

# Morphology of discontinuous coarsening in fully lamellar TiAl<sup>①</sup>

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**Abstract:** The morphology of discontinuous coarsening in Ti-48Al-2Cr (mole fraction, %) was investigated. Three types of morphology were observed in TiAl specimens heat-treated at temperatures ranging from 950 °C to 1250 °C. Type I has straight coarsened secondary lamellae nearly parallel to the colony boundary, and it forms along the colony boundaries nearly normal to the primary lamellae. Type II has straight coarsened secondary lamellae nearly normal to the colony boundary. Type III consists of curved secondary lamellae that have no distinct orientation with the colony boundary and the primary lamellae. At the same time, the effect of temperature and the orientation between the lamellae and the colony boundaries on the morphology was analyzed.

**Key words:** TiAl based alloy; discontinuous coarsening; morphology

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## 1 INTRODUCTION

The fully lamellar TiAl based alloy has been known to be one of the most promising candidates for high temperature structural applications for its high fracture toughness and creep resistance<sup>[1]</sup>. It shows limited room temperature ductility, but some improved room temperature ductility has been obtained by lamellar colony refinement through thermomechanical treatments and alloying<sup>[2-4]</sup>. Because of the low energy semicoherent  $(0001)_{\alpha_2} \parallel \{111\}_{\gamma}$  interfaces in the lamellar structure, the thermal stability of the lamellae is basically good<sup>[5]</sup>. But the edges of  $\alpha_2$  and  $\gamma$  plates near lamellar colony boundaries may cause the discontinuous coarsening of the TiAl based alloy<sup>[6]</sup>.

So the high temperature properties may be decreased by the thermal microstructure instability. Numerous experimental studies were focused on the discontinuous coarsening in the TiAl based alloy, but most of the studies were dedicated to the kinetic and driving force of the discontinuous coarsening process. Although the major driving force for the discontinuous coarsening reaction is considered to be the reduction of the surface free energy<sup>[7]</sup>, the residual chemical free energy<sup>[8]</sup> and the elastic strain energy in the surface layer<sup>[9]</sup> may also be the contributing factors. However a limited number of investigations were concerned with the morphology of the discontinuously coarsened lamellae<sup>[10]</sup>.

In the present study, the morphology of the discontinuously coarsened lamellae was studied. At the same time, the effect of temperature and the orientation between the lamellae and the colony boundaries on the morphology was analyzed.

## 2 EXPERIMENTAL

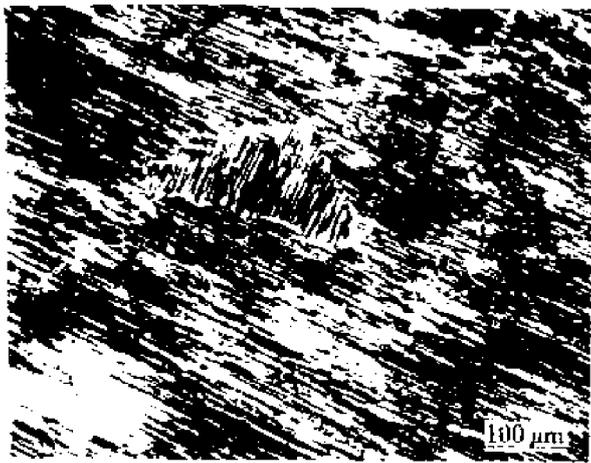
The alloys used were Ti-48Al-2Cr (mole fraction, %), which were prepared by consumable electrode arc melting under argon atmosphere by using high purity Ti (99.9%) and Al (99.99%). The ingots were remelted for three times to get homogenous composition. The ingots were cut into specimens of 15 mm × 15 mm × 15 mm. Heat-treatments were conducted at 850 °C, 950 °C, 1050 °C, 1150 °C and 1250 °C for 1 h, 10 h and 60 h respectively followed by air cooling to room temperature. Nephopt II optical microscope was used to observe microstructures. The etchant used was 1.5 HF and 2.5 HNO<sub>3</sub> (both in volume fraction, %) in distilled water.

## 3 RESULTS

The as-cast Ti-48Al-2Cr alloy consists of fully lamellar colonies and the colony size was about 800  $\mu\text{m}$ . When the specimens were heat-treated at 850 °C, the microstructures did not change. Heat-treatment at 950 °C for 1 h also did not change the microstructures significantly. Heat-treating at 950 °C for 10h resulted in the discontinuous coarsening along the lamellar colony boundaries. Fig. 1 shows the morphology of this type of discontinuous coarsening whose reaction takes place in the places that the primary lamellae on each side of the colony boundary are normal or nearly normal to the colony boundary, and it has coarse straight secondary lamellae that are parallel or nearly parallel to the colony boundary. This type of discontinuous coarsening is named as type I. Extending the heat-treating time resulted in the expansion of the area of this type of discontinuous coarsening.

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**Fig. 1** Optical microstructures of TiAl heat-treated at 950 °C for 10 h

Fig. 2 shows the microstructures of the specimens heat-treated at 1050 °C. Compared with Fig. 1, Fig. 2 shows more significant discontinuous coarsening and the morphology changes. As seen in Fig. 2 (a), besides type I discontinuous coarsening in zone A, in zone B there is another type of discontinuous coarsening with coarsened straight secondary lamellae that are nearly normal to colony boundary, and formed in the zones that the primary lamellae on one side of the colony boundary are normal to the colony boundary while those on the other side of the colony boundary are nearly parallel to the colony boundary. This type of discontinuous coarsening was named as type II. From Fig. 2(b), it is also found that type I discontinuous coarsening develops faster than type II does. Fig. 3 shows the microstructures of the specimens heat-treated at 1150 °C. As seen in Fig. 3, there is type III discontinuous coarsening coexisting with type I and type II discontinuous coarsening in the specimens. This type of discontinuous coarsening consists of curved secondary lamellae that have no distinct orientation with the colony boundary and the primary lamellae on each side of the boundary. At the

same time, the spacing of the secondary lamellar of type III is far thicker than that of type I and type II. With extending heat treating time, type I and type III discontinuous coarsening develop faster, but type II grows slower.

Heat-treating at 1250 °C for 1 h resulted in the significant discontinuous coarsening. Fig. 4(a) shows optical microstructures of the alloys that were heat-treated at 1250 °C for 10 h. As seen from this figure, most of the discontinuous coarsening is type III. And there is only a little type I and no type II. Extending heat-treating time resulted in fast growth of the discontinuous coarsening, but type III developed faster than type I (Fig. 4(b)). From Fig. 4(b), it is also found that most of the discontinuous coarsening develop along the colony boundaries.

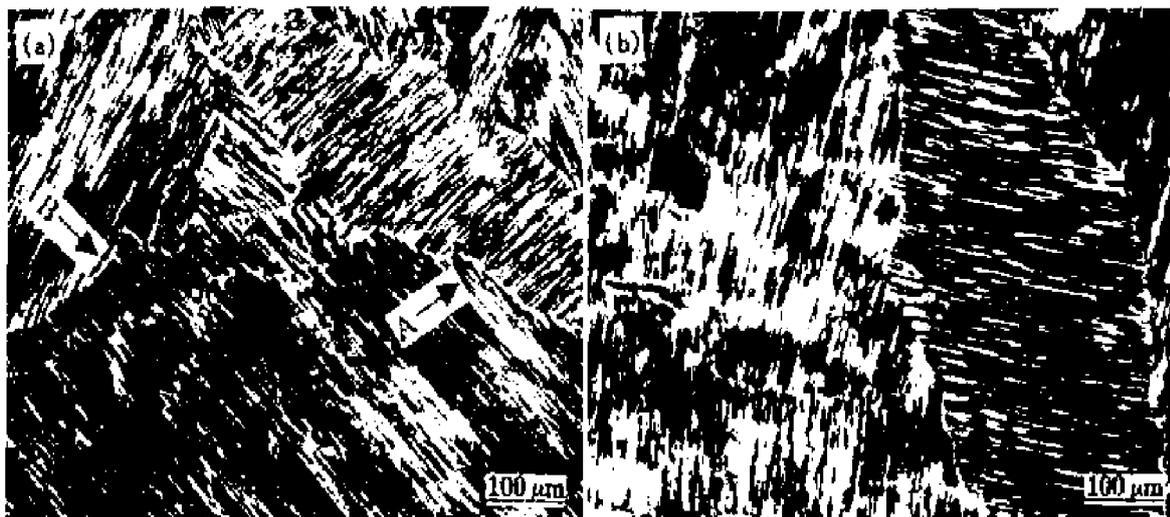
#### 4 DISCUSSION

Three types of morphology of the discontinuous coarsening in the TiAl based alloy are schematically drawn in Fig. 5. When the specimens were heat treated at 950 °C, only type I discontinuous coarsening was observed; but when heat-treated at higher temperatures, most of the discontinuous coarsening were type III and there was a little type I. It was difficult for type II discontinuous coarsening to form, however when the specimens were heat-treated at 1050 °C and 1150 °C, this type of discontinuous coarsening still could be observed.

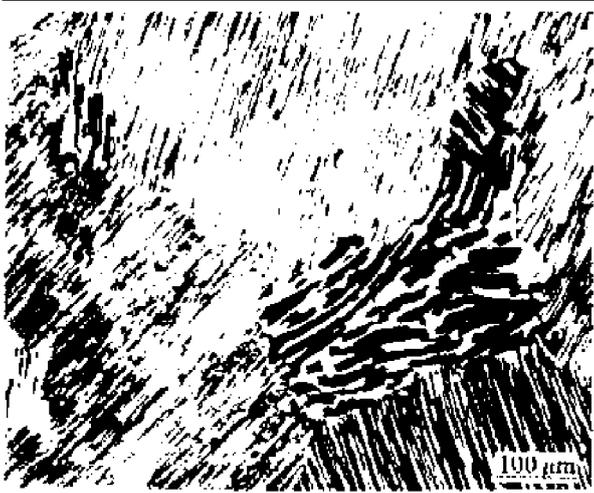
Now let us, through analyzing the formation condition of the discontinuous coarsening, discuss three types of discontinuous coarsening in terms of their dependence on the temperature and the orientation relationship between the lamellae and the colony boundaries. In general, the free energy terms that give rise to the driving force for the discontinuous coarsening process can be stated as

$$\Delta F = \Delta F_s + \Delta F_c + \Delta F_{sl} + \Delta F_{pl} \quad (1)$$

where  $\Delta F_s$  is the surface free energy,  $\Delta F_c$  is the



**Fig. 2** Optical microstructures of TiAl heat-treated at 1050 °C for (a) 10 h and (b) 60 h



**Fig. 3** Optical microstructures of TiAl heat-treated at 1150 °C for 10 h

chemical free energy,  $\Delta F_{st}$  is the strain free energy and  $\Delta F_{pt}$  is the phase transformation free energy. Depending on the system and the experimental conditions, all of these energy terms may be operative. The strain free energy exists on the surface layer of the specimens, so it exerts little influence on the discontinuous coarsening process<sup>[9]</sup>. If  $\alpha$  and  $\gamma$  are stoichiometric compounds, the chemical free energy may be neglected. When the specimens are heat-treated at temperatures under  $T_e$ , there is no effect of the phase transformation energy on the discontinuous coarsening reaction, so the surface energy could be the principal influence on the discontinuous coarsening process.

When only the surface free energy term is considered, the force exerted on the colony boundary by the lamellae can be given as

$$F = 2 \gamma \sin \theta / \lambda \quad (2)$$

where  $\gamma$  is the interface free energy,  $\theta$  is the angle between the lamellae and the colony boundary and  $\lambda$  is the spacing of the lamellae. The orientation of the force is along the lamellae. Fig. 6 shows the schematic drawing of the force whose normal component is

$$F_N = 2 \gamma \sin^2 \theta / \lambda \quad (3)$$

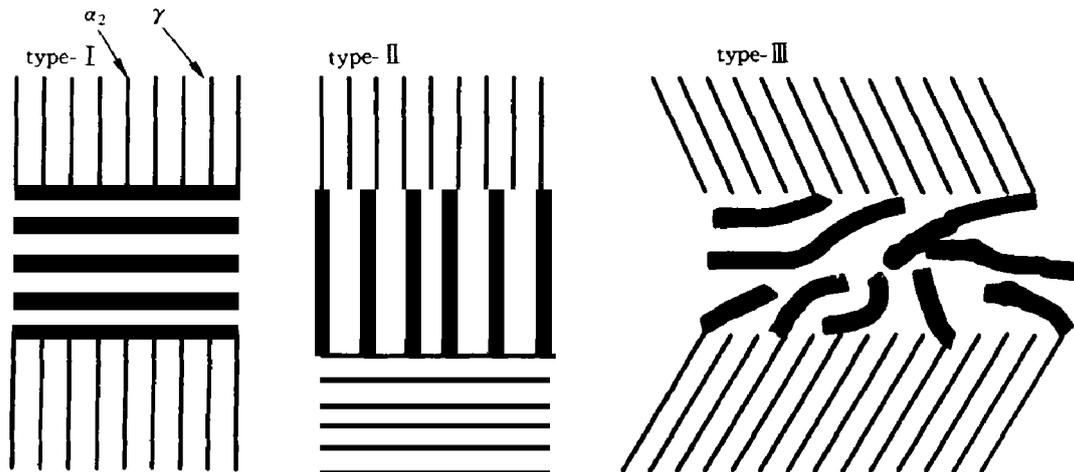
The parallel component of the force is

$$F_P = 2 \gamma \sin \theta \cos \theta / \lambda = \gamma \sin 2\theta / \lambda \quad (4)$$

$F_N$  is the driving force of the colony boundary migration and  $F_P$  causes the colony boundary to be elastically deformed. When  $F_N$  is larger than the limiting value for the formation of the discontinuous coarsening,  $[F_N]$ , the discontinuous coarsening reaction may take place. From the formation condition of

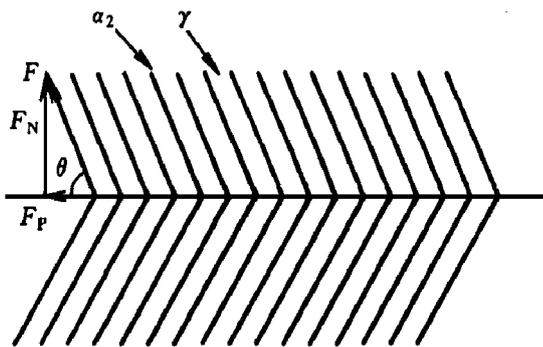


**Fig. 4** Optical microstructures of TiAl heat-treated at 1250 °C for (a) 10 h and (b) 60 h



**Fig. 5** Schematic drawing of three types of discontinuous coarsening morphology

the discontinuous coarsening discussed above, we can discover that increasing the interface free energy and the angle between the primary lamellae and the colony boundary and decreasing the spacing of the primary lamellae may be beneficial to the formation of the discontinuous coarsening. Because all the specimens were cooled in air, the spacing of the primary lamellae can be thought as constant. The effect of the spacing on the discontinuous coarsening may be neglected. Increasing heat-treatment temperature leads to the increase of the interface free energy, so it benefits to the formation of the discontinuous coarsening. When the primary lamellae is normal or nearly normal to the colony boundary and the secondary lamellae are parallel or nearly parallel to the colony boundary, it is easy for the colony boundary to migrate.



**Fig. 6** Schematic drawing of force acting on grain boundary

When the specimens are heat-treated at 850 °C, owing to the low interface free energy, it is impossible for the colony boundary to migrate even when the primary lamellae are normal to the colony boundary. When the specimens are heat-treated at 950 °C, the larger interface free energy can result in the colony boundary migrating in the zones that the primary lamellae are normal to the colony boundary, but the coarsened secondary lamellae are parallel to the colony boundary. When the specimens are heat-treated at 1050 °C, it is easy for the colony boundary to migrate and the coarsened secondary lamellae may be not parallel to the colony boundary. But it is easier for the secondary lamellae that are parallel to the colony boundary to develop. When the specimens are heat-treated at 1150 °C and 1250 °C, besides the interface free energy, the phase transformation free energy may exert great influence on the discontinuous coarsening process. Under the common roles of the surface free energy and the phase transformation free energy, the discontinuous coarsening may be easy to take place and the discontinuous coarsening process may develop very fast. Therefore, the coarsened secondary lamellae of type III discontinuous coarsening are far thicker than that of type I and type II. When the colony boundary is curved, the forces exerted on the colony boundary by the lamellae may be different in

different places because the angle between the lamellae and the colony boundary is different in different places. The difference including magnitude and orientation may cause the colony boundary to deflect. The phase interface of the coarsened secondary lamellae may deflect with the deflecting of the colony boundaries because the discontinuous coarsening lamellae are beneficial to form along the orientation that is parallel to the colony boundaries thus.

## 5 CONCLUSIONS

1) Three types of morphology of discontinuous coarsening were observed in TiAl. Type I has straight coarsened secondary lamellae that are nearly parallel to the colony boundary. Type II has straight coarsened secondary lamellae that are nearly normal to the colony boundary. Type III consists of curved lamellae that have no distinct orientation with the colony boundary and the primary lamellae.

2) The discontinuous coarsening reaction is easy to take place in the places that the primary lamellae are normal to the colony boundary.

3) Increasing temperature promotes the discontinuous coarsening process.

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