Materials Science & Engineering A 709 (2018) 17–29

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

The effect of residual stresses and strain reversal on the fracture toughness of TiAl alloys

Fritz Appel[a,*], Jonathan D.H. Paul[a], Peter Staron[a], Michael Oehring[a], Otmar Kolednik[b], Jozef Predan[c], Franz Dieter Fischer[d]

[a] *Institute of Materials Research, Helmholtz-Zentrum Geesthacht, D-21502 Geesthacht, Germany*
[b] *Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, A-8700 Leoben, Austria*
[c] *Faculty of Mechanical Engineering, University of Maribor, SI-2000 Maribor, Slovenia*
[d] *Institute of Mechanics, Montanuniversität Leoben, A-8700 Leoben, Austria*

ARTICLE INFO

Keywords:
Titanium aluminides
Fracture behaviour
X-ray analysis
Finite element analysis
Intermetallics
Plasticity
Residual stresses

ABSTRACT

The effect of local deformation on the fracture behaviour of TiAl alloys was investigated. Roller indentations impressed parallel to the crack plane significantly improve the fracture toughness. The residual strains present in the indentation zone were characterized by X-ray diffraction and modelled using finite element (FE) calculations. The experimentally observed macrostrains exhibit remarkable crystallographic anisotropies and are unequally shared between the major alloy constituents. The mechanisms behind the observed toughening have been discussed in terms of the residual strains and factors improving the crack tip plasticity. With regard to intended high-temperature applications, the temperature retention of the toughening effect was studied.

1. Introduction

The attractive thermo-physical properties of titanium aluminide alloys make them potentially useful for a variety of high-temperature structural applications [1,2]. However, current materials used in applications, for which replacement by TiAl alloys is being considered, have superior toughness and ductility, a fact that sets severe limitations on the design and handling of TiAl components. In component design, stress intensity factors, termed K_I, are used by arguing that the material can withstand a critical intensity of the crack-tip stress and strain field, characterized by the critical stress intensity, K_{Ic}. This K_{Ic} value is a measure of the fracture toughness of the material. If the loading parameter K_I exceeds K_{Ic}, a mode-I crack propagates. The failure stress σ_a of a component is related to the crack length a_c and the fracture toughness K_{Ic} by [3]

$$\sigma_a = \frac{K_{Ic}}{\alpha\sqrt{\pi a_c}}. \tag{1}$$

The quantity α is a geometrical parameter generally on the order of unity. The allowable stress σ_a in the presence of a crack of length a_c is directly proportional to K_{Ic}, while the allowable crack length for a given stress is proportional to the square of K_{Ic}. Based on the desired service stress and typical defect sizes that are practical for inspection, the material must have at least a minimum toughness to obtain acceptance in the design community.

The low toughness of titanium aluminides is essentially caused by the poor resistance against cleavage fracture of low-index crystallographic planes in the γ(TiAl) and α_2(Ti_3Al) phases. For example, the theoretical stress intensity factor for a mode-I crack on an $\{111\}_\gamma$ plane was determined by first-principles total energy calculations to K_{Ic} = 0.90–0.94 MPa√m, depending on cleavage direction [4]. Similar values hold for the basal plane of the α_2 phase and for crack propagation along a TiAl/Ti_3Al interface. The sensitivity to cleavage fracture of the isolated γ(TiAl) and α_2(Ti_3Al) phases was confirmed by electron microscope observations [5] and fracture toughness testing [6]. Thus, once nucleated in these phases, cleavage cracks may grow extremely fast to a critical length, unless no other toughening mechanism is available. In spite of the brittleness of the individual phases, two-phase ($\alpha_2+\gamma$) alloys can be significantly tougher, mainly depending on the phase morphology [7–9]. The best room temperature toughness was recognized in fully lamellar alloys [8,9]; a finding that was also justified by molecular simulations of crack growth [10]. However, fully lamellar alloys exhibit little room temperature ductility; thus, for technical applications, the so-called duplex microstructure is favoured, which is comprised of lamellar colonies and equiaxed grains. Modern types of alloys with such a microstructure exhibit room temperature yield stresses in excess of 1 GPa combined with a plastic tensile elongation of about 2% [2,11]. Unfortunately, the toughness of these alloys seldom exceeds 10 MPa√m, i.e., their capability to withstand process- or

* Corresponding author.
E-mail address: fritz.appel@hzg.de (F. Appel).

http://dx.doi.org/10.1016/j.msea.2017.10.010
Received 12 July 2017; Received in revised form 30 September 2017; Accepted 3 October 2017
Available online 07 October 2017

service-induced defects at the yield stress level is limited. This compares with a toughness of 40–50 MPa√m, which is typical for Ni-based superalloys. Thus, in order to use the high-strength TiAl alloys at their full potential, improvement of the fracture toughness is required. Microstructural manipulation towards higher toughness of duplex alloys seems to be exhausted after decades of research and development in this field; for reviews see [2,12]. Thus, finding mitigation strategies to overcome the low damage tolerance could be important for widespread use of TiAl alloys. In this context, the effect of uniaxial pre-stressing on the fracture toughness was investigated [2,13]. A moderate increase of the toughness was recognized, which was attributed to the presence of residual stresses and crack tip blunting by deformation induced defect structures.

In the present paper, the effect of a mechanical surface treatment by roller indentation on the fracture toughness of duplex and nearly lamellar TiAl alloys has been investigated. The compressive residual stresses left by the indentations are thought to favourably alter the constraint conditions at the crack tip so that the crack driving force decreases and the fracture toughness increases. However, indentation could inadvertently introduce flaws and residual tensile stresses, which may support crack initiation and propagation [14]. Given this dual role of residual stresses, proper characterization of their values and effects on crack initiation is vital. Thus, fracture toughness testing was combined with X-ray analysis of the stress state introduced by the roller indentations and micro-mechanical modelling of the experiment. The investigation is believed to be of general interest because the influence of local deformation on the fracture behaviour is of fundamental importance for accurate and reliable structural integrity assessment of components and structures.

2. Experimental details and numerical modelling

2.1. Alloys investigated and preparation of fracture toughness specimens

The composition and major constitution of the alloys investigated are briefly described in Table 1.

The alloys were produced by triple vacuum arc re-melting (VAR) or plasma arc melting (PAM) and consolidated by canned hot extrusion at about 1230 °C [11]. Cylindrical sections of the extruded bars 30 mm in length were either subjected to the thermal treatments T_1 or T_2, with

T_1: annealing at 1030 °C, 2 h; furnace cooling, 10 h
T_2: annealing at a temperature $T = T_\alpha - 20$ °C for 30 min; quenching in a forced air stream; annealing at 810 °C, 6 h; furnace cooling, 10 h. T_α is the alpha-transus temperature.

Treatment T_1 resulted in a duplex microstructure in which the lamellar and equiaxed constituents are present in a banded morphology. The banded structure is attributable to the Al and Nb segregation in the VAR ingots, which occurs during their peritectic solidification [15]. After extrusion, the concentration of these elements still varies on a length scale of about 1 mm, which is comparable to or slightly smaller than that of the cast material. The duplex material exhibited a light preponderance of γ grains with an orientation parallel to the extrusion direction [15]. Apart from the γ(TiAl) and α_2(Ti_3Al) phases, alloys #2 and #3 contained significant amounts of β/B2 phase with a body

Table 1
Composition and constitution of the alloys investigated.

No.	Composition (at%)	Major Constitution
1	Ti-47.5Al-5.4Nb-0.4W-0.2B-0.2C (VAR)	γ(TiAl), α_2(Ti_3Al)
2	Ti-45.6Al-7.7Nb-0.2C (VAR)	γ(TiAl), α_2(Ti_3Al), β/B2, B19
3	Ti-45Al-8.5Nb-0.2W-0.2B-0.1C-0.05Y (PAM)	γ(TiAl), α_2(Ti_3Al), β/B2, B19

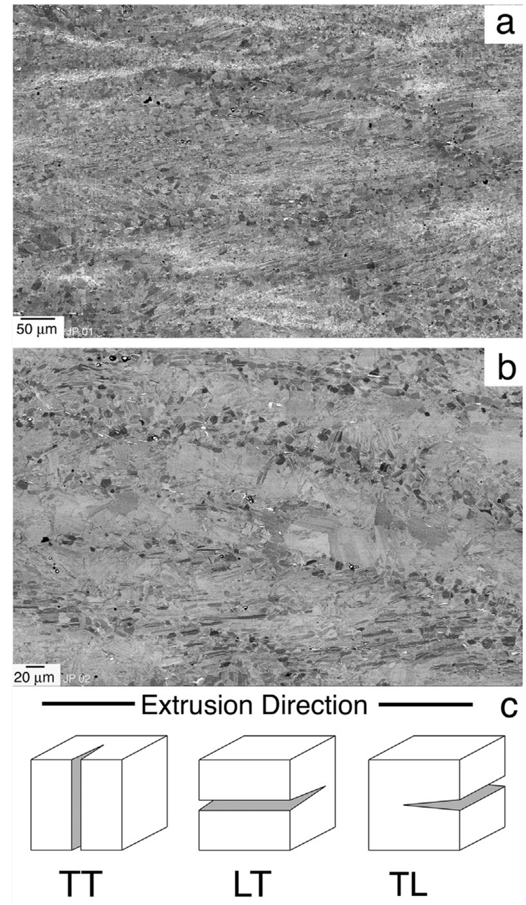

Fig. 1. Microstructure and sample orientation. Scanning electron micrographs in the backscattered electron mode showing the microstructure of alloy #3; the extrusion direction is indicated below. (a) Banded duplex microstructure and (b) nearly lamellar microstructure. (c) Orientation code of the chevron ligament with respect to the extrusion direction: TT – crack front and crack propagation direction perpendicular to extrusion direction, LT – crack front parallel and crack propagation direction perpendicular to extrusion direction, TL – crack front perpendicular and crack propagation direction parallel to extrusion direction.

centred cubic (bcc)/simple cubic (sc) structure and an orthorhombic phase that could be attributed to the B19 (oP4, *Pmma*) or oC16 (*Cmcm*) structure [16,17]. The orthorhombic phase has a close structural relationship to the $D0_{19}$ structure of α_2(Ti_3Al) [16,17]. Treatment T_2 resulted in a nearly lamellar microstructure. Fig. 1 shows these two microstructures as observed by scanning electron micrographs in the backscattered electron mode.

2.2. Fracture toughness testing

For characterizing the effects of residual stress on the fracture toughness, three types of samples were prepared.

(i) Blanks cut from the extruded and heat treated alloys were machined into bending bar specimens of nominal dimensions W = 5.5 mm, B = 4.5 mm and L = 26 mm. A chevron notch with an angle of about 54° was cut into the samples by electrical-discharge machining utilizing a 50 µm diameter wire. The apex of the chevron was positioned at a depth of a_0/W = 0.2. The definitions of specimen geometry terms are illustrated in Fig. 2a. The plane of the chevron ligament was differently oriented with respect to the extrusion direction, as specified below and in Fig. 1c. Orientation TT: Crack front and crack propagation direction perpendicular to extrusion direction. Orientation LT: Crack front parallel and crack