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On the role of microstructure in fatigue-crack growth of γ-based titanium aluminides[1]

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Abstract

Room temperature fatigue-crack growth behavior is investigated in a wide range of γ-based titanium aluminide microstructures. The influence of microstructural variables such as lamellar colony size and volume fraction of equiaxed γ grains are systematically analyzed in terms of their effects on crack growth resistance. It is found that the coarse lamellar microstructures exhibit the best resistance to cyclic crack growth, while the duplex and single-phase γ microstructures exhibit the worst. Additionally, a wide range in fatigue-crack growth resistance is observed for the various lamellar microstructures investigated. These trends in material properties are explained in terms of extrinsic crack-tip shielding mechanisms, including crack closure and uncracked (shear) ligament bridging, the potency of which are functions of microstructure. © 1997 Elsevier Science S.A.

Keywords: Titanium aluminide; Fatigue; Microstructure; Crack shielding

1. Introduction

Titanium aluminide intermetallic alloys based on the γ-phase are currently being studied as potential replacements for conventional Ti alloys in gas turbine engines [1–4]. Two classes of microstructure have been prominent: a lamellar structure consisting of colonies, which are generally very coarse in size (~ 1–2 mm), containing alternating γ and α_2 platelets and a much finer duplex structure consisting of equiaxed grains of γ with small amounts of α_2 or lamellar grains [1]. In general, duplex structures display better elongation and strength, whereas lamellar structures show better toughness and fatigue-crack growth resistance [2,5–8]. Recent research efforts on γ-based titanium aluminides have also focused on variants of the coarse lamellar and fine duplex microstructures, including lamellar structures with refined colony sizes [9], refined lamellae thickness [10] and significant volume fractions of equiaxed γ grains (nearly lamellar microstructures) [9,11]. The effects of these microstructural variations on fracture behavior and fatigue-crack growth are not yet well understood.

This paper presents the results of a study on the room temperature fatigue-crack growth behavior of several dual-phase ($\gamma + \alpha_2$) TiAl alloys with a range of microstructures which vary in volume fraction of lamellar colonies and in colony size, including coarse fully lamellar, refined fully lamellar, refined nearly lamellar and duplex. Comparison of these microstructures indicates that fatigue-crack growth resistance depends strongly upon microstructure. The observed variation in fatigue-crack growth resistance is analyzed in terms of extrinsic crack shielding mechanisms, specifically crack closure and uncracked (shear) ligament bridging.

2. Materials and experimental methods

Three γ-TiAl intermetallic alloys are examined in the present study. Relevant structural parameters for each microstructure in each alloy are given in Table 1. The first alloy, Ti–47.7Al–2.0Nb–0.8Mn (at.%) containing ~ 1vol.% TiB_2 particles, was fabricated by the XD™ process, which is a proprietary method for incorporating in situ ceramic particulate, whisker or short fiber reinforcements [12]. This alloy was permanent mold cast into 40 mm diameter rods and then hot-isostatic pressed (HIPed) at 1260°C and 172 MPa pressure for 4

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Table 1
Microstructure of γ-based TiAl alloys

Microstructure/composition (at.%)	Lamellar colony size (μm)	Lamellae spacing (μm)[a]	Equiaxed γ phase	γ Grain size (μm)	Yield strength (MPa)
XD nearly lamellar/Ti–47.7Al–2.0Nb–0.8Mn + 1vol% TiB_2	120	2.0	30%	23	546[b]
MD fully lamellar/Ti–47Al–2Nb–2Cr–0.2B	145	1.3	4%	5–20	426
MD duplex/Ti–47Al–2Nb–2Cr–0.2B	—	—	90%	17	384
G7 coarse lamellar/Ti–47.3Al–2.3Nb–1.5Cr–0.4V	1000–2000	1.3	<5%	10–40	450
G7 duplex/Ti–47.3Al–2.3Nb–1.5Cr–0.4V	—	—	90–95%	15–40	450

[a] Center-to-center spacing of the α_2 phase.
[b] Reported data for a material of similar composition and microstructure [31].

h. The resulting nearly lamellar microstructure (~ 30% equiaxed γ grains) contained refined lamellar colonies (~ 120 μm in diameter) (Fig. 1a; XD nearly lamellar). The TiB_2 phase was distributed randomly among γ grains and lamellar colonies as needle-like particles (20–50 μm in length, 2–5 μm in diameter). The second alloy, Ti–47Al–2Nb–2Cr–0.2B (at.%) was processed to yield both a fully lamellar microstructure with refined colony size (~ 145 μm) (Fig. 1b; MD fully lamellar) and a duplex microstructure (Fig. 1c; MD duplex). The third alloy, Ti–47.3Al–2.3Nb–1.5Cr–0.4V (at.%) was treated to yield a fully lamellar microstructure with coarse colony size (~ 1–2 mm) (Fig. 1d; G7 coarse lamellar) and a duplex microstructure (Fig. 1e; G7 duplex). The processing details for Ti–47Al–2Nb–2Cr–0.2B and Ti–47.3Al–2.3Nb–1.5Cr–0.4V are presented elsewhere [8,13].

Long (> 5 mm) fatigue-crack growth studies were performed in room temperature air on compact tension specimens. Tests were conducted at frequencies of 25 Hz (sine wave) under automated stress-intensity (K) control in general accordance with ASTM Standard E647. A constant load ratio, $R = K_{min}/K_{max}$, of 0.1 (tension–tension) was maintained, where K_{min} and K_{max} are the minimum and maximum stress intensities of the loading cycle. Fatigue thresholds, ΔK_{TH}, were defined as the applied stress–intensity range corresponding to growth rates below $\sim 10^{-10}$ m cycle^{-1}. Crack lengths were monitored using electrical-potential measurements on NiCr foil gauges bonded to the side face of specimens and/or back-face strain compliance methods.

Elastic compliance data were also utilized to measure the extent of crack-tip shielding from crack closure and crack bridging. Crack closure was evaluated in terms of the closure stress intensity, K_{cl}, which was approximately defined at the load corresponding to the first deviation from linearity on the unloading compliance [14,15]. Crack bridging was assessed using a method [16] involving a comparison of the experimentally measured unloading compliance (at loads above those associated with closure) with the theoretical value for a traction-free crack in a compact tension sample [17–19]. With this technique, a bridging stress intensity, K_{br}, representing the reduction in K_{max} due to the bridging tractions developed in the crack wake was estimated.

3. Results and discussion

3.1. Role of microstructure

The fatigue-crack growth resistance of the XD nearly lamellar, MD fully lamellar, MD duplex, G7 coarse lamellar and G7 duplex microstructures are compared in Fig. 2. Also shown for comparison is the crack growth resistance of a single-phase γ alloy (Ti–55Al (at.%) with traces of Nb, Ta, C and O) [20] with grain sizes of ~2–10 μm. In general, the lamellar microstructures show superior fatigue-crack growth resistance compared to the equiaxed γ grain materials, i.e. duplex and single-phase γ, consistent with results reported by other authors [4,8,21]. It is interesting to note that the rank ordering of these microstructures in terms of fatigue-crack growth resistance parallels exactly their relative toughness under monotonic loading [9,22]. For all alloys and microstructures, the fatigue-crack growth rates, da/dN, are a strong function of ΔK, particularly for the duplex microstructures, where the entire $da/dN(\Delta K)$ curve lies within a ΔK range of ~ 1 MPa $\sqrt{m}$ or less. Comparatively, the lamellar microstructures show greater damage tolerance, with higher crack-growth thresholds and improved $da/dN(\Delta K)$ slopes in the mid-growth rate regime.

The various lamellar microstructures investigated, which differ in lamellar colony size, dimension of the individual lamellae and volume fraction of equiaxed γ grains, display a range of cyclic crack growth resistance nearly as large as that observed between the lamellar and duplex structures. While the G7 lamellar microstructure, with by far the largest colony size investigated, exhibits the best fatigue-crack growth resistance, the MD fully lamellar material possesses only slightly

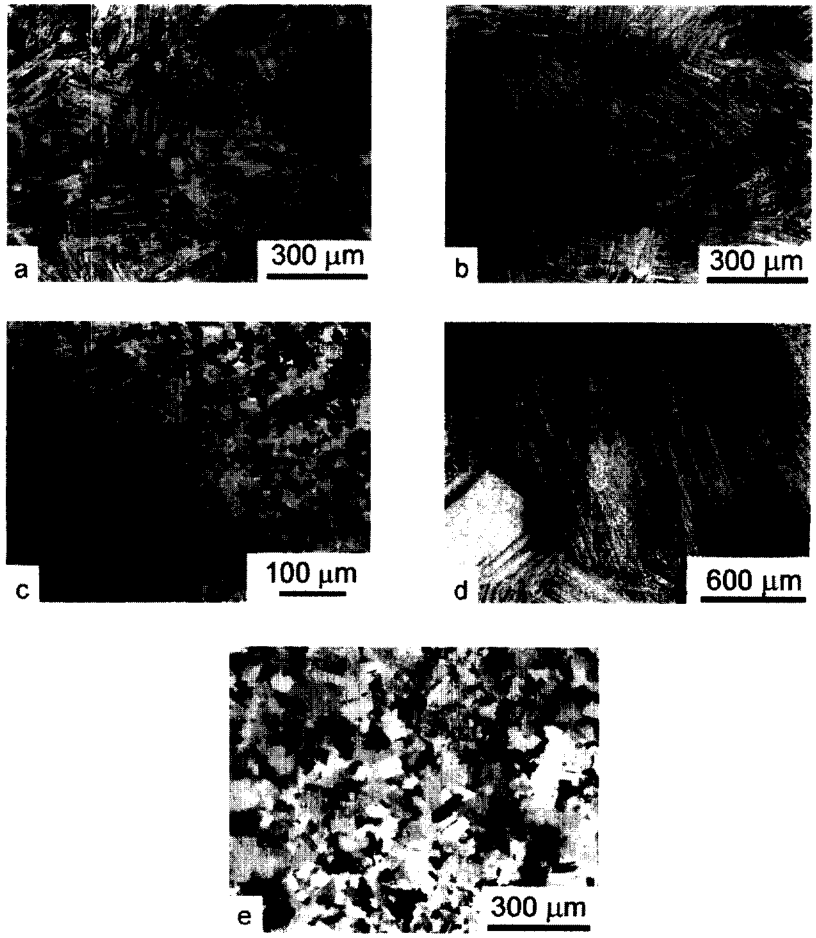

Fig. 1. Optical micrographs of (a) Ti–47.7Al–2.0Nb–0.8Mn + 1 vol.% TiB_2 (XD nearly lamellar); (b) Ti–47Al–2Nb–2Cr–0.2B (MD fully lamellar); (c) Ti–47Al–2Nb–2Cr–0.2B (MD duplex); (d) Ti–47.3Al–2.3Nb–1.5Cr–0.4V (G7 coarse lamellar); and (e) Ti–47.3Al–2.3Nb–1.5Cr–0.4V (G7 duplex) microstructures.

lower crack-growth resistance despite an order of magnitude reduction in colony size. The difference in crack growth resistance is largest near the threshold; ΔK_{TH} = 8.6 MPa $\sqrt{m}$ for the MD fully lamellar, compared to $\Delta K_{TH} \sim 10$ MPa $\sqrt{m}$ for the coarser G7 structure. The XD nearly lamellar microstructure, on the other hand, with a colony size (~ 120 μm) roughly equivalent to that of the MD fully lamellar material (~ 145 μm), displays significantly lower crack growth resistance. In fact, the XD microstructure shows only marginal improvements in near-threshold fatigue properties ($\Delta K_{TH} = 7.1$ MPa $\sqrt{m}$) over the equiaxed γ materials (e.g. $\Delta K_{TH} = 6.5$ MPa $\sqrt{m}$ and 5.9 MPa $\sqrt{m}$ for the G7 duplex and MD duplex microstructures, respectively), although its fatigue resistance is improved above $\sim 10^{-8}$ m cycle^{-1}. The most prominent microstructural difference between the XD nearly lamellar and MD fully lamellar materials is the high volume fraction (~ 30%) of equiaxed γ grains present in the XD structure. The inferior crack growth behavior of the single-phase γ, G7 duplex and MD duplex microstructures (Fig. 2), all with high volume fractions of equiaxed γ grains, suggests that this morphology of the γ phase may be detrimental to fatigue-crack growth resistance. A deleterious correlation between fatigue-crack growth resistance and equiaxed γ grains is illustrated in Fig. 3, where ΔK_{TH} is plotted as a function of the volume fraction of equiaxed γ phase. A similar degradation in toughness due to the presence of the equiaxed γ phase has also been observed [22]. It is believed that the equiaxed γ grains degrade crack growth resistance by inhibiting the activity of extrinsic shielding mechanisms, specifically crack closure (where the γ grains allow for a less tortuous crack path) and uncracked ligament bridging [23,24] (where the γ grains do not participate in uncracked ligament formation).

4. Extrinsic crack-tip shielding (crack closure and bridging)

The disparity in fatigue-crack growth resistance be-

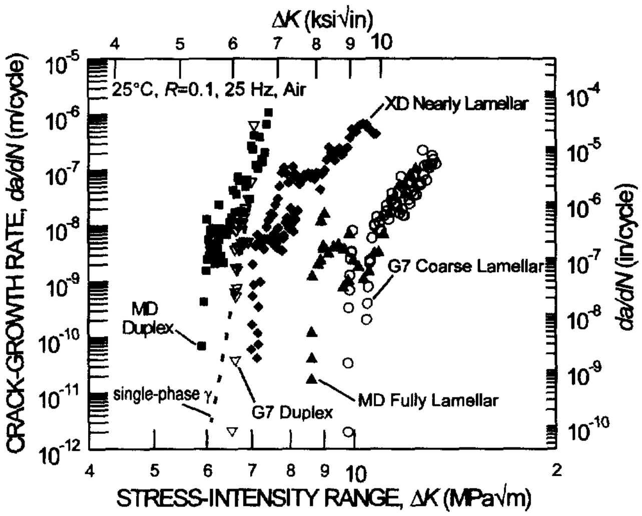

Fig. 2. Room temperature fatigue-crack growth resistance in G7 coarse lamellar, G7 duplex, MD fully lamellar, MD duplex, XD nearly lamellar, and single-phase γ microstructures. In general the lamellar microstructures show superior fatigue-crack growth resistance compared to the equiaxed γ structures (i.e. duplex and single-phase γ). The various lamellar microstructures investigated display a range of cyclic crack growth resistance nearly as large as that observed between the lamellar and duplex structures.

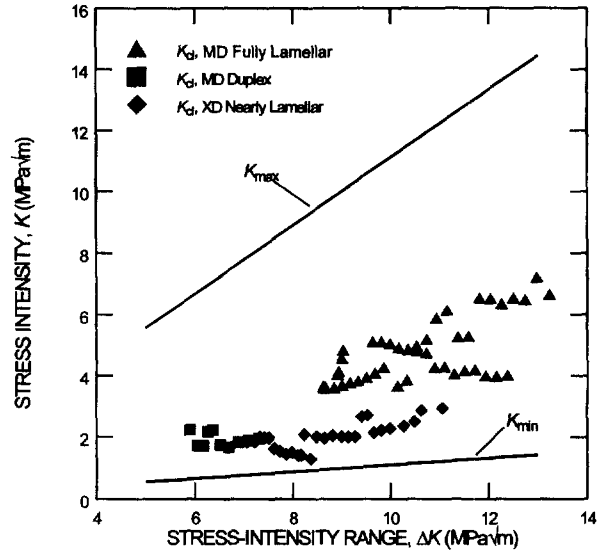

Fig. 4. Measured crack closure stress intensities, K_{cl}, as a function of ΔK ($R = 0.1$) in the MD fully lamellar, MD duplex, and XD nearly lamellar microstructures. Solid lines indicating K_{max} and K_{min} are also presented. K_{cl} is observed to be largest in the MD lamellar microstructure ($\sim$ 4–7 MPa $\sqrt{m}$), however $K_{cl} > K_{min}$ for all microstructures at all ΔK levels.

tween the duplex and lamellar microstructures and between the various lamellar microstructures can be related to differences in the degree of crack-tip shielding provided by crack closure and uncracked ligament bridges. Fig. 4 presents measured K_{cl} for the XD nearly lamellar, MD fully lamellar and MD duplex structures as a function of ΔK for $R = 0.1$. Closure stress intensities are highest in the MD fully lamellar microstructure ($\sim$ 4–7 MPa $\sqrt{m}$); however, K_{cl} is greater than K_{min} at all ΔK for each microstructure. There is considerable scatter in the measured K_{cl} for the MD fully lamellar microstructure; however, an increase in K_{cl} with ΔK is observed. This trend is believed to be associated with the formation of uncracked ligament bridges at high ΔK. Although the interpretation of crack closure in the presence of bridging is uncertain, the present results suggest an enhanced closure effect.

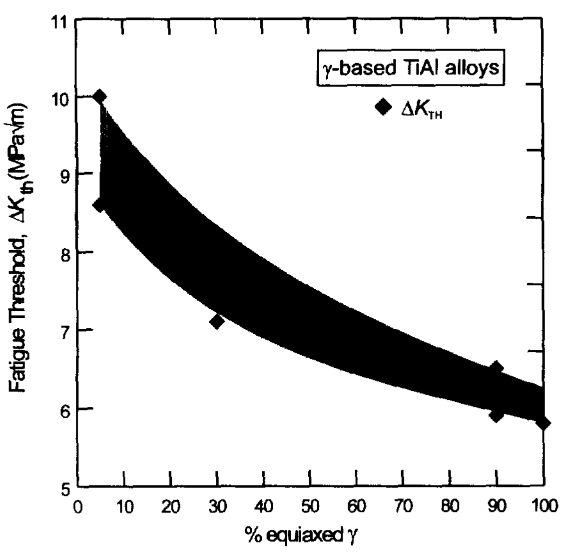

Fig. 3. The fatigue threshold, ΔK_{TH}, as a function of the volume fraction of equiaxed γ grains in several γ-based TiAl microstructures (XD nearly lamellar, MD fully lamellar, MD duplex, G7 coarse lamellar, G7 duplex, and single-phase γ). A deleterious correlation between fatigue-crack growth resistance and the equiaxed γ phase is observed.

It has been well documented [8,24–27] that uncracked ligaments in the crack wake are an important toughening mechanism for monotonic loading in lamellar γ-based TiAl. However, it is often observed that bridging mechanisms, such as ductile phase reinforcements, which are potent under monotonic loading become ineffective during cyclic loading [20,28]. This results from a cyclic degradation of the bridges or from an inability of the bridges to form at the lower stress intensities typical of fatigue (compared to monotonic fracture). In the present study, direct microscopic examination of the crack wake indicates that uncracked ligament bridges can form in lamellar structures during cyclic loading (Fig. 5); however, the magnitude of shielding from these ligaments is substantially reduced from that seen under monotonic loading. Indeed previous investigators have reported fractographic evidence of bridge formation during fatigue-crack growth in lamellar TiAl microstructures [29].

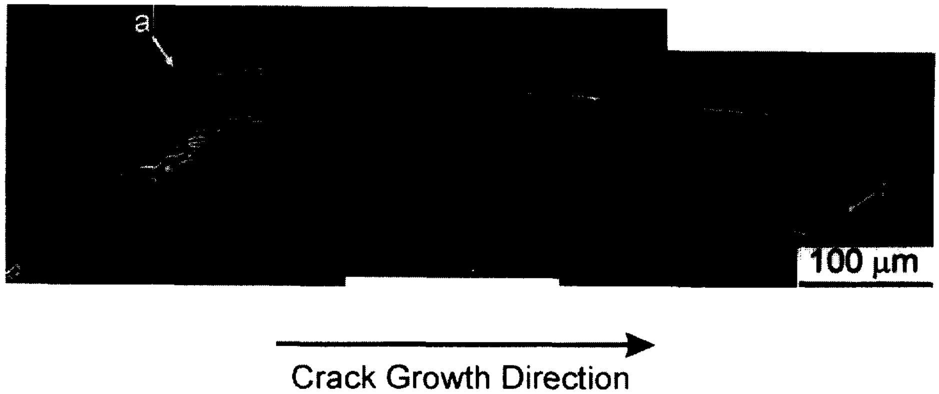

Fig. 5. Scanning electron micrograph of a fatigue-crack profile in the MD fully lamellar microstructure (recorded at sample mid-thickness) showing the presence of uncracked ligament bridges. The arrows a and b indicate the beginning of the crack at the top of the bridge and the end of the crack at the bottom of the bridge, respectively. This region of the sample was tested at a constant ΔK of 12.5 MPa $\sqrt{m}$ ($R = 0.1$).

The magnitude of shielding provided by uncracked ligaments for both the XD nearly lamellar and MD fully lamellar microstructures was estimated by comparing measured and theoretical unloading compliance [16]. The results are presented in Fig. 6, where K_{max}, K_{min} and $K_{max} - K_{br}$ are plotted as a function of ΔK. The magnitude of shielding provided by uncracked ligament bridging, K_{br}, is given by the difference between the K_{max} and $K_{max} - K_{br}$ lines. Only small amounts of shielding are observed in the XD nearly lamellar TiAl at all ΔK and in the MD fully lamellar structure at near-threshold loading ($K_{br} \leq 0.5$ MPa $\sqrt{m}$). However, significant shielding does occur in the MD fully lamellar TiAl at higher ΔK, with $K_{br} = 2.1$ MPa $\sqrt{m}$ (14% of K_{max}) at $\Delta K = 12.6$ MPa $\sqrt{m}$. Although substantial, this shielding contribution in fatigue is significantly lower than that which occurs during monotonic fracture, where $K_{br} \sim 4–25$ MPa$\sqrt{m}$ [9,30]. The greater propensity for uncracked ligament bridge formation under cyclic loading in the MD fully lamellar microstructure relative to the XD nearly lamellar material is consistent with behavior observed for monotonic loading, as suggested by superior resistance-curve behavior in the MD fully lamellar TiAl [9,22].

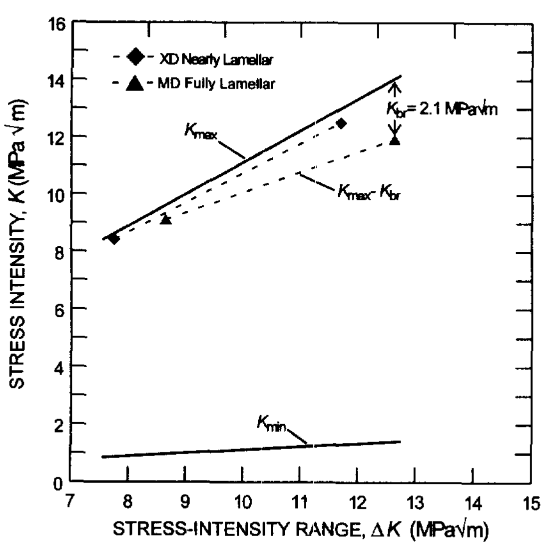

Fig. 6. K_{max}, K_{min}, and $K_{max} - K_{br}$ as a function of ΔK ($R = 0.1$) for the MD fully lamellar and XD nearly lamellar microstructures. The magnitude of shielding provided by uncracked ligament bridging, K_{br}, is given by the difference between the K_{max} and $K_{max} - K_{br}$ lines. Only small amounts of shielding are observed in the XD nearly lamellar TiAl ($K_{br} \sim 0.2–0.5$ MPa $\sqrt{m}$). Significant shielding does occur in the MD fully lamellar TiAl at higher ΔK, with $K_{br} = 2.1$ MPa $\sqrt{m}$ (14% of K_{max}) at $\Delta K = 12.6$ MPa $\sqrt{m}$.

Based on the closure and bridging stress intensities presented in Figs. 4 and 6, the overall crack-tip shielding contribution can be quantified by defining an effective, near-tip stress intensity range, ΔK_{eff}, as follows

$$\Delta K_{eff} = (K_{max} - K_{br}) - K_{cl}, \tag{1}$$

for $K_{cl} > K_{min}$. Plotting the measured fatigue-crack growth rates as a function of the closure and bridging corrected ΔK_{eff} indicates that these shielding mechanisms are largely responsible for the differences in crack growth resistance of the various microstructures. In Fig. 7, growth rates are plotted as a function of both the applied stress intensity range, ΔK, and ΔK_{eff} for the MD fully lamellar and MD duplex microstructures (no shielding from uncracked ligament bridging was measured in the duplex material). For the lamellar microstructure, the shielding correction was applied to crack-growth rates at applied ΔK within 0.5 MPa $\sqrt{m}$ of the stress intensity ranges at which K_{br} was measured. This allowed for plotting a sufficient number of shielding corrected data points; it was assumed that the true values of K_{br} would not vary significantly over this small range of ΔK. After 'correcting' for the extrinsic shielding mechanisms, the discrepancy in fatigue-crack growth resistance between the MD fully lamellar and MD duplex microstructures is significantly reduced; the difference in crack growth thresholds is reduced from

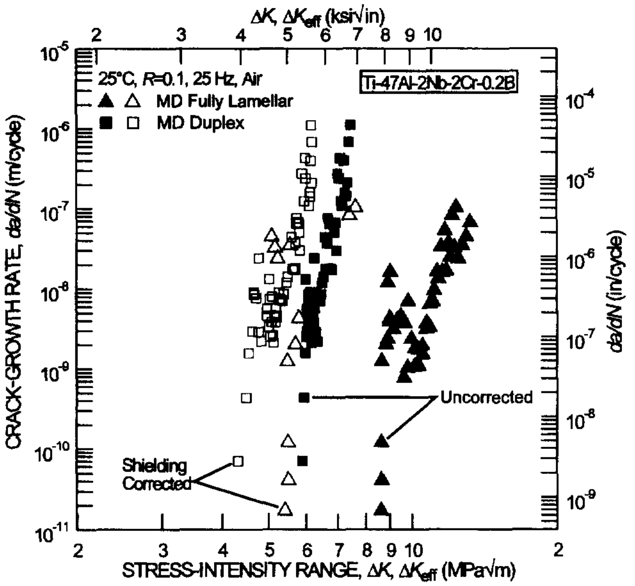

Fig. 7. Fatigue-crack growth rates, da/dN, for long cracks in the MD fully lamellar and MD duplex microstructures are plotted as a function of the applied stress intensity range, ΔK, and an effective, near-tip stress intensity range, ΔK_{eff}, from which the effect of extrinsic crack shielding mechanisms (closure and bridging) have been 'subtracted'. It is apparent that these extrinsic shielding mechanisms are largely responsible for the disparity in fatigue-crack growth resistance between the two microstructures which is observed when crack-growth rates are plotted as a function of ΔK.

~ 3 MPa $\sqrt{m}$ to only ~ 1 MPa $\sqrt{m}$ ($\Delta K_{TH,eff} = 4.3$ and 5.5 MPa $\sqrt{m}$, respectively, for the duplex and lamellar structures). These results suggest that the difference in intrinsic fatigue-crack growth resistance between the lamellar and duplex microstructures is small. Affirmation of this point is provided by results reported by Campbell et al. on the growth of small (25–275 μm) fatigue cracks in these same microstructures [13]. Crack-growth rate data sets for small cracks, which are far less affected by shielding contributions due to their limited wake, show considerable scatter in the MD fully lamellar and MD duplex microstructures, but essentially overlap.

The range of crack-growth resistance exhibited by the various lamellar microstructures can also be attributed in part to extrinsic crack-tip shielding. In Fig. 8, crack-growth rates in the XD nearly lamellar and MD fully lamellar microstructures are plotted both as a function of the applied ΔK and the closure and shielding corrected ΔK_{eff}. The discrepancy in crack-growth resistance between the two microstructures is virtually eliminated when da/dN are plotted as a function of ΔK_{eff}, particularly in the near-threshold regime, with $\Delta K_{TH,eff} = 5.5$ MPa $\sqrt{m}$ for both materials. The scatter at higher growth rates for the shielding-corrected data in the MD fully lamellar microstructure results from scatter in the measured K_{cl} (Fig. 4).

Clearly, comparisons between the various lamellar and duplex microstructures based on 'long-crack' fatigue-crack growth properties (Fig. 2) indicate that the coarser lamellar structures are superior. However, such improved crack-growth resistance has been shown to result primarily from extrinsic shielding mechanisms (bridging and closure) which operate behind the crack tip. Considering the steep slope of the da/dN(ΔK) curves exhibited by these intermetallic alloys, for many fatigue critical applications the fatigue threshold in the presence of small cracks (where shielding is ineffective) may well be a critical design parameter. Under these design specifications, the duplex microstructures exhibit performance nearly equivalent to that of lamellar microstructures. In fact, in the fatigue-limited applications for which γ-based titanium aluminides are being considered, the duplex structures may well be superior as they display higher (smooth bar) fatigue limits [4] and, due to their finer microstructures, small-crack growth rates are prone to far less scatter [13].

5. Conclusions

Based on a study of room temperature fatigue-crack growth in a wide range of γ-based TiAl alloys and microstructures, including duplex, fully lamellar with

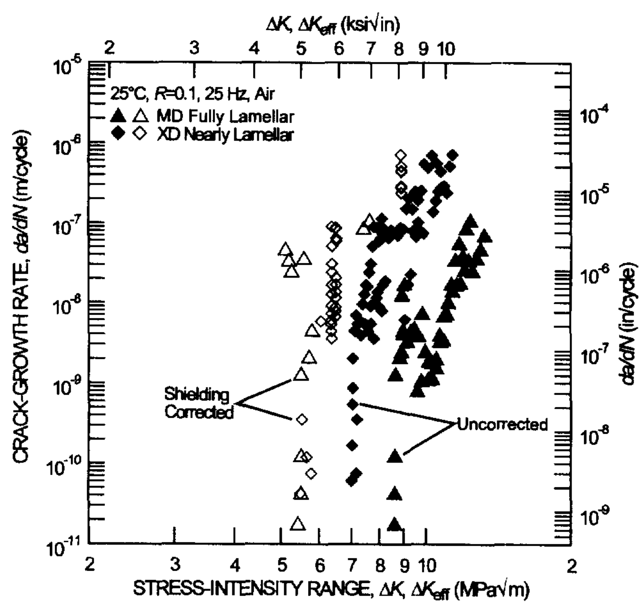

Fig. 8. Fatigue-crack growth rates, da/dN, for long cracks in the MD fully lamellar and XD nearly lamellar microstructures are plotted as a function of the applied stress intensity range, ΔK, and an effective, near-tip stress intensity range, ΔK_{eff}, from which the effect of extrinsic crack shielding mechanisms (closure and bridging) have been 'subtracted'. The normalization of growth rates by ΔK_{eff} indicates that the range of fatigue-crack growth resistance observed for the various lamellar microstructures can be largely attributed to variations in the degree of crack shielding provided by crack closure and uncracked ligament bridging.

coarse colony size, fully lamellar with refined colony size and nearly lamellar with refined colony size, the following conclusions can be made:

(1) Fatigue-crack growth resistance depends strongly on microstructure. In general, lamellar microstructures exhibit superior damage tolerance, with higher crack-growth thresholds, ΔK_{TH}, and improved $da/dN(\Delta K)$ slopes in the mid-growth rate regime, when crack growth is characterized in terms of long (>5 mm) crack behavior and the far-field (applied) stress intensity range.

(2) The discrepancy in fatigue-crack growth resistance between lamellar and duplex microstructures in Ti–47Al–2Nb–2Cr–0.2B (at.%) can largely be attributed to higher crack-tip shielding (from closure and bridging) in the lamellar structure. Variations in the degree of shielding provided by these extrinsic toughening mechanisms are also responsible for some of the discrepancy in fatigue-crack growth resistance between the various lamellar microstructures investigated.

(3) A deleterious correlation is observed between fatigue-crack growth resistance and the presence of equiaxed γ grains. It is believed that the equiaxed γ phase degrades crack growth resistance by inhibiting the action of crack closure and uncracked ligament bridging.

(4) Given that the superior fatigue-crack growth resistance of the lamellar microstructure in Ti–47Al–2Nb–2Cr–0.2B (at.%) can be largely attributed to extrinsic toughening mechanisms which act in the crack wake, it is expected (and has been observed [13]) that fatigue-crack growth resistance in the presence of small cracks, which are not significantly influenced by extrinsic crack shielding due to their limited wake, will be comparable in the lamellar and duplex microstructures.

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