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Fracture characteristics of notched investment cast TiAl alloy through in situ SEM observation

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Abstract: TiAl alloys were produced by investment casting method combined with induction skull melting (ISM) technique. In situ scanning electron microscopy (SEM) was utilized to study the fracture characteristics and crack propagation of a notched investment cast TiAl specimens in tension under incremental loading conditions. The whole process of crack initiation, propagation and failure during tensile deformation was observed and characterized. The results show that the fracture mechanism was sensitive to not only the microcracks near the notched area but also lamellar orientation to loading axis. The high tensile stress leads to the new microcracks nucleate along lamellar interfaces of grains with favorable orientation when local stress intensity reaches the toughness threshold of the material. Thus, both plasticity and high tensile stress are required to cause notched TiAl failure.

Key words: TiAl alloys; investment cast; fracture characteristics; in situ SEM observation

1 Introduction

Gamma TiAl alloys have been widely regarded as very demanding structural materials for applications in the aerospace and automotive industries owing to a set of favorable properties, such as low density, high melting temperature, good elevated-temperature strength, high resistance to oxidation and excellent creep properties [1−3]. Investment casting process allows large-scale mass production of TiAl components, which reduce fuel consumption and emissions [4,5]. It has attracted extensive attention to casting of TiAl alloys in the field of turbocharger [6], exhaust valve [7] and turbine blade [4,8].

However, the significant drawback of TiAl alloys is their relatively limited ductility and crack-growth resistance at room temperature. The low ductility means that damage in terms of cracks is more inclined to result in the challenges of applications for TiAl components [9]. It is widely recognized that the problem of fracture becomes more sensitive in the presence of notches which can degrade both ductility and strength. Understanding how cracks initiate and propagate in TiAl alloys could provide useful information on the performance of TiAl components.

Many works have been published in the past few years that described experimental studies of fracture in TiAl alloys. In Ref. [10], the effects of load–unload-induced microcrack damage on fracture behavior of directionally solidified Ti−47.5Al−2.5V−1.0Cr (mole fraction, %) were investigated in flat specimens by tensile tests. A study on the fracture toughness tests was conducted on Ti−48Al−2Cr sheet material by hot rolling [11]. ZAN et al [12] made investigations on the tensile behaviors and fracture modes of TiAl (Ti−46.5Al−2Nb−2Cr, mole fraction, %) alloys at different temperatures and in different strain rate ranges, and found that fracture modes of the two alloys change from planar cleavage fracture to a mixture of transgranular and intergranular fractures, and finally to totally intergranular fracture.

Hitherto, the most of available data of crack growth testing are related to TiAl alloys produced by thermomechanical processing, such as forging and

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rolling. As reported early by CAO et al [13], the fracture behavior in a notched TiAl specimen was different from that in a smooth tensile test specimen. Investment casting which can produce near net shape components with a good surface finish and high metal yield, at the lowest projected cost, is a subject of growing interest [14]. A systematic study of fracture toughness testing and crack growth resistance of investment cast TiAl alloys has not been reported yet. Therefore, with the goal of providing information pertinent to the design of TiAl castings, the present study mainly focuses on the process of crack initiation and propagation of cracks in an investment cast TiAl alloy in order to characterize the mechanisms associated with these processes. The effects of grain boundaries and microcracks are given special attention.

2 Experimental

TiAl castings with a nominal composition of Ti−47Al−2Cr−2Nb (mole fraction, %) were produced by ISM technique. The parent materials used in this study were titanium sponge, high purity aluminum (99.99%), chromium (99.5%) and Al−Nb (53.5%, mass fraction). The alloy was melted in a water-cooled copper vacuum induction skull melting furnace which has a capacity of ~30 kg of TiAl alloy (ALD Vacuum Technologies GmbH, Germany). Details of investment casting process have been published previously [15].

Samples for characterization and in situ tensile test were cut from the investment cast specimens. Dimensions and macro picture of the prepared in situ tensile test specimen are shown in Fig. 1. In situ tensile specimens were cut by electric-discharged machining from the casting. The specimen was polished after machining. A notch was introduced as crack source, so as to control the site of crack initiation. In situ axial tensile test was performed and imaged by Hitachi S-570 SEM.

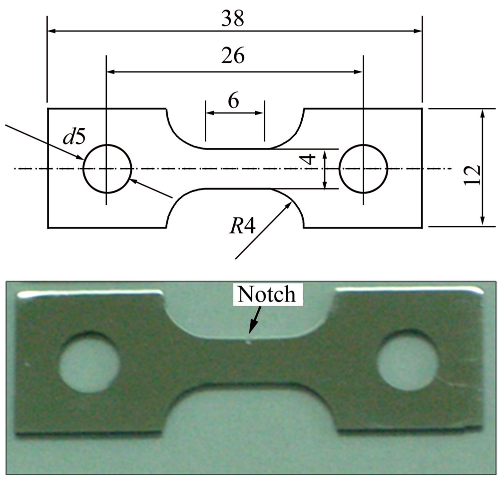

Fig. 1 Dimensions and macroscopic view of in situ tensile test specimen (Unit: mm)

Monotonic loading was carried out manually. In the whole tensile process, the sample was observed carefully in order to understand the initiation and propagation of crack. The loading was increased continuously until the specimen fractured to catastrophic failure. Special attention was put on the fracture facet pictures taken along the path of surface crack extension which developed during in situ tensile tests.

3 Results and discussions

3.1 Microstructure of TiAl casting

The microstructures of TiAl casting are shown in Fig. 2. As can be seen from Fig. 2, it is a typical near lamellar columnar structure. The microstructure exhibits coarse grains and the grain size varies among different grains. The average grain size is about 500 μm. There exists a little γ phase. Irregular serration is presented by the reason that lamellar grows into neighbor colony

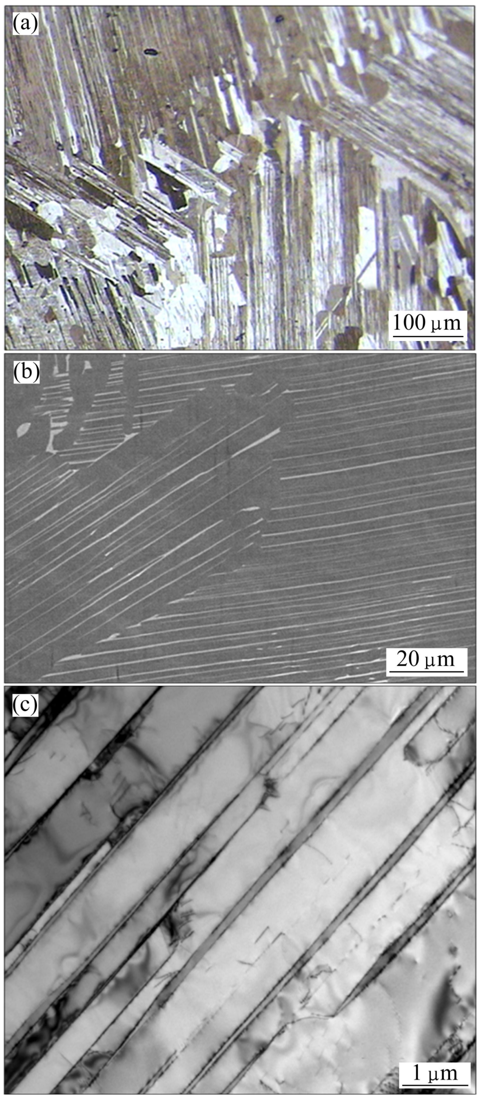

Fig. 2 Microstructures of TiAl castings: (a) Optical microstructure; (b) SEM image; (c) TEM lamellar microstructure

which is near to the boundary of lamellar group. Lamellar orientation in the internal and single lamellar is identical. TEM microstructure of TiAl casting is illustrated in Fig. 2(c). Biphase of α_2/γ is found and the lamellar spacing is 400 nm.

3.2 Observation of in situ tensile test

From the fracture process of TiAl alloy during the tensile test (Fig. 3), it is observed that the main cracks I, II and III perpendicular to the loading direction initiate firstly and many microcracks emerge at the same time

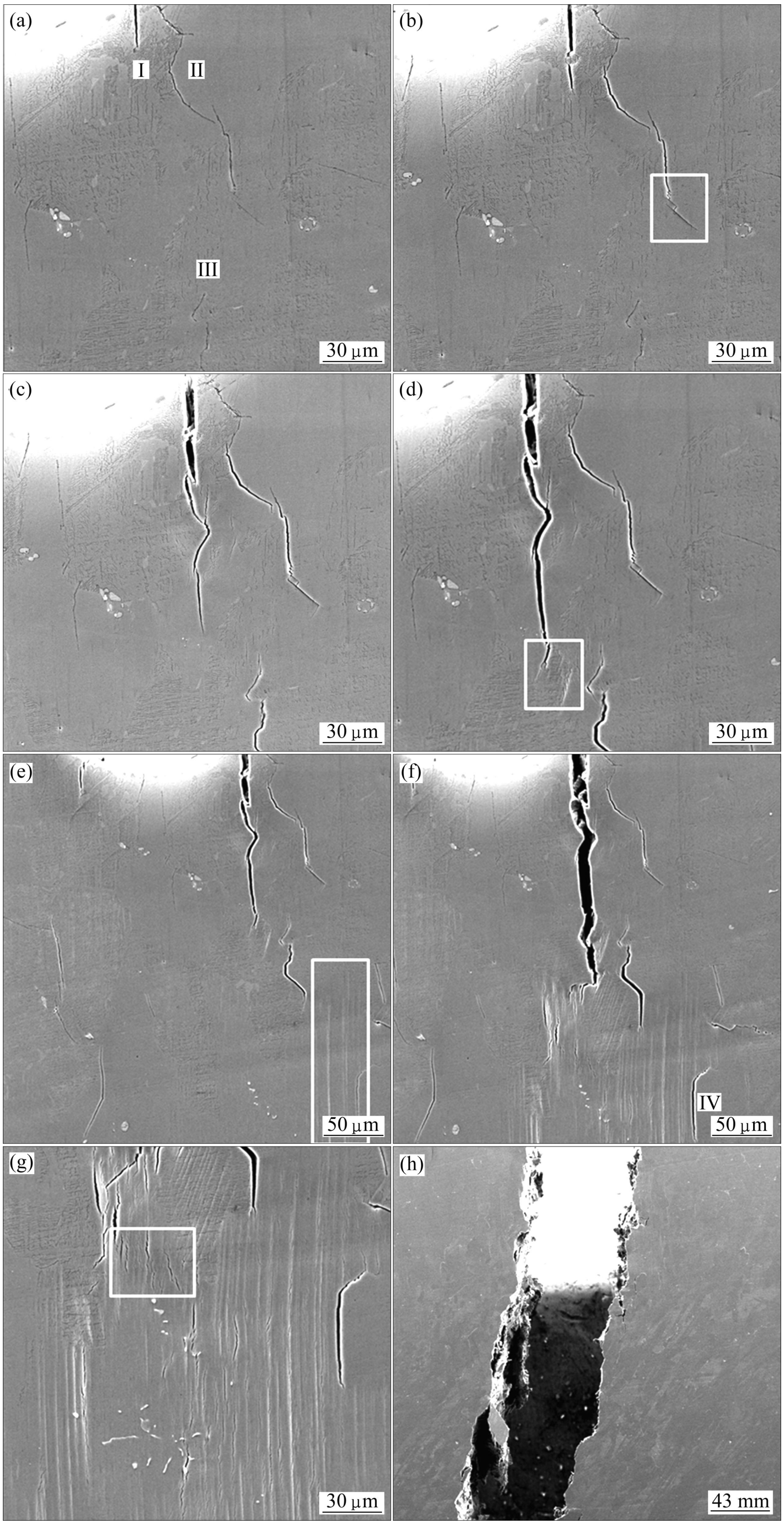

Fig. 3 Fracture process of TiAl alloy during in-situ tensile test with horizontal loading: (a)−(g) Cracks initiation and propagation under various strains; (h) Failed SEM specimen

(Fig. 3(a)). Main cracks I and II expand when further loading is applied. Among them, the width of crack I is increased obviously (Fig. 3(b)). Crack I expands rapidly with continuous loading and its length is equivalent to crack II (Fig. 3(c)). In Fig. 3(d)), crack I expands obviously meanwhile slip bands are observed at the front-end of crack I. The angle between orientation of slip bands and tensile direction is 45°. It shows a tendency to be overlapped with crack III (rectangle area in Fig. 3(d)). A small amount of slip bands perpendicular to loading direction are observed in lower right corner of crack III (rectangle area in Fig. 3(e)). However, there is no obvious variation for crack II. As the loading continues, the width of crack I increases continuously. Front slip bands seem to be teared up. New crack IV which is perpendicular to the tensile direction and locates at the lower right corner of crack III is observed in Fig. 3(f)). When loading goes up, uncontinuous microcracks overlap (rectangle area in Fig. 3(g)), thus leading to failure finally (Fig. 3(h)).

Based on the observation of in situ tensile test process of TiAl alloys in Fig.3, it can be concluded that there exists large stress concentration near the notched area and microcracks will initiate along interlamination when the initial loading is first applied to the specimen. Part of microcracks will have enough time to initiate and expand (Path 1 in Fig. 4). As the loading increases, once the microcracks form, they will fracture through entire grain size rapidly because they have no time to expand. In this case, TiAl alloys are indicated to have strong notch sensitivity (Path 2 in Fig. 4).

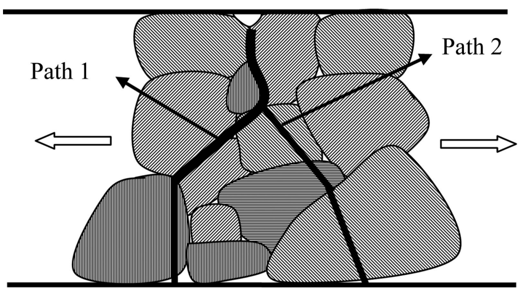

Fig. 4 Cracks initiation and propagation path of TiAl alloy under in situ tensile test

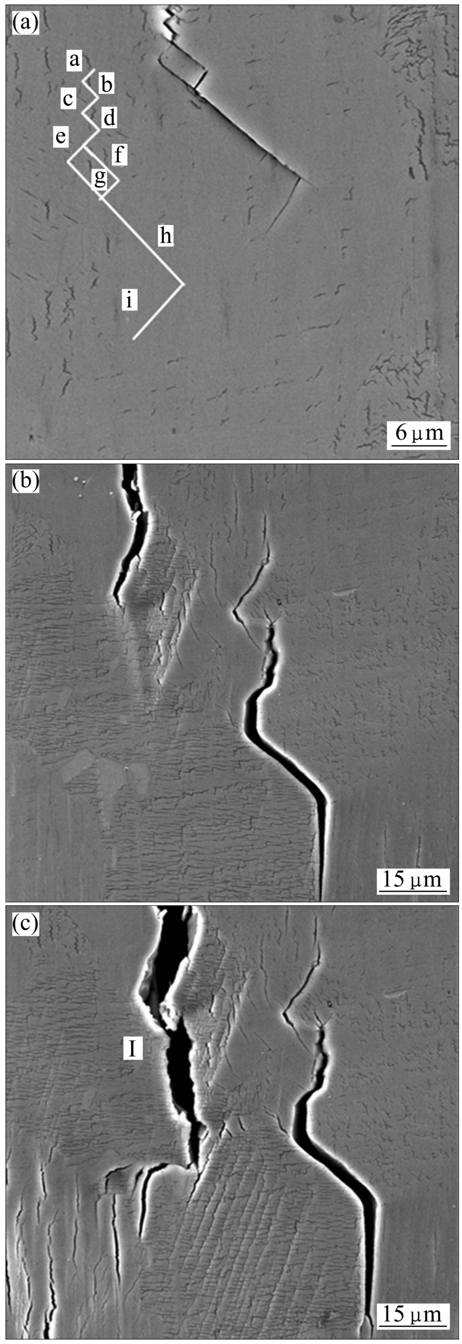

Fig. 5 SEM images showing initiation and propagation of microcracks in TiAl

3.3 Fracture mechanism of investment cast TiAl alloys

Figure 5(a) shows a high magnification of main crack II in rectangle area of Fig. 3(b). Cracks perpendicular to lamellar are triggered out at the tip of zigzag. The cracks connect each other by cleavage along the lamellar interface. The crack path appears to be serration. Lamellar cleavage cracks (a, c, e, g, i) are indicated in Fig. 5(a). Cracks (b, d, f, h) extend along lamellar. Microcracks nucleate along lamellar in Fig. 5(b). At the surrounding of cracks, there exists numerous slip bands. Thus, it is proved that microcracks nucleate along slip bands. In Fig. 5(c), the front-end of main crack I is decomposed into multiple slip bands and further develops into cleavage microcracks. And part of them connects each other. Microcracks can also be observed along phase interface. For TiAl alloys, the gliding plane is {111} and the cleavage planes are {111}, {100} and {110} [16]. In Fig. 5(c), slip bands at the front end of main crack I will stop in lamellar interface when coming cross unfavorable lamellar direction.

A large number of dislocations and stacking faults make deformation easy to coordinate in the low strain deformation rate process to some extent. The stress is buffered in the loading process and internal stress concentration at the notched place of specimens is relaxed obviously. TiAl alloys exhibit insensitive to the defects, and fracture mainly happens at parallel segment when the strain rate is low. Figure 6 represents dislocation pile-up in slip bands in TEM image. Previous research results showed that local plastic deformation happened firstly at the crack tip [17]. Cracks initiate when local plastic deformation is developed to the threshold with the increase of stress intensity factor. It can be deduced that atomic bond breaks up while the dislocation pile-up group is long enough. That is to say, stress concentration at micro zone of the front-end of dislocation pile-up group is larger than or equal to atom bond strength. Combining with the analysis of Fig. 5, it can be concluded that slip bands tend to terminate in a lamellar while the direction will be changed when it passes through another lamellar. This indicates that lamellar is not only the obstacle of movement of dislocation but also the obstacle of the initiation and expansion of microcracks. The increase of fracture resistance force with the expansion of cracks can be attributed to plastic deformation before the initiation of cracks.

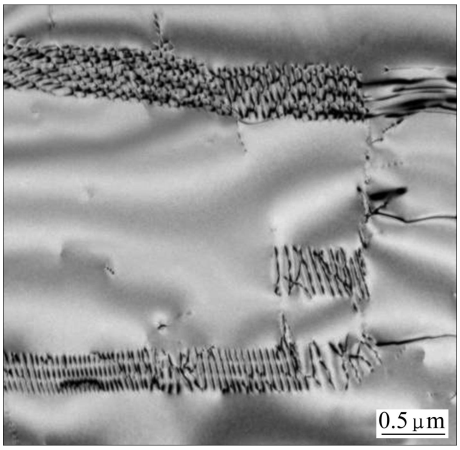

Fig. 6 TEM morphology of dislocations pile-up in slip bands

4 Conclusions

1) The characteristics of observed cracks propagation in notched TiAl casting could be divided into two modes: inter-layer and trans-layer. The preferred path of cracks usually initiate in the weakest site of interface of α_2/γ or γ/γ.

2) There exists plastic zone around the tip of cracks. Slip bands tend to terminate in a lamellar while the direction will be changed when they pass through another lamellar.

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带缺口的熔模铸造 TiAl 合金断裂特性的扫描电镜原位观察

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摘　要：采用感应凝壳熔炼技术和熔模铸造方法制备 TiAl 合金。在增量加载情况下，采用扫描电镜原位观察技术观察带缺口的熔模铸造 TiAl 合金试样的裂纹扩展和断裂特性。在拉伸变形的整个过程中，观察并分析裂纹萌生、扩展直至断裂的全过程。结果表明，TiAl 合金的断裂机制不仅对于缺口区域附近的微裂纹敏感，而且与层片方向和加载轴的位向有关。当局部应力大于 TiAl 合金的断裂韧性时，高的拉伸应力就会导致裂纹萌生、扩展直至断裂失效。因此，TiAl 合金的塑性和高的拉伸应力导致带缺口的 TiAl 合金的断裂失效。

关键词：TiAl 合金；熔模铸造；断裂特性；扫描电镜原位观察

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