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A high-performance β-solidifying TiAl alloy sheet: Multi-type lamellar microstructure and phase transformation

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A B S T R A C T

TiAl alloys are widely used in the aerospace industry and, hence, a thorough understanding of the corresponding microstructural evolution is crucial for providing insight into the fabrication of high-performance TiAl alloy sheets. In this study, a high-performance β-solidifying Ti-43Al-9V-0.2Y alloy sheet with multi-type lamellar structures was obtained via hot-rolling at an initial rolling temperature of 1260 °C. Owing to the temperature drop and reheat associated with multi-pass rolling, relatively fine irregular β/γ and regular α_2/γ lamellar microstructures (average size: ~25 μm) with nano-scaled antiphase domains (APDs) were generated by the $\beta \rightarrow \gamma$ and $\alpha + \gamma \rightarrow \alpha_2 + \gamma/\gamma_T$ phase transformations. These two lamellar structures have different formation mechanisms. The results of electron backscatter diffraction and transmission electron microscopy revealed that the nucleation and growth of (i) β/γ and (ii) α_2/γ lamellar structures are induced mainly by (i) stress and (ii) a combination of the stress and temperature drop during hot-rolling, respectively. Thin γ_T precipitates from the α/α_2 or γ phases. This precipitation is induced by the higher stress and lower temperature associated with the later stage (compared with those occurring in the initial stages) of hot-rolling. Moreover, compared with the corresponding as-forged alloy, the as-rolled TiAl alloy sheet exhibits better performance at both room and elevated temperatures. The improvement in the tensile properties is attributed to the duplex microstructure consisting of fine multi-type lamellar structures with nano-scaled APDs. The interface boundaries of β/γ, α_2/γ and APDs, which are effective in retarding dislocation motion, contribute mainly to strengthening of the alloy sheet.

1. Introduction

TiAl alloys with outstanding specific properties (such as low density, high melting point, high modulus, excellent oxidation resistance, and favorable creep properties) are considered as promising high-temperature structural materials for aerospace applications [1–3]. In particular, β-solidifying TiAl alloys are suitable for various applications and exhibit good processability. These alloys, are widely used as the preferred materials in thermomechanical processing (especially hot-rolling) owing to their soft disordered β phase at elevated temperatures [4–7]. However, compared with those of other TiAl alloy components, the strength of β-solidifying TiAl alloy sheets is only moderately higher and sometimes even lower than those of the as-forged counterpart alloys [8].

Microstructural variations, which result from numerous transformation modes induced by heat treatment or thermomechanical deformation, have a significant effect on the mechanical properties [9–11]. Controlling the microstructure through the adjustment of the process parameters is therefore essential for improving the properties of alloys. Several studies, aimed at obtaining high-performance TiAl alloys, have focused on detailed characterization of the microstructure of these materials [12–16]. The typical microstructures of TiAl alloy can be broadly divided into four categories: near γ, duplex (DP), near lamellar (NL), and fully lamellar (FL) microstructures. Microstructures consisted of α_2/γ lamellar structures represent the most promising microstructure for excellent high-temperature performance, and are beneficial for strength enhancement of TiAl alloys. Fine and homogeneous DP structures may yield good ductility [17]. Therefore, to ensure sufficient ductility of the materials, a certain volume fraction of fine lamellar structures that yield improved strength are desirable [6,18].

The development of lamellar microstructures in TiAl alloy sheets is associated with three main factors: (1) remnants of the initial materials; (2) heat treatment; (3) thermomechanical processing. The lamellar microstructures in the as-rolled TiAl alloy sheet are usually the remnants of the initial ingot or the as-forged alloys. According to previous studies [19], these remnant colonies are characterized by a coarse lamellar structure and are inhomogeneously distributed in the alloy

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sheet. Shen [20] has reported that the Nb-containing TiAl alloy sheet subjected to 60% reduction is composed of a fibrous microstructure with remnant lamellar colonies consisting of coarse γ and α_2 lamellae. The grain size (> 50 μm) of these coarse lamellar structures ranges from tens to hundreds of micrometers. Moreover, refinement and homogenization of the grain size, via the subsequent heat treatment (even when relatively high cooling rates and short holding times are employed), are difficulty [11,21]. The mechanical properties (the strength or ductility) of the TiAl alloy sheet are usually reduced after heat treatment [8]. However, the thermomechanical processing route constitutes a very effective means of controlling the microstructure. Owing to the various solid-state phase transformations induced by cooling from the single-phase or multi-phase regions, relatively fine α_2/γ lamellar structures can be obtained via hot-deformation processing [22,23]. Studies on the evolution of the lamellar structure and its formation mechanism during the hot-rolling of β-solidifying TiAl alloys have, to date, rarely been reported. Therefore, the present work focuses on the analysis of lamellar microstructures generated during and after the final hot-rolling pass at an initial rolling temperature of 1260 °C. The main objective is to provide insight into the fabrication of high-performance β-solidifying TiAl alloy sheets. In contrast to previous studies [19,24,25], this work found that multi-type lamellar structures (such as β/γ, α_2/γ, APD and α_2/γ mixed lamellar structures) were newly formed after hot-rolling of the alloy. The morphology and nucleation-growth details of the lamellar structures, as well as the phase transformation mechanisms of fine β/γ and α_2/γ lamellar structures are discussed. The corresponding tensile properties of the as-rolled alloy sheet are also investigated.

2. Materials and Experimental Procedure

The β-solidifying Ti-43Al-9V-0.2Y alloy sheet was obtained via hot-pack rolling at an initial rolling temperature of 1260 °C. The rectangular preform (size: 100 × 60 × 20 mm^3) was cut from the as-forged pancake, cleaned via mechanical grinding, and encapsulated (via brazing) in 304 stainless steel. Afterward, the packed billet was preheated for ~1 h prior to hot-rolling, and then subjected to multiple passes under a room-temperature rolling mill. A sheet was rolled to a total reduction of 80% at a rolling speed and rolling reduction per pass of ~50 mm/s and ~25%, respectively. The packed alloy sheet was reheated at 1260 °C for 10–20 min during each pass. Subsequently, the as-rolled alloy sheet was tempered at 800 °C for 4–6 h and furnace-cooled to room temperature. The schematic diagram of the hot-rolling process is shown in Fig. 1. The resulting 390 × 78 × 3.5 mm^3 smooth and crack-free TiAl alloy sheet with uniform thickness is shown in Fig. 2.

The microstructure and phase composition of the as-forged and hot-rolled TiAl alloys were characterized using the back-scattered electron (BSE) mode on a FEI Quanta 200FEG electron microscope equipped with an electron backscatter diffraction (EBSD) detector. The samples (10 × 10 × 5 mm^3) for scanning electron microscopy (SEM) and EBSD observations were cut from the center of each alloy using electron discharge machining. These samples were then electro-polished (voltage: 25 V) in a solution of 60% methanol, 30% *n*-butanol, and 10% perchloric acid at −25 °C. An accelerating voltage of 25 kV, sample tilt of 70° and a working distance of 15 mm were used. The EBSD data was collected using a step-size of 0.2 μm and then analyzed with TSL OIM Analysis 6.14 software. The orientations of the β/γ and γ/α_2 grains were determined and represented as a triplet of Bunge Euler angles. Transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) observations were conducted on a Talos F200X-type microscope operating at 300 kV. TEM specimens (size: Φ10 mm × 0.3 mm) were cut from the SEM samples and then prepared via (i) mechanical polishing to a thickness of 100 μm, (ii) punching samples (size: Φ3 mm) from the plate and (iii) subsequent twin-jet electropolishing to the final thickness. The twin-jet electropolishing solution, temperature and voltage were same as those on preparing EBSD specimens. Flat tensile specimens (gauge size: 20 mm × 5 mm × 2 mm) were cut from the as-forged alloy and along the rolling direction of the hot-rolled sheet, and then polished with 2000-grit sand paper. Tensile tests at room and elevated temperatures were performed on an Instron 5569 testing machine at initial strain rates of $1.0 \times 10^{-4}\,s^{-1}$ and $5.0 \times 10^{-4}\,s^{-1}$, respectively.

3. Results and Discussion

3.1. Initial Microstructure of the As-forged Ti-43Al-9V-0.2Y Alloy

The initial microstructures of the as-forged Ti-43Al-9V-0.2Y alloy are shown in Fig. 3. Our previous phase composition analysis revealed that this alloy consists of γ (TiAl), β/B2, and a small amount of α_2 (Ti_3Al) and Y-rich phases [26]. Compared with the corresponding as-cast microstructure [27], the coarse β/γ lamellar structures (colony size: 50–100 μm) are only partially broken down and bent along the forging direction (see Fig. 3a). The TEM image (see Fig. 3b) reveals the very large average lamellar spacing of these coarse lamellar microstructures. However, SEM or TEM examination/observation reveal that α_2/γ lamellar structures are absent from the as-forged alloy. This indicates that the coarse β/γ lamellar structures are remnants of the ingot and new lamellar structures are generated in processes other than the hot-forging process.

3.2. Variation of Microstructure in the Hot-rolled Ti-43Al-9V-0.2Y Sheet

Microstructural observations of the hot-rolled Ti-43Al-9V-0.2Y alloy sheet are shown in Fig. 4. The coarse residual β/γ lamellar structures of the as-cast ingot are totally broken down after multi-pass hot-rolling, and a duplex microstructure is formed. The fine recrystallized γ grains (3–20 μm) in this microstructure are significantly smaller than those in the as-forged alloy. In addition, the lamellar colonies (average size: ~25 μm) newly formed after hot-rolling are smaller than that of the coarse residual β/γ lamellar ones. Based on the morphology, these newly-formed lamellar structures can be divided into two types: irregular coarse and regular fine ones, as shown in Fig. 4b and c, respectively.

EBSD micrographs and analysis results of the lamellar structures in the TiAl alloy sheet are shown in Fig. 5. The phase composition of the alloy sheet remains almost unchanged, and is characterized mainly by the presence of γ (TiAl), β/B2, and a small amount of α_2 (Ti_3Al) phase (see Fig. 5a). Therefore, the hot-rolling process has a very weak effect on the phase composition. However, the newly formed lamellar constituents, consisting of two types of lamellar structures (irregular coarse β/γ and regular fine α_2/γ ones) undergo significant changes. The inverse pole figures and pole figures (Fig. 5b and c) show the distribution of crystallographic orientations (COs) in these colonies. For the irregular lamellar constituents (Fig. 5b), the γ lamellae (grass-green contrast) and the β lamellae (pink contrast) in a single colony are each characterized by a unique CO. The same holds true for one regular lamellar colony (Fig. 5c), where a small fraction of α_2 lamellae (soft orange contrast) is also characterized by a unique CO. However, most of the γ lamellae are characterized by two different COs (orange and aqua contrast). The orientation relationship (OR) describing the relationship among the β, γ, and α_2 phases in the lamellar constituent zones is further investigated. During this investigation, the Euler angles and the corresponding pole figures (PFs) of five selected grains (see Fig. 5) are considered. The coincident points in the PFs of the grains indicate that these lamellar structures are composed of alternatively distributed β/γ or α_2/γ ones, described by $\{111\}_\beta \| \{110\}_\gamma$ (Fig. 5b) and $\{0001\}_{\alpha2} \| \{111\}_\gamma$ (Fig. 5c) ORs, respectively. In addition, the PFs and Euler angles of grain 4 and grain 5 indicate that the two differently oriented γ grains are characterized by a twin relationship that occurs on the {111} plane.

Further TEM analyses of the multi-type lamellar structures in the