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Quantitative study of surface relief produced by formation of lamellar microstructure in a γ-TiAl based alloy

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ABSTRACT

Surface relief produced during lamellar transformation in a Ti48Al2Cr2Nb (at.%) alloy was quantitatively studied. Three-dimensional representations and quantitative data exhibit there are three kinds of surface reliefs, single-tilt, regular-terrace and irregular-strip, corresponding to narrow-width, moderate-width and large-width lamellae, respectively. Observation on fine structure reveals that kinks and ledges of the three kinds of surface reliefs are different. All the surface reliefs are related to diffusional terrace-ledge-kink growth mechanism and only single-tilt surface relief combines displacive character. The γ lamellae grow forward by nucleation of growth islands one upon the other and increase length and width by kink migration. The kink density and size control the lateral growth and further determine the lamellar width.

1. Introduction

Titanium-aluminide alloys based on TiAl (γ) phase (γ-TiAl based alloys) have received special attention for high temperature applications in recent years due to their attractive properties [1]. It has been established that the mechanical properties of the alloys with lamellar microstructure are sensitive to lamellar parameters [2]. Formation process of lamellar microstructure can be considered to consist of precipitation reaction $\alpha \rightarrow \gamma$ to form γ lamellae and ordering reaction $\alpha \rightarrow \alpha_2$ to form α_2 lamellae from the high-temperature disordered α phase. Three different types of transformation mechanisms involved in formation of γ lamellae have been established, which are displacive [3], diffusional [4–7] and displacive-diffusive [8]. However, little work has been done to relate the growth mechanisms to the formation of γ lamellae with different width. One effective way is to investigate the surface relief of the lamellar microstructure by atomic force microscopy (AFM). The AFM technique has been applied for observation of fine structures of surface reliefs in steels [9] and substantially improves the understanding of involved transformation mechanism. The surface relief in γ-TiAl based alloys was firstly noticed by Valencia *et al.* [10], and then qualitatively examined by Sun and regarded as invariant-plane-strain (IPS) type [11]. However, the detailed structure of surface relief accompanying the lamellar formation in TiAl alloys has not been reported.

Therefore, in this work, topography and fine structures of surface relief produced during lamellar formation are quantitatively investigated. The aim is to inspect the essential characteristic of lamellar formation and reveal the growth mechanism controlling formation of γ lamellae with different width.

2. Materials and methods

Alloy with a nominal composition of Ti48Al2Cr2Nb (at.%) was chosen in this study. The alloy was prepared by vacuum arc melting (VAR) process. Specimens with 6 mm in diameter and 3.5 mm in thickness were polished by standard metallographic techniques, then put into a VL200DX-SVF17SP high-temperature laser scanning confocal microscopy in a high purity argon atmosphere. The specimens were heated to the single α phase field region (1430 °C) at 1.67 °C/s and held for 5 min, and then were cooled at 0.05 °C/s to form lamellar microstructure.

The as-prepared surface was directly examined at ambient temperature under scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) on a VEGA-LMH II. Quantitative characterization of the surface relieves was conducted by AFM on NT-MDT equipment.

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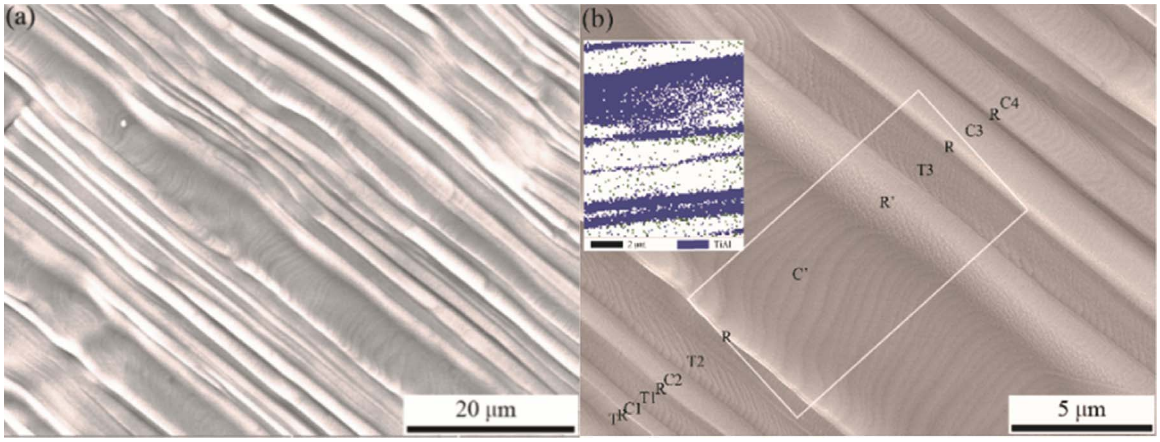

Fig. 1. SEM image and EBSD result of surface relief: (a) SEM image; (b) the magnified image of (a) and EBSD phase map inset of (b).

3. Results and discussion

3.1. SEM observation and phase identification

In the present study, the low cooling rate produces a microstructure with small γ grains distributed at boundary of lamellar colony [12]. The lamellae in lamellar colony generally have near equal width of 0.5–3 μm and occasionally show large width of 7–9 μm, and the typical microstructure is shown in Fig. 1(a). Fig. 1(b) exhibits that the surface reliefs could be classified into three types: shallow-corrugation structure (labeled by C) in narrow-width lamellae, regular-terrace structure (T) in moderate-width lamellae and irregular-corrugation structure (C′) in large-width lamellae. These structures are divided by sharp ridges (R) and wide ridges (R′). The combination of T-R-C-T-R-C structure is commonly observed in the microstructure except that T structure occasionally disappears and R-C-R-C is left, such as R-C3-R-C4. These indicate that surface reliefs of lamellae with near equal and large width are different.

EBSD result (inset in Fig. 1(b)) shows phase map of the rectangle area in Fig. 1(b). It demonstrates that T, C and C′ are certainly γ phases. The white areas cannot be identified due to poor signal quality.

3.2. Surface relief characterization by AFM

Three-dimensional (3-D) representation of the T-R-C1-T1-R-C2-T2 is presented in Fig. 2(a). It can be found that R-C1 and R-C2 correspond to single-tilt surface reliefs, and T1 and T2 correspond to regular-terrace surface reliefs. The single-tilt surface relief consists of an inclined surface, a corrugation structure and a cambered surface. The regular-terrace surface relief consists of ledges with their terrace planes parallel to each other. The 3-D representation of C′-R′-T3-R-C3-R-C4 (Fig. 2b) presents that R-C-R-C actually appears as two single-tilt surface reliefs, and C′ is irregular-stripe surface relief with rough undulation.

The topographic line-scans along AB and CD are shown in Fig. 2(c) and (d), and AB and CD are chosen to be perpendicular to the ridge of C1 and C3, respectively. The profile curves are divided into sections to obtain quantitative data according to the 3-D morphology. The height is approximately 90–190 nm for C1 to C4 and 60–80 nm for T1 and T2, respectively. This is in good agreement with the work of Sun [11].

The relief angle is used to characterize whether the single-tilt surface relief is IPS-type. If it is, the angles between inclined surfaces and horizontal plane should be approximately equal according to the definition of IPS [13]. However, the values are scattered and do not agree with the theoretical calculated relief angle value 19.5° [14]. Therefore, single-tilt surface relief could not belong to the IPS type.

3.3. Fine structure observation

To obtain a deeper understanding of the formation of lamellae with different width, fine structures of surface reliefs are investigated in detail. In addition to the parallel terrace planes, kinks and ledges are found on both terrace planes and side surfaces in regular-terrace surface relief T2 in moderate-width lamellae, as indicated by arrows in Fig. 3(b). It demonstrates that terrace-ledge-kink growth mechanism [15] is involved in the formation of γ lamellae. A special phenomenon of regular terrace (in T3) is shown in Fig. 3(b), which exhibits a pyramid terraces configuration with growth islands. These growth islands are new precipitated ledges at different growth stages. Kinks distribute on side surfaces of these islands, and especially concentrate on the side surfaces which are nearly perpendicular to the length direction of γ lamellae. It implies that the γ lamellae grow forward by nucleation of growth islands one upon the other and increase length and width by migration of kinks on side surfaces of the growth islands (or ledges). These growth islands can be produced by migration of partial dislocations in α_2 matrix and are an evidence of sympathetic nucleation [6,7].

Fig. 3(c) clearly reveals that the corrugation structures in single-tilt surface relief C3 in narrow-width lamellae are fine regular terraces. However, the fact that the inclined and cambered surfaces remain flat means no obvious ledges exist on these two surfaces, which indicates some displacive mechanism could be involved.

Fig. 3(d) demonstrates the irregular strips in C′, which is produced by formation of γ lamellae with large width, share common parallel terrace planes. Therefore, these strips are actually terraces with irregular edges, on which ultra-high density kinks can be observed. This characteristic is more obvious on the adjusted height scale (Fig. 3(e)). Furthermore, density and size of kinks are different along irregular edges. It verifies that fluctuations of density and size of these kinks cause change in local lateral growth rates, and then produce poorly shaped edges.

Quantitative data of height and spacing (h and s) of the ledges obtained by line scans along EF, GH, IJ and KL are shown in Table 1. It reveals that ledge size changes from several nanometers to hundreds nm, which is in good agreement with stacking faults spacing and the ledge heights measured by TEM [16]. However, the effect of ledge size on formation of lamellar width is not obvious. Based on the fact that the observed kink density increases with the increase of lamellar width, it can be concluded that formation of γ lamellae with different width is controlled by migration of kinks which is different for different types of lamellar transformation according to the work of Zghal et al. [6].

4. Conclusions

(1) The surface reliefs are produced by formation of γ lamellae and can