FRACTURE MECHANISM OF A TIAL ALLOY

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ABSTRACT

Combining with in-situ tensile tests, the macro-results of 3PB tests and detailed observations of fracture surfaces and remaining cracks in unloaded precracked specimens of a two-phase TiAl alloy, results of series investigations on the fracture mechanisms of a TiAl alloy are summarized. The results reveal that Cracks prefer to initiate and propagate along lamellar interfaces, which are the weakest link in the near fully lamellar microstructure. The interlamellar strength calculated is less than the translamellar strength. The tensile stress is the driving force for crack initiation and propagation. The inverse relationship between ductility and fracture toughness of finer duplex and coarser near fully lamellar microstructures is caused by the difference of the crack propagation path taken by the crack in the tensile test and in the bending test of precracked specimens where the sampling volume is different. On the fracture surfaces of the coarse near fully lamellar microstructure, less low-energy interlamellar fracture facets are observed, which means that it is more difficult for the crack to bypass the coarser near fully lamellar grain with unfavorable direction and to take the interlamellar path. But in tensile tests, due to the much larger sampling volume, the cracks take the weakest path and show an inferior ductility in a coarse grain microstructure. The toughening mechanisms, which make propagation of the main crack difficult to propagate or cause it to be stopped, could be: Reducing the driving force by blunting of crack tip; Bifurcation of the crack tip; Deflection of the crack by lamellae and formation of a diffuse zone of microcracks; Stopping the crack at the boundary of a grain with unfavorable orientation or γ grains and forcing the crack to bypass the barrier grain and take a tortuous path, or cross the barrier grain spending more energy.

1 INTRODUCTION

Considerable interest exists in the development of titanium aluminide (TiAl) alloys for use in high-temperature structural applications, due to their low density, strength retention at high temperature, and potential for excellent fatigue resistance (Kim [1, 2]). Many research work has been done on the fracture processes and toughening mechanisms of TiAl alloys. Chen [3] has found the tensile stress is the driving force for crack propagation. Chan et al [4] has shown that the initiation of micro-cracks either at colony boundaries, along lamellar interfaces, or at equiaxed γ grains located at colony boundaries and the linkage of the micro-cracks with the main crack by shear fracture of the near-tip ligaments dominate the fracture process in the lamellar microstructure. Lu et al [5] and Inui et al [6] indicated that the crack propagates either along lamellar interfaces (interlamellar fracture) or skews to the lamellae (translamellar fracture), depending on the direction of the main crack relative to the lamellae.

Recently, Chan et al [7] showed that the magnitude of the resistance to crack growth offered by the boundaries was dependent on the lamellar misorientation across the boundaries. However, in the Wang [8], they have demonstrated that the preferred fracture mode within a colony is delamination along γ/α_2 interfaces and or within α_2 lamellae and that this occurs with virtually no resistance (K_{eq}=0.6-1.8 MPam$^{1/2}$). But colony boundaries were effective in stopping an advancing crack if the lamellar twist misorientation across the boundaries are large. Guo at al [9] found that internal stress play an important role in determining the fracture toughness of the TiAl-based alloy, the compression internal stresses in γ phase and the tensile internal stresses in α_2 phase may be responsible for the delamination along the γ/α_2 boundaries.

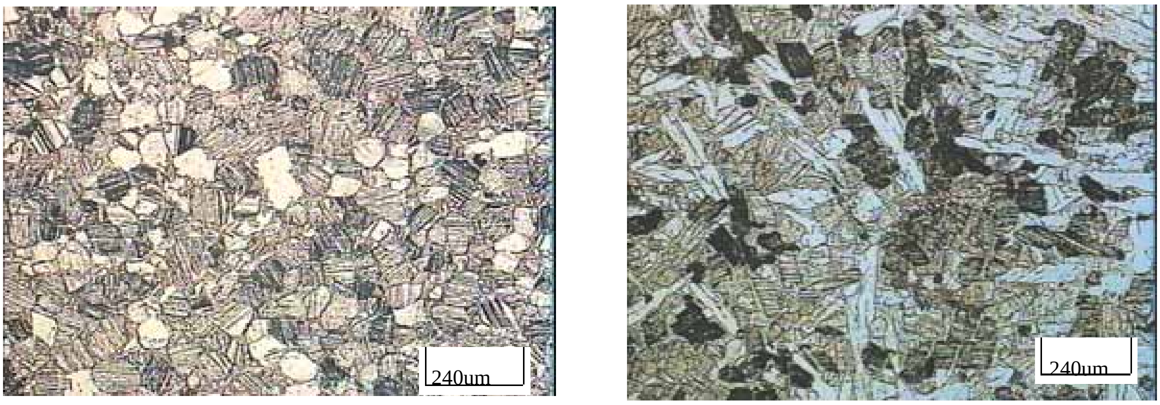
In this paper the present authors summarize the results of the recent work related to the TiAl alloy.

2 EXPERIMENTAL

A nominal chemical composition of the material is Al 46.3, V 2.0, Cr 1.0, Ni 0.5, B 0.1 and balance Ti. All the compositions in this paper are given in atom percentage. Two types of microstructures, duplex (DP) and near fully lamellar (NFL) were prepared. The DP microstructure is shown in Figure 1(a) as 160 μm γ/α_2 lamellar grains with γ grains at the boundaries. The NFL microstructure is shown in Figure 1(b) as elongated γ/α_2 lamellar grains of 80×320 μm in length.

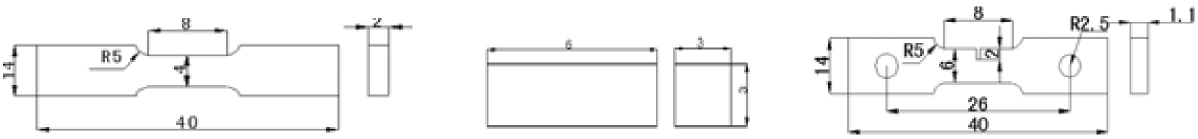
All specimens are shown in Figure 2. Tensile and compression specimens were used to measure mechanical properties. *In-situ* tensile specimens were used to observe fracture process. 3PB specimens for metallographic observations were prepared for observations of cracks configuration at various applied load. 3PB, 4PB(single notch and double notches) were used to measure fracture toughness and observe fracture feature. The double notch specimens were used specially for observing cracks remaining in fracture specimens.

Tensile and compression tests were conducted in air at room temperature by SHIMADSU AG-10TA universal test machine with a cross head speed of 0.025mm/min. *In-situ* tensile tests were performed in vacuum using a calibrated loading stage in a scanning electron microscope (SEM) S-520. The specimens were slowly step-loaded manually and the crack patterns at various loading steps were recorded by SEM. The crack initiating and propagating processes in conjunction with applied loads were recorded. Fracture surface observations were carried out along the path of *in-situ* observed surface crack extension. 3PB and 4PB tests were carried out in air at room temperature by a SHIMADZU AG-10TA universal test machine with a cross head speed of 0.5mm/min. Five metallographic sections were cut perpendicular to the precrack tip for each unloaded specimen or to the surviving notch root after another notch was fractured, fracture surfaces were observed by SEM. FEM calculations and simulations were carried out by the ABAQUS code.

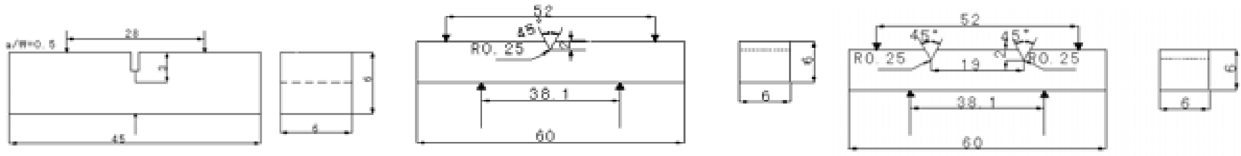


(a) (b)

Fig.1. Microstructures of (a) duplex (b) near fully lamellar TiAl alloy



(a) (b) (c)



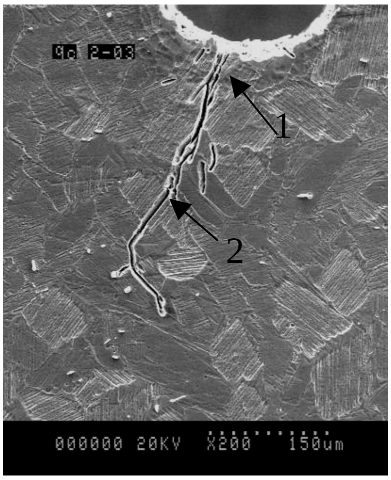
(d) (e) (f)

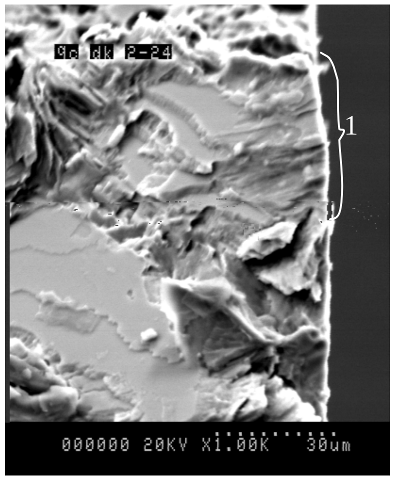
Fig.2—Dimensions of specimens for (a) Tensile, (b)Compression, (c) In situ observations, (d)3PB, (e)single notch 4PB, (f)double notches 4PB

3 RESULTS AND DISCUSSION

3.1 Fracture process

Cracks prefer to be initiated and propagated along lamellar interfaces, it is shown in Figure 3 (a) (crack 1 and 2). The interlamellar strength (around 50MPa) is apparently lower than the translamellar strength (around 120MPa) in near fully-lamellar microstructure. That means the weakest link is the lamellar interfaces in the near fully-lamellar microstructure. Table 1 lists various stresses calculated at the moment of initation of several microcracks as in-situ observed in very thin specimen F02. It is revealed that all values of either equivalent stresses or shear stresses acting at the moment of crack initiation are lower than those of the lowest values for inducing yielding in the soft mode deformation (σ_e=100MPa and τ=50MPa)[6]. Therefore, at the microscopic scale, the stresses are also insufficient to induce yielding at the moment of initiation of interlamellar cracks. *In situ*-observations did not find any slip traces before micro-crack initiation on the surfaces. There was no evidence to support the argument that micro-yield is a necessary precursor for the macroscopic cleavage cracking. Based on above observations, it is argued that for the present alloy at the microscopic scale, cracks are initiated within an elastic environment in a thin tensile specimen. A reasonable inference is that the driving force for initiating a cleavage crack is the tensile stress rather than the shear stress or the plastic strain.





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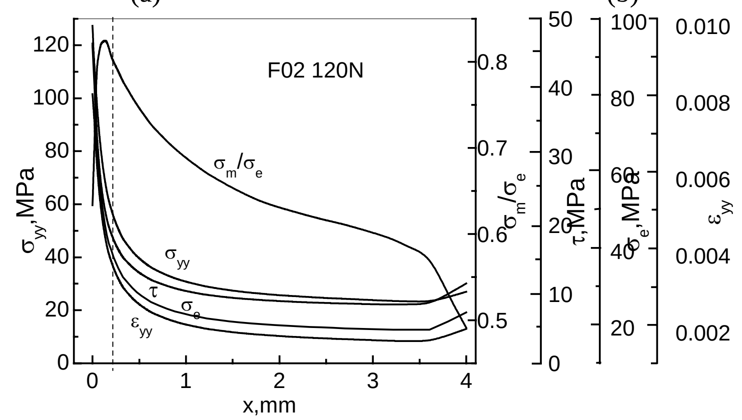


(c)

Figure 3 At applied load of 120N (a) in situ observed surface (b) fracture surface showing a facet corresponding the new crack 1 (pointed by the white bracket 1) (c) stress, strain, stress triaxiality, equivalent stress and shear stress distributions at the surface of specimen (dash vertical line showing crack-tip position of crack 2)

Table 1. Various stresses at the moment of initiation of micro-cracks

Stress	Crack 1	Crack 2	Crack 3	Bifurcated crack	Crack 7	Yield stress [6]
σ_{yy} (MPa)	<120	57	109-118	43	60	—
σ_e (MPa)	93	38.7	74-81.8	86.6	75.4	100
τ (MPa)	—	18.4	37-38.2	14.1	39.6	50

σ_{yy} =normal stress to the crack surface, σ_e =equivalent stress at the crack location τ =shear stress acting on the crack surface, yield stress measured in the soft mode deformation of PST crystal with an angle of 31^0 between the lamellar boundary and the tensile loading axes.

3.2 The reason for the inverse ductility/K_{1C} relationship

The stress-strain curves obtained from tensile and compression tests of the specimens with the two microstructures are plotted in Figure 4 (Chen [10]), it is found that tensile ductility of finer duplex microstructure is superior to that of coarser near fully-lamellar microstructure. The inferior properties presented for the tensile tests are believed to be caused by the damage of the material, which occurs at much lower applied loads prior to yielding. The fracture stress and strain of the specimens with duplex microstructure are superior to those with near fully-lamellar microstructure. From Table 2(Chen [11]) and Chen [12], it is found that the values of fracture toughness on average are higher for coarser NFL microstructure than for finer DP microstructure, it is similar to the results of Chan [4]. Thus the inverse ductility/K_{1C} relationship observed by [4] is also seen in this work.

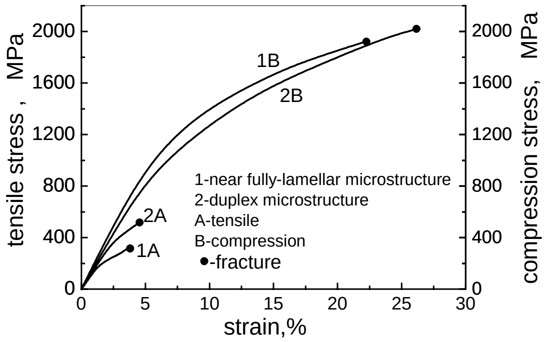


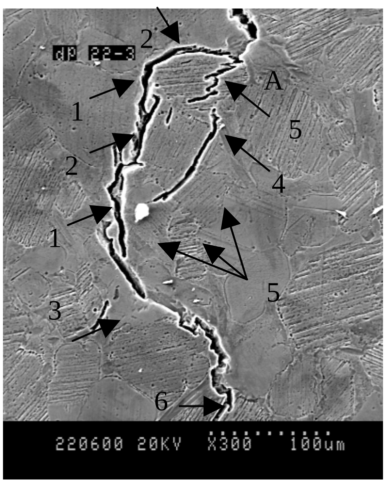
Fig.4—Engineering stress-strain curves

Table 2. Results of 4PB tests at room temperature

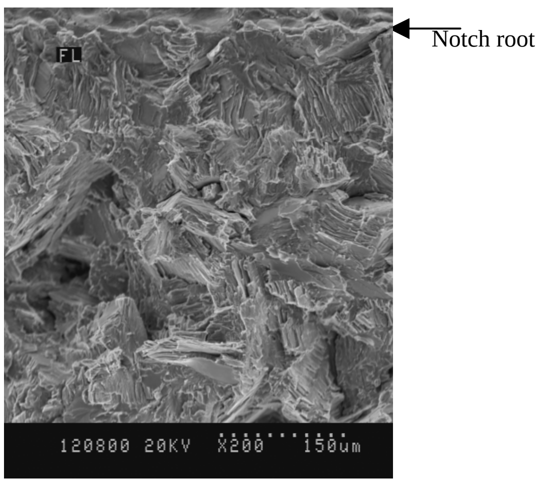
No	Notch type	w(J)	w'(J/mm^2)	P_f(N)	W(mm)	B(mm)	a(mm)
NFL31	Single notch	0.332	13.29*10^{-3}	1999.2	6.068	6.116	2
NFL32	Double notch	0.321	12.18*10^{-3}	2146.2	6.141	6.292	2
NFL33	smooth	0.626	33.39*10^{-3}	1842.4	6.115	3.066	-
DP31	Single notch	0.199	7.804*10^{-3}	1528.8	6.134	6.157	2
DP32	Double notch	0.243	9.554*10^{-3}	1728.7	6.142	6.141	2

No=specimen's number, NFL=near fully-lamellar, DP= Duplex, P_f=fracture load, w=energy absorbed in fracture, w'=fracture energy by unit area, W=specimen's width, B=specimen's thickness, a: notch depth

In the precracked 3PB specimens, the sampling volume is restricted in the vicinity along the precrack direction. If there is a barrier made by a grain with a lamellar interface orientation unfavorable for crack propagation. Either the propagating crack bypasses the barrier by deflection and travels through interlamellar cracks with a longer path (Figure 5 (a)) (Chen [12]) or crosses it by translamellar cracking which should spend more energy, it is concerned with colony boundaries resistance to crack propagation in lamellar [8]. In coarser NFL microstructure, the crack should cross more larger grains with unfavorable orientation (Figure 5(b)) (Chen [12]) or bypass them by longer and much more tortuous path, which causes a much rougher fracture surface. This is why the coarser NFL microstructure shows higher fracture toughness to that of the finer DP microstructure. The tensile conditional yield strength and the tensile fracture stress and strain of the specimens with the coarser NFL microstructure are inferior to those of specimens with the finer DP microstructure. These phenomena are attributed to the much higher sampling volume in tensile tests, which involves all volume within the gauge. In contradiction to the case of precracked specimen, in the tensile specimen the cleavage fracture is able to take the weakest way with highest portions of interlamellar cracking. In this case, the cleavage fracture stress σ_f will be determined by the largest grains (Chen [13]). The coarser NFL microstructure will show a lower strength due to its larger lamellar grains.



(a)



(b)

Fig.5 (a) Section surfaces of unloaded specimens DP22 at applied load=523N, (b)fracture surface of NFL12

In Figure 6 [12], a fact supporting this idea is shown that from a notch, the fatigue crack can make a choice to take a path with lower resistance. It is reasonable to infer that for a smooth plan specimen for tensile test, more choices of lower resistance paths can be taken, where much larger sampling volume exists. Therefore in a tensile specimen the cleavage fracture is able to take the weakest way with highest portions of interlamellar cracking. The superiority of coarse lamellar grains shown in the precracked specimen, where the sampling volume is seriously restricted, cannot act in effect in tensile tests. This also explains the phenomenon that tensile ductility and fracture toughness depend upon colony or grain sizes in an opposite manner.

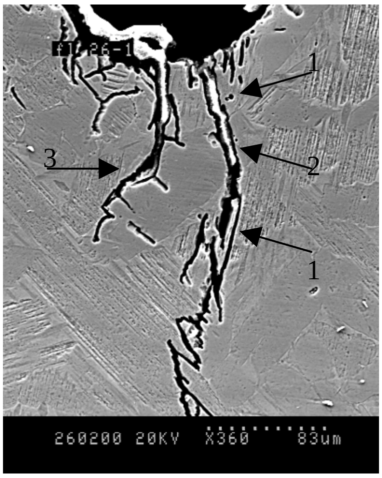
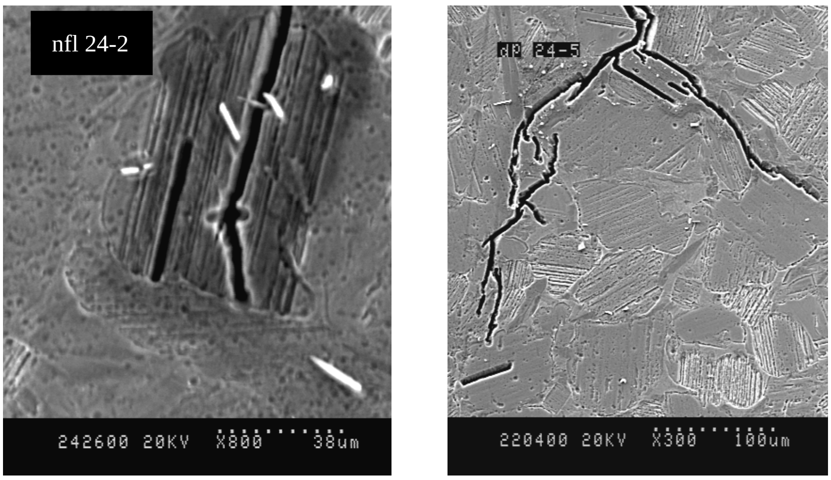


Fig.6 Competition between two fatigue cracks initiating at same notch root

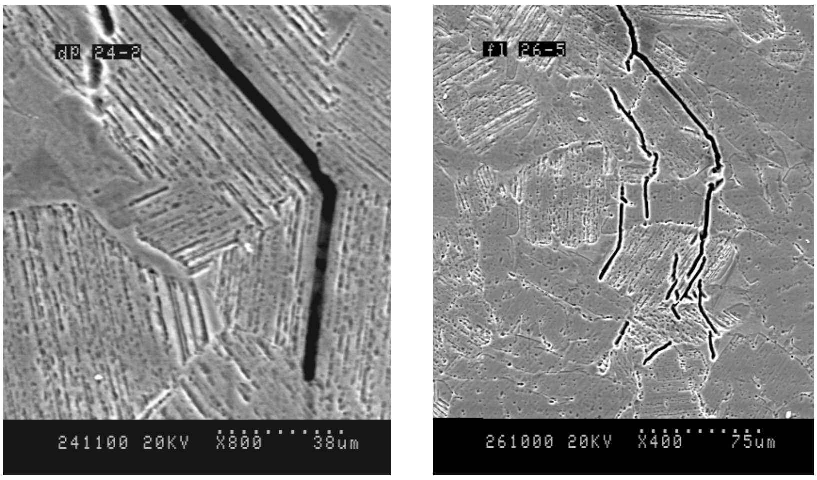
3.3 Toughening mechanism in TiAl alloy

In work [10], the tensile stress is identified as the driving force for crack propagation. In summary following factors can be listed to reduce the driving force for crack extending:

(1) Blunting of crack tip: It is surprising that in such a brittle alloy of TiAl almost in all cases the crack tips are blunted to 2-6μm in radius much larger than that in steel at low temperature. the crack tips are blunted by plastic strain, but here the crack is widened by tearing the end of the perpendicular layer along the horizontal layer of the barrier grain (Figure 7 (a)). The bluntness of crack is caused by the brittle decohesion of interlamellar layer. The bluntness of the crack tip remarkably reduces the tensile stress at it.
(2) A bifurcation of crack branch as shown by Figure 7 (b), which results in the deflection of the main crack and disperses the tensile stress.
(3) The deflection of the main crack is caused by the inclined lamellae as shown by Figure 7 (c), which makes lower the tensile stress perpendicular to the lamellar interface.
(4) Formation of a diffused zone of micro-cracks (Figure 7 (d), which reduces the stress triaxiality around the main crack and disperses the tensile stress.



(a) NFL24 (b) DP24



(c) DP24 (d) NFL26

Fig.7 Configurations of terminal ends of cleavage cracks

These mechanisms are considered as the main factors toughening the TiAl alloy. In summary, almost all mechanisms are related to the lamellar structure, which could be thought of as a composite consisting layer by layer of more plastic γ and of harder α_2. The interlamellar strength is very low, but the translamellar strength is much higher than the interlamellar strength. The lamellar structure with different strength in trans- and inter-lamellar directions can deflect the crack, blunt its tip, cause bifurcation and produce a defused zone of microcracks. It is the reason why the fully lamellar structure is used in growth. But in our work, the shear-ligament toughening suggested by previous work [4-7] is not found.

4 SUMMARY

1) Cracks prefer to initiate and propagate along lamellar interfaces, which are the weakest link in the near fully lamellar microstructure. The interlamellar strength calculated is less than the translamellar strength in a thin in-situ tensile specimen. The tensile stress is the driving force for crack initiation and propagation.
2) The inverse relationship between ductility and fracture toughness of finer duplex and coarser near fully lamellar microstructures is caused by the difference of the crack propagation path taken by the crack in the tensile test and in the bending test of precracked specimens where the sampling volume is different.
3) The lamellar structure with different strength in trans- and inter-lamellar directions can deflect the crack, blunt its tip, cause bifurcation and produce a defused zone of microcracks, these factors decrease the driving force in the way, which makes the fracture toughness increase.

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