FRACTURE TOUGHNESS OF GAMMA-BASED TITANIUM ALUMINIDES

Brigitte BITTAR* and Paul BOWEN*

This paper considers the effects of microstructure and testpiece size on fracture toughness values at room temperature of a gamma-based titanium aluminide. The alloy under investigation is of nominal composition Ti-47Al-1Cr-1Mn-0.2Si-2Ta (at%) with 1at% addition of boron. Nearly fully lamellar microstructures of different lath thickness have been considered. Microstructure is found to have a significant influence on fracture toughness values. Conversely, the difference in the mean K_Q values between small and larger specimens does not prove to be significant at the 95% confidence level but the range in the toughness values is reduced for the larger specimens.

INTRODUCTION

TiAl (gamma)-based aluminides combine good modulus and good oxidation resistance at temperatures of up to 800°C. Combined with a density that is twice lower than that of nickel-based superalloys, they are good candidate materials for application in aircraft engines. However, problems such as low fracture toughness and low ductility must still be considered carefully [1].
It is now well established that the fracture resistance of gamma based aluminides strongly depends on microstructure: fully gamma microstuctures with an average gamma grain size of 90 μm typically yield low fracture toughness values of the order of 8-10MPa√m; duplex microstructures exhibit higher values of typically 15-18MPa√m; and fully lamellar microstructures can give values of 25-30MPa√m when the crack is forced to traverse the thin weakly bonded lamellae [2]. Although the fully lamellar microstructure clearly can give high values of fracture toughness, mechanisms of fracture remain brittle and are strongly dependent on the angle between the lamellae orientation to the mode I direction [3].Care must also be taken when an average fracture toughness is given for large grained microstructures. As shown elsewhere [5] the process zone of importance when performing a fracture toughness test often extends only to 250μm from the precrack tip. Therefore, the number of colonies usually sampled during a fracture

*School of Metallurgy & Materials / IRC in High Performance Materials, University of Birmingham, Edgbaston, Birmingham, U.K.

toughness test in a large grained microstructure (colony size of about 400μm or more) is extremely limited and the presence of a predominant weak lamellar orientation can drastically reduce the fracture toughness. Researchers have refined the colony size by means of heat-treatments, alloy additions, grain refiners and/or thermo-mechanical processing. The most effective grain refiner described in the literature is boron. For example the addition of more than 0.5at% boron in a Ti-47Al-1Cr-1Mn-0.2Si-2Ta alloy decreases the lamellar colony size in the as-cast ingot from more than 2000μm to 100μm and randomises the lamellar orientation in the ingot [4].
The present study deals with the fracture toughness at room temperature of a grain refined Ti-47Al-1Cr-1Mn-0.2Si-2Ta+1B(at%) alloy in the as-cast condition and after heat-treatment to produce a near fully lamellar structure. The cooling rate was controlled in order to produce a variation of lamellar lath thickness compared with the as-cast condition. The influence of testpiece size has also been examined.

EXPERIMENTAL DETAILS

The material under investigation is a grain refined gamma-based titanium aluminide with the nominal composition Ti-47Al-1Cr-1Mn-0.2Si-2Ta+1B(at%). The ingot was produced by plasma arc-cold hearth melting at the IRC. The ingot was cast with a diameter of 100mm, a height of 1.4 m and weighed approximately 17 kg. Slices of 110 mm height were cut from the ingot and samples of 6x12x55mm (hereafter referred to as small specimens) and 12x24x110mm (hereafter referred to as large specimens) were prepared using electrodischarge machining. These samples were subsequently polished to 1μm diamond paste and notched to an a/W=0.25 ratio, where a is the notch length and W is the sample width. A quarter slice was heat-treated in a furnace under a vacuum of approximately 10e-4 torr at a temperature of 1360°C for 60 minutes and then furnace cooled under vacuum at 1°C/min.
Fracture toughness tests were carried out on an ESH servo-hydraulic machine in four-point bending at a nominal crosshead speed of 0.5mm/min. A fatigue pre-crack was first grown to an a/W ratio of about 0.5 using a stress ratio, R, (ratio of minimum stress intensity factor to maximum stress intensity factor) of 0.1. Crack growth was monitored using potential drop technique. Fracture toughness specimens were fitted with clip-gauges to measure local displacements and charts of load versus clip-gauge displacement were recorded. The fracture toughness was determined using the 5% offset method in all cases and the value of the stress intensity factor at the peak load was also calculated. The fracture surfaces were examined using a JEOL 6300 and 5410 SEMs both operating at 0° tilt and 20kV.

RESULTS AND DISCUSSION

MICROSTRUCTURE

The microstructures of the material are shown in Fig1. The as-cast microstructure is near fully lamellar with an average grain size of 180μm, and with approximately 5% gamma grains localised at grain boundaries and these have an average grain size of 50μm. Lamellar laths are approximately 1.4μm thickness and the lamellar colonies have interlocking boundaries. The heat-treated material also possesses a near-fully lamellar microstructure. Due to the very slow cooling rate of 1°C/min, growth of the gamma grains localised at boundaries in the as-cast microstructure occurred during the time spent in the (alpha+gamma)-phase field. This phenomenom has also been seen elsewhere following similar heat-treatments [5]. This results in the presence of blocky gamma grains with an approximate grain size of 80μm. The lamellar colony size is measured at 150μm, and the lamellar lath thickness is significantly larger with an average thickness of 3μm. In both microstructures, an inhomogeneous distribution of boron during casting induced an inhomogeneous distribution of boride particles in the material. These particles, identified as TiB_2 and TaB [4], can also form elongated or circular "islands" of co-operative particles. These islands may have an average size of 400μm although occasionally, sizes of up to 1100μm in length and 300μm in width have been observed.

FRACTURE TOUGHNESS

EFFECTS OF TESTPIECE SIZE. Fracture toughness values and K_{MAX}, stress intensity factor values calculated at peak load, are presented graphically in Fig2. Twenty four specimens were tested. K_Q values were calculated from load/clip-gauge displacement charts using the 5% offset procedure as required in British Standard BS7448. Out of 24 charts, 19 exhibited "pop-ins", and only 2 were completely linear to failure. None of the "pop-ins" are significant based on the 5% offset procedure. All specimens satisfied the testpiece size conditions required by the standard for plane strain fracture toughness testing. However, due to the high value of the m exponent of the Paris law for this material, the maximum stress intensity factor during fatigue cycle did not meet the requirements of BS7448. In addition the traces, in general, contained too much non linearity to allow K_{MAX} not to exceed 1.1 K_Q. For these reasons, K_Q values may not be quoted stricly as K_{IC} values. The average values of K_Q, K_{MAX} and the standard deviations are presented in table1. For both microstructures, the average K_Q and K_{MAX} values are actually higher for the larger specimens. For the as-cast microstructure, K_Q and K_{MAX} values are respectively 16 and 19.3MPa√m for the large specimens comparing with 13.5 and 16.2MPa√m for the smaller specimens. Moreover, the standard deviations calculated for the large as-cast specimens are lower (0.9MPa√m) than those of the small specimens (2.1MPa√m). This illustrates the decrease in the range of values when the testpiece size is increased. Several of the above observations are noteworthy. First, the small scale of the colonies (≤180μm) results in "pop-in" values in the load-displacement traces that may be ignored (according to the procedures of BS7448). This is in sharp contrast to the behaviour of larger colonies, where premature interlamellar failure must be taken as the onset of catastrophic failure [5]. Second, although the testpiece size conditions for plain strain fracture toughness testing have been met, a substantial amount of non-linearity is seen in the load-displacement traces (such that the K_{MAX} values usually exceed 1.1 times the K_Q values). In conventional structural metals this would lead to concern that this excessive amount of plasticity could have raised the value of K_Q measured above a minimum value (and hence K_Q cannot be defined as K_{IC} for this reason), but for titanium aluminides such concerns are probably inappropriate (and indeed the modest increase in K_{MAX} values seen for the larger testpieces would tend to support this particular viewpoint). Third, the trend in K_Q andK_{MAX} values obtained for the larger testpieces compared with the smaller testpieces is somewhat unusual. Indeed, in conventional metals although the range in such values can often be reduced for larger testpieces, the expectation would be that values obtained from large testpieces would tend to lie towards the minimum values obtained from smaller testpieces. In the present work this remains an interesting observation only, because the difference in average values is not statistically significant, and the difference in sampling volume is a modest factor of two. However, this will be an area of interest for future studies.

EFFECTS OF MICROSTRUCTURE: In the present study, on heat-treatment of the as-cast material there is a large increase in the lamellar lath thickness from 1.4 to 3μm, and this is also combined with a slight increase in the size of equiaxed gamma grains from 50 to 80μm. It is possible that either factor could be responsible for the significant reduction of fracture toughness obtained after heat-treatment with average K_Q values decreasing from 14.4 to 10.7MPa√m, and further fractography is required to quantify the precise mechanism of failure. Clearly, it is tempting to favour the increased lamellar plate thickness as being of greater significance since isolated equiaxed gamma grains can be involved only in cleavage initiation (representative fractographs are shown in Fig3). There may also be possible detrimental effects of individual boride particles and/or larger "islands" of particles. In the present study some evidence has been obtained that such "islands" will reduce the values of K_Q and K_{MAX}, because detailed observation of the fracture surface of the as-cast specimen that failed with the lowest K_Q value (10.5MPa√m) revealed that this testpiece had nine "islands" of boride particles close to the pre-crack front. Such observations confirm the importance of large defects in reducing the toughness of these brittle materials, and their general suceptibility to localised defects will be a challenge to the engineering application of these alloys.

CONCLUSIONS

1 For the Ti-47Al-1Cr-1Mn-0.2Si-2Ta+1B (at%) alloy heat-treatment of the as-cast material within the alpha phase field and cooling at 1°C/min results in a near fully lamellar microstructure with a coarse lamellar plate thickness of 3μm. This compares with a near fully lamellar microstructure with a lamellar plate thickness of 1.4μm which is present for the as-cast condition.

2 For these as-cast near fully lamellar microstructures of fine colony size (≤180μm) although no statistically significant effect of testpiece size is seen on fracture toughness values, larger testpieces tend to produce higher toughness values and exhibit a reduced range in fracture toughness values.

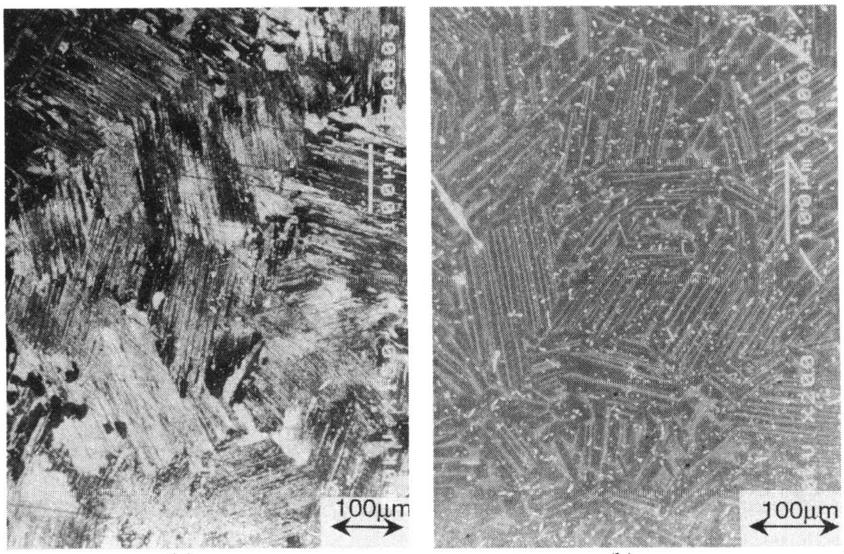
3 A lamellar lath thickness of 3μm and/or the presence of gamma grains of increased size at lamellar colony boundaries decrease the fracture toughness from 14.5 to 10.7MPa√m if compared to an as-cast microstructure of 1.4μm lamellar lath thickness.

REFERENCES

1 J.C. Chesnutt and J.C. Williams, Metals and Mats, vol6, no.8 1990 pp509-511,
2 N. J. Rogers and P. Bowen, pp231-240, First International Symposium on Structural Intermetallics (ISSI), Seven Springs, Pennsylvania, TMS, 1993.
3 A. W. James and P. Bowen, The Processing, Properties and Applications of Metallic and Ceramic Materials, Conference Proceedings, Birmingham, UK, September 1992, pp. 677-682, EMAS, UK.
4 A. B. Godfrey and M. H. Loretto, "Grain refinement of gamma-based titanium aluminides", to be published, Ninth World Conference on Titanium, Birmingham, UK, October 1995, IOM, UK.
5 P. Bowen, N. J. Rogers and A. W. James, pp849-865, Gamma Titanium Aluminides, Las Vegas, February 1995, TMS, USA.

STRESS INTENSITY FACTOR (MPa.√m)	SPECIMENS TESTED	SIZE	AVERAGE (MPa√m)	STANDARD DEVIATION	MAXIMUM (MPa√m)	MINIMUM (MPa√m)
a) as-cast microstructure						
K_Q	9	small	13.5	2.1	16.9	10.6
K_{MAX}	9	small	16.2	3.3	20.9	12.3
K_Q	6	large	16.0	0.9	17.6	14.8
K_{MAX}	6	large	19.3	1.5	21.2	17.2
K_Q	15	both sizes	14.5	2.1	17.6	10.6
K_{MAX}	15	both sizes	17.4	3.1	21.2	12.3
b) heat-treated microstructure						
K_Q	7	small	9.5	1.9	12.2	7.3
K_{MAX}	7	small	11.3	2.2	15.4	8.9
K_Q	2	large	14.8	n.a	15.9	13.7
K_{MAX}	2	large	16.2	n.a.	16.7	15.7
K_Q	9	both sizes	10.7	2.9	15.9	7.3
K_{MAX}	9	both sizes	12.4	2.9	16.7	8.9

Table1: Fracture toughness results. The heat-treated (HT) microstructure possesses a reduced fracture toughness. The variation in toughness values decreases for the larger specimens. (n.a.= not applicable)



(a) (b)

Fig1: Microstructure a) as-cast b) HT=60 min. at 1360°C, cooling rate 1°C/min.

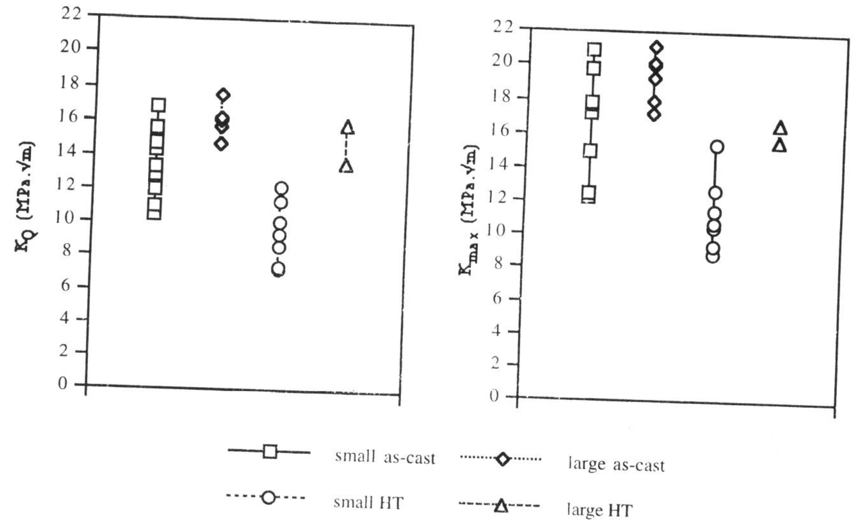
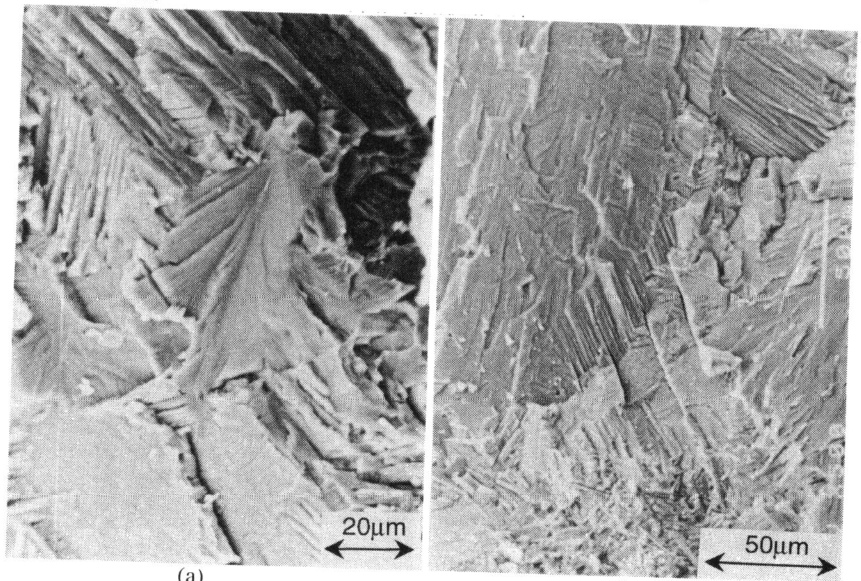


Fig2: Fracture toughness and K_{max} values plotted as a function of testpiece size and microstructure



(a) (b)

Fig3: Representative fractographs of (a) as-cast (b) heat-treated conditions. Failure modes includes transgranular cleavage, interlamellar and translamellar fracture.