructure

Fig. 3 shows the columnar grains under the same power of 55 kW and different pulling velocities. As shown in Fig. 3(a) and (c), the columnar grains exhibit elongated colonies along the pulling direction at a velocity of 5 μm/s, while the columnar grains transform to mixed equiaxed colonies with the faster pulling velocity. The phenomenon is consistent with the results of solidified Ti–44Al–6Nb–1.0Cr–2.0V [16] and Ti–47Al–2Nb–2Cr–0.2Er [17] alloys. The solidification path of the present alloy is $L \rightarrow L + \beta \rightarrow \beta \rightarrow \beta + \alpha \rightarrow \alpha \rightarrow \alpha + \gamma$, during which the β/α phase transformation is related to the solidified microstructure. Moreover, the pulling velocity also influences the nucleation rate of the β/α phase transformation. When the pulling velocity is lower, the nucleation rate is lower, resulting in fewer grains because of the slow cooling rate. Meanwhile, the slow cooling rate can also promote growth of the α phase crystal nucleus in the direction perpendicular to pulling because of long-range diffusion of Ti in the β phase. Therefore, the α phase crystal nucleus can be easily grown continuously without being hindered and form elongated colonies. However, the high cooling rate induces abundant nucleation of the α phase because of the larger supercooling. Consequently, the as-cast microstructure is composed of equiaxed colonies when the pulling velocity is faster. Meanwhile, the solidified Ti–43Al–2Si alloy is composed of γ-TiAl, α_2-Ti_3Al, and Ti_5Si_3 phases. The α_2/γ lamellae of solidified ingots under different pulling velocities are displayed in Fig. 3(b) and (d), respectively. The α_2/γ lamellae are parallel or inclined at an angle of 45° to the columnar grain growth direction [17]. Because the growth directions of columnar