ORAL REFERENCE: ICF100880OR

ELEVATED TEMPERATURE FRACTURE AND CRACK GROWTH IN TiAl BASE INTERMETALLICS

Bilal Dogan

GKSS Research Centre, Institute for Materials Research
Max-Planck-Str., D-21502 Geesthacht, F.R.Germany

ABSTRACT

New materials and processes are bringing about radical changes in the aerospace and transport industry. Due to the high premiums tied to weight reductions in advanced engines the application of TiAl base intermetallic alloys look especially attractive because of their high specific modulus, high specific creep strength, and good oxidation resistance at elevated temperatures. The fracture and high temperature crack growth behaviour of a γ-TiAl base intermetallic alloy, Ti48Al2Cr, with a duplex microstructure were studied at 700°C. Compact tension (CT) type specimens were tested both with EDM slit notches and fatigue precracks. The loading mode was varied to study the applicability of different test techniques.
The present investigation showed that the inhomogenity in microstructure needs to be considered in fracture toughness testing and crack growth assessment of TiAl base intermetallics. The starter sharp crack may be introduced by fatigue precracking and also by EDM provided notch root radius ρ is $\leq$0.05mm. The crack growth rate data showed loading mode dependence. Brittle fracture directs attention to the crack length measurement method that requires improvement. The crack growth rate data were correlated with K and $C^*(t)$, and the applicability of the existing test method for crack growth characterisation of TiAl intermetallics is discussed. The emphasis is placed on the correlation between microstructure, fracture and crack growth behaviour of the alloys.

KEY WORDS: TiAl, Intermetallics, High Temperature, Fracture, Creep Crack Growth

INTRODUCTION

Enormous effort has been made in the field of intermetallic materials during the past two decades [1-3]. The work was concentrated on the light weight γ-TiAl base intermetallic alloys which are considered for future high temperature engineering applications to replace the current Ni and Ti base alloys. Several potential applications have been identified for TiAl-based alloys in the aerospace, automotive and turbine power generation markets. Aerospace industry is pursuing the implementation of these alloys in aircraft engine components [4]. Considering the potential application temperatures of about 700°C, the γ -TiAl base intermetallic alloys stand as promising materials for engineering applications provided the problems of relatively low fracture toughness and fast crack growth rates are overcome. The concern is that component life will then be limited in the presence of relatively small existing or in service-initiated defects or flaws. Therefore, the understanding of mechanisms of deformation, fracture and high temperature crack growth need be improved that has been recognised and being worked on intensively [2,5-9].

The fracture mechanics approach has not been fully developed in the research field of intermetallics. Therefore, the fracture toughness values reported in the literature reflect the various methods used for fracture toughness determination [5]. Furthermore, during fracture mechanics testing the crack deviation at lamellae may result in an invalid test [7]. Creep crack growth (CCG) testing of creep brittle materials, such as intermetallics, has been subject to an international effort [10], that produced recommendations to be incorporated in the only existing test method for creep crack growth rate testing of metals, ASTM E 1457-92 [11].

The present paper reports on a study of deformation, and crack initiation and crack growth in γ-TiAl base intermetallic alloys. Creep and crack growth data are determined at 700°. Some of the issues pertinent to fracture and CCG testing of creep brittle materials are highlighted using experimental data obtained on a TiAlCr alloy. The fracture behaviour strongly depends on the microstructural constituents and the orientation of the lamellae in the process zone of the crack tip. Microcracking and crack branching increases with temperature up to 700°C that affect the crack growth assessment.

EXPERIMENTAL PROCEDURE

Material and Metallography

A γ-TiAl base intermetallic alloy, Ti 48at%Al 2at%Cr, (TiAlCr), was investment cast (IC) and subsequently hot isostatically pressed (HIP) at 1200°C [5].
Metallographic specimens were prepared using conventional methods. The test specimens were sectioned from the IC+HIPed billets, some of which were heat treated at 1300°C in air.

Specimens and Testing

The tensile, creep and compact tension (CT) specimens were spark eroded (Electric Discharge Method, EDM) from investment cast near net shape forms and ground to final specimen dimensions. The CT specimens were 50mm wide and 10mm thick and side grooved 20% after precracking or machining of the EDM notches. The slit notches in CT specimens were introduced by EDM using a 0.1 mm diameter wire where the notch root radius, ρ, was 0.05mm.
The tensile properties of the material were determined at 700°C in air at cross head speed of 5mm/min. Creep tests were done at 700°C under constant load determined for an initial stress level to reach the test times that cover a wide stress-strain rate range.
Creep crack growth tests were carried out under displacement rate control at 1, 5 and 10 μm/h, and under constant load on an electro-mechanical machine. The load, displacement in the load line, V_{LL}, and the crack length were continuously monitored and recorded for further evaluation. The direct current potential drop (DCPD) method was employed to monitor crack initiation and crack growth in CT specimens. The crack length was evaluated from the electrical potential measurements and the crack growth rate, da/dt, was determined using 7 point incremental (second order) polynomial method, following the test standard [11].

CCG Data assessment

Due to the brittle fracture behaviour of TiAlCr at 700°C the crack growth data is correlated with K and $C^*_{(t)}$ following ASTM standards E399 [12] and E1457 [11]. For the tests where the load, the load-line deflection rates, and the crack size measurements is available, $C^*_{(t)}$ is determined from,

$$C^*_{(t)} = (F(dV/dt)/BW)\ \eta\ (a/W,n) \qquad (1)$$

where F is the applied load, B and W are the specimen thickness and width, respectively, dV/dt is the measured load-line deflection rate, n is the creep exponent, and η is a geometric function whose value depends on the crack size and n [11].

RESULTS

Tensile and Creep tests

The tensile and creep data determined at 700°C on materials as cast + HIPed (As Cast), and HIPed + heat-treated at 1300°C (HT 1300°C) are given in Table 1. The reported tensile data is an average value of two tests, which had a marginal scatter. The creep exponents reported in Table 1 are average values for the entire data set for a material condition.

TABLE 1: TENSILE AND CREEP DATA OF TiAlCr AT 700°C

Material	$R_{p0.2}$ (MPa)	R_m (MPa)	E-Modulus (MPa)	A_5 (%)	D_1	m	n
As Cast	372	522	152 450	0,03	8,0E-5	6,56	7,78
HT 1300°C	326	412	152 000	0,34	7,0E-5	9,13	9,19

Creep Crack Growth Tests

The scatter and pop-ins in recorded experimental data may be related to the mixed fracture mode with secondary cracking and crack front tunneling. The crack tip deformation and crack extension studied in a SEM on sectioned specimens.

The complete set of creep crack growth data obtained from CT specimens of both As Cast and HT 1300°C materials at 700°C are correlated with crack tip parameters K and $C^*(t)$ in Figures 1 and 2, respectively.

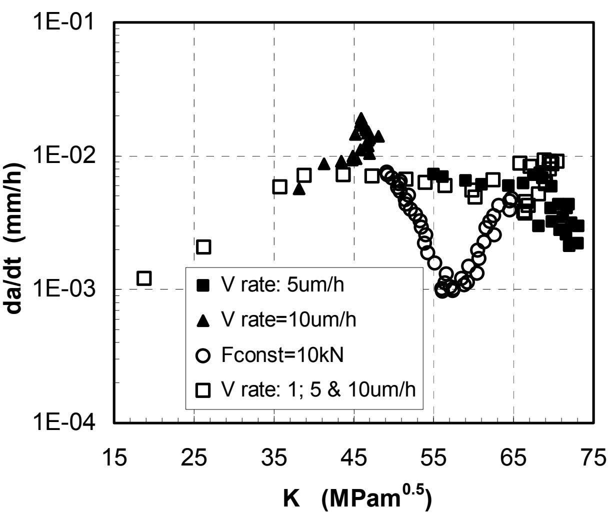


Fig.1.Crack growth rate as a function of K at 600°C (complete set of data).

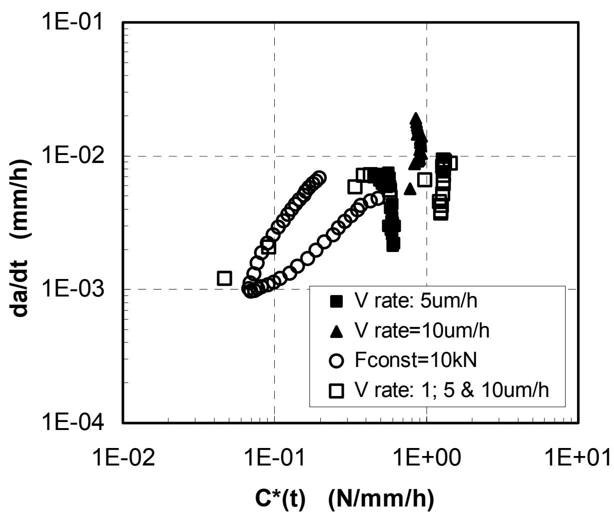


Fig.2.Crack growth rate as a function of C*(t) (complete set of data).

The CCG rate data correlated with K are reduced to transition range, i.e. $\Delta a<0.2$mm, showing a good correlation, as depicted in Figure 3. On the other hand, the crack growth data from displacement rate controlled tests (Vrate in Fig.2) showed decreasing $C^*(t)$ due to crack growth rate effect beyond F_{max}.

This data is reduced up to F_{max} in Figure 4, which gives a linear crack growth correlation. The data from constant load test, however, shows two parts that calls for study of effects of sharp starter crack and loading mode in CCG testing and validity of crack growth data. Therefore, the crack growth data is further analysed comparing the data from constant load and displacement rate control tests in Figures 5 and 6, respectively. Both tests showed the ratio of creep component of displacement rate, $\dot{V}_c$, to total displacement rate, $\dot{V}_t$, $\dot{V}_c/\dot{V}_t$>0.9 for the whole range of tests (Figs.5 a and b), satisfying the validity requirement of the test standard [11]. However, the rather brittle fracture mode observed in SEM calls for

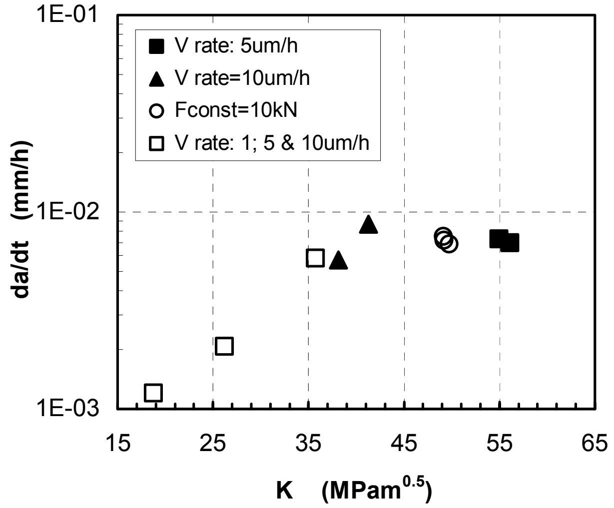


Fig.3. Crack growth rate as a function of K (reduced data for Δa<0.2mm).

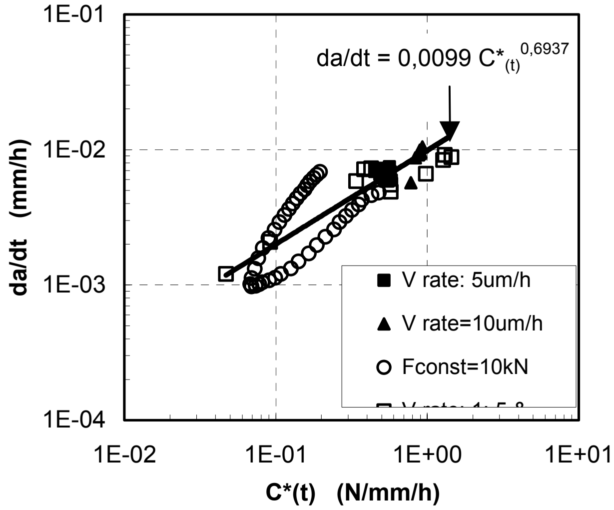
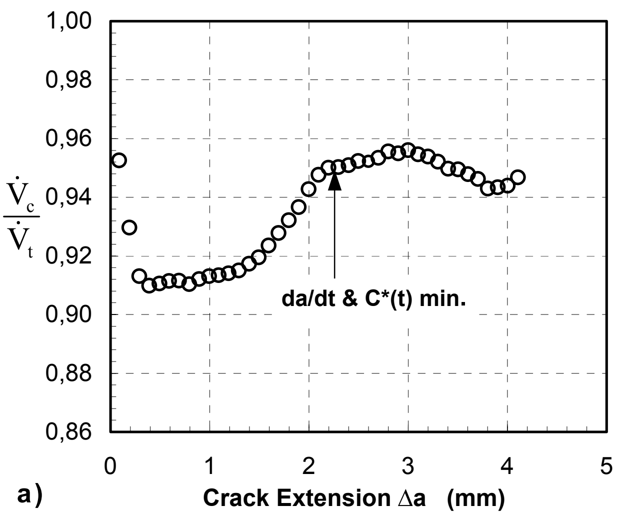


Fig.4. Crack growth rate as a function of $C^*(t)$ at 600°C (reduced data for $F<F_{max}$).

analysis of deformation and deflection rate partitioning. The total load line deflection, V_t, together with elastic, V_e, and creep components of deflection, V_c, are shown in Figure 6 a and b, for constant load and displacement rate control tests as a function of normalised time, t/t_f, respectively. A difference in the growth of creep deformation is noted from the variation of creep component of deflection, V_c, in the figures.



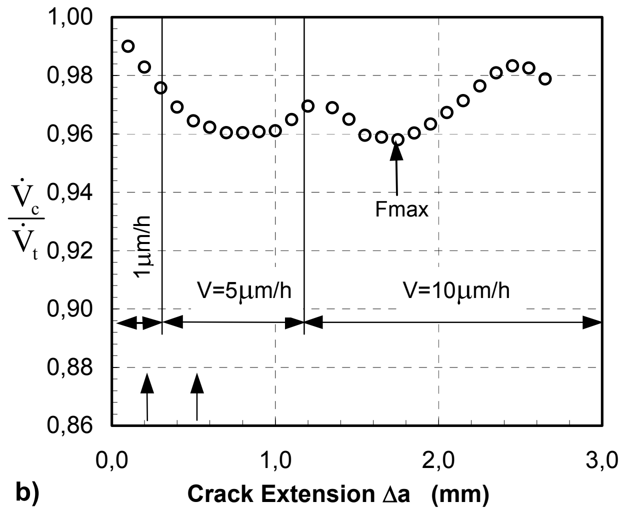


Fig.5.Ratio of load-line deflection rate due to creep (dV_c/dt) to total load-line deflection rate (dV_t/dt) as a function of crack extension (Δa) for HT1300°C TiAlCr tested at 700°C a) under constant load, b) displacement rate control.

DISCUSSION

The microstructure, particularly lamellar grain size and orientation, affects the fatigue crack initiation and fatigue crack growth leading to multi-crack initiation and crack branching [7], mainly affected by the lamellar orientation at the crack tip. The FCP load calculated from formulas given in the test procedures [11,12] overestimate the precrack loads by a factor of three. The difficulty faced with introduction of sharp starter crack may be overcome by spark erosion (EDM) of a fine, i.e. tip radius ρ<0.05mm [8], starter slit notch. The crack growth monitored during testing CT specimens using the DCPD method.

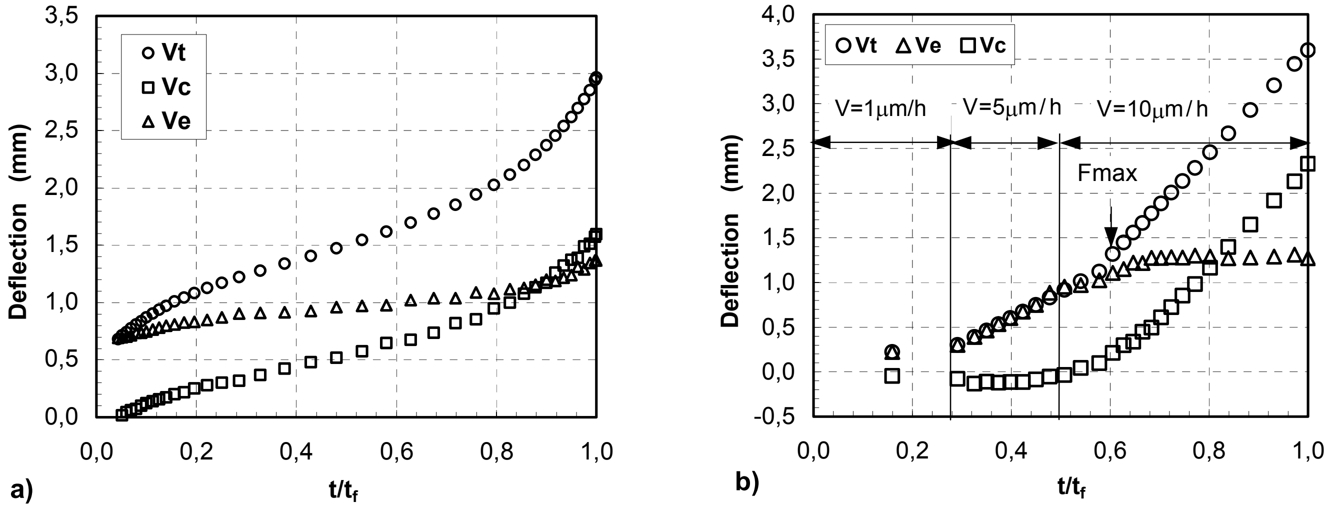


Fig.6.Load line deflection (Vc: creep component, Ve: elastic component, Vt: total load-line deflection) as a function of normalised test time, t/t_f, for HIPed + HT1300°C TiAlCr tested at 700°C a) under constant load, F=10kN, b) displacement rate control, Vrate=1,5&10μm/h.

Crack lengths determined from DCPD were compared with those determined from fracture surfaces. The difference was as high as 50 per cent, with those measured on fracture surfaces were higher, which also did not satisfy the standard requirement. In determining the crack lengths on fracture surfaces the unbroken shear ligaments were ignored, whereas crack lengths from the DCPD were erronous because of surface contacts and unbroken ligaments. The measurement of crack length in toughness testing of TiAlCr requires further study. Crack lengths measured on the side surfaces of specimens were smaller than those measured on fracture surfaces by up to 30 per cent. The crack fronts were uneven and the crack growth was non-uniform by more than 20 per cent or 0.15 mm that is not satisfying the standard test requirements [11]. Crack tunnelling and unbroken ligaments on fracture surfaces contribute to the discrepancy in crack length measurements. Crack branching and bifurcation lead to violation of the validity criteria.

Large grains and lamellae particularly promote the out-of-plane cracking. Out-of-plane cracking limits need to be specified for titanium aluminides similar to the one in Fig 8 of ASTM E647 [13]. The crack deflection at an excess of 20° may call for mixed-mode stress analyses to compute K as it is also suggested in ASTM E647.

The complete set of creep crack growth data is correlated with both C*(t) and K (Figs.1,2), followed by the reduced data (Figs.3,4) to shed some light on the applicability of the concepts of K and C*(t) in these materials. The data from transition range correlate only with K. This is because immidiately after loading, an elastic, or elastic-plastic stress distribution is generated ahead of a crack tip prior to the onset of creep. The criteria was set in the standard [11] to ensure the extensive creep stress distribution will be produced ahead of the crack for the data to correlate with C*(t). The complete CCG data satisfied transition time

$t_{test} > t_T$, and deflection rate ratio $\dot{V}_c / \dot{V}_t$>0.9, although the material is brittle. The variation of deflection rate ratio in Fig.5 does not follow the predicted behaviour [14]. Similar discrepancy is also reported for creep brittle Al and Ti alloys [15]. As numerical work was not done in the present study, it may be noted that this aspect need further clarification particularly if the assessment of component made of TiAl is to be done and the crack tip parameter C_t [14] is considered.

The stationary stress state is achieved in the second part of constant load test (Fig.4). The decreasing part of the constant load test crack growth rate correlation is attributed to the transition of crack growth mode of a fatigue precracked specimen where initial crack growth follows the transgranular fatigue crack path that changes to creep crack mode with accumulation of grain boundary damage with time. This behaviour in TiAl is also reported by Fuji et al [9]. It is important to note that this transition occurs (Fig.5.a) over a period of finite crack extension, as large as 50% of the total test time, t/t_f=0.5.

The data from displacement rate controlled tests exhibited typical transition behaviour over a range of crack growth caused by change of stress state via changing applied load under displacement rate control in creep brittle material. This discussion is supported by the partitioned deflection in Figure 6, where creep component of deflection is 0 for a long period of time, t/t_f>0.5. It was followed by constant V_e and increasing V_c, however, crack growth rate effect dominates after F_{max}. On the other hand the constant load test shows an increasing V_c from beginning of the test onwards as expected.

CONCLUSIONS

The microstructure influences the deformation and creep behaviour of TiAlCr alloys. The fracture mode in CT specimens at 700°C is brittle with microcracking observed in γ-phase and along lamellar interfaces. Large discrepancy, up to 50 per cent, between crack lengths measured on fracture surfaces and those determined using DCPD method were caused by unbroken lamellar ligaments, and crack branching and crack tunneling.
EDM slit notches with tip radius of 0.05mm can be used as sharp starter cracks.
Creep crack growth tests can be done both under constant load and displacement rate control provided the effects of crack growth on stress state is accounted for.
Crack growth data from displacement rate controlled tests beyond maximum load (F_{max}) may not be correlated with crack tip parameters.
The data from transition range i.e. $\Delta a<0.2$mm may be correlated with K.
The time dependent crack growth data assessed following the ASTM standard [11] correlates with $C^*(t)$. However, much work is needed particularly for starter sharp crack requirement, crack length measurements and validity of data in order to assess the components made of creep brittle intermetallics.

ACKNOWLEDGEMENTS

The author would like to thank B. Petrovski for motivating discussions and scientific support and J. Granacher of T.U.Darmstadt for carrying out creep tests.

REFERENCES

1. Kim, Y.-W. (1995) Proc. Symp. Gamma Titanium Aluminides, Y.-W.Kim, R.Wagner and M.Yamaguchi Eds., TMS. Warrendale, Pa.,USA, pp. 637-654.
2. Appel, F. and Wagner, R. (1998) Materials Sci. and Engg., R22 (5), 187-268.
3. Yamaguchi, M., Inui, H. and Ito, K. Acta Mater. 2000, 48, pp.307-322.
4. Kim, Y.-W. JOM, TMS, 1995, 39-41.
5. Dogan, B. (2000) Proc. Int. Conf. Life Assessment of Hot Section Gas Turbine Components, 1999, R.Townsend et.al. Eds. IOM Book B731, pp.209-227.
6. Dogan, B., Schöneich, D., Schwalbe, K.-H. and Wagner, R. (1996) Intermetallics, 4 (1), pp.61-69
7. Dogan, B. and Schwalbe, K.-H. (1997) Engineering Fracture Mechanics, 56 (2), pp.155-165.
8. K.S.Chan and Y.-W.Kim, Met. Trans.A, 1993, 24A, pp.113-125.
9. Fuji, A., Tabuchi, M., Yokobori Jr., A.T. and Yokobori, T. (1999) Engineering Fracture Mechanics, 62 (1), pp.23-32.
10. VAMAS (Varsailles Project on Advanced Materials and Standards) TWA19: High Temperature Fracture of Brittle Materials, 1993-1998.
11. ASTM E1457-98, (1998), Standard Test Method for Measurement of Creep Crack Growth Rates in Metals. Annual Book of ASTM Standards, Philadelphia, 03.01., pp.1031-1034.
12. ASTM E399-90, (1990), Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials, Annual Book of ASTM Standards, 03.01., April 1991, pp.485-515.
13. ASTM E647-95, (1995), Standard Test Method for Measurement of Fatigue Crack Growth Rates, Annual Book of ASTM Standards, 03.01., April 1995, pp.485-515.
14. Saxena, A. Hall, D.E. and McDowell, D.L., (1999) Engineering Fracture Mechanics, 62, pp.111-122.
15. Kwon, O., Nikbin, K.M., Webster G.A. and Jata, K.V. (1999) Engineering Fracture Mechanics, 62, pp.155-165.