The tensile behaviour of gamma titanium aluminide intermetallic

T. S. SRIVATSAN
Department of Mechanical Engineering, The University of Akron, Akron, OH 44325, USA
M. STRANGWOOD
School of Metallurgy and Materials, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
W. O. SOBOYEJO
Department of Materials Science and Engineering, Ohio State University, 116 West, 19th Avenue, Columbus, OH 43210, USA

The titanium aluminide alloys based on gamma have, in recent years, engendered considerable scientific and technological interest because they offer several useful properties that are either comparable to or better than those of the conventional alloys of titanium and nickle-base superalloy families. In this paper, the tensile behaviour of a gamma-TiAl intermetallic is reported. The intermetallic has a near lamellar microstructure comprising regions of single-phase γ grains, coarse twin-related lamellae and fine lamellae. The tensile properties of the intermetallic containing chromium and niobium are inferior to those of the binary counterpart. Tensile fracture was primarily by intergranular rupture with microcracking along the grain boundaries.

1. Introduction

The ordered titanium aluminide intermetallic, based on γ-TiAl, has in recent years, engendered considerable scientific and technological interest for use in a spectrum of intermediate-temperature (700–1000 °C) structural applications, and as an attractive aerospace structural material, because of their light weight, strength retention, creep/stress rupture and fatigue resistance at elevated temperatures over the monolithic titanium alloys [1–3]. The elastic moduli of these compounds are typically higher than those of the superalloys, thus making them attractive alternative candidates for engine applications [4, 5]. Unfortunately, however, extensive use of the gamma-based TiAl alloys in aerospace, and other high-performance applications, has been restricted by: (a) their low ductility and toughness at temperatures below 600 °C [1, 5]; (b) low fabricability due to poor workability and machinability [6]; and (c) a limited understanding of possible deformation and fracture mechanisms [7–10].

The maximum application temperature for γ-based intermetallics is determined by their oxidation resistance rather than by improvements in ductility, strength retention and creep–rupture properties. In an attempt to overcome the limited mechanical properties of gamma (γ) titanium aluminides and to extend their applicability to high temperatures, efforts have been made to establish and improve processing–microstructure–property relationships for the near-γ titanium aluminides (TiAl) [11–15]. These initial efforts have examined microstructural developments through modifications in alloy composition for achievement of attractive combinations of strength, ductility, fracture toughness, creep/stress rupture and fatigue resistance. In particular, alloying with chromium [16], manganese [17] and vanadium [18] has been shown to result in improved ductility, due to twinning [16], lower tetragonality [19] and decreased unit cell volume [19]. Alloying with tungsten was also found to improve strength [20] and creep resistance [21] via Orowan strengthening by precipitation of α_2 and/or the β precipitates.

The second approach that has been used to engineer a balanced combination of properties in gamma alloys relies on the intrinsic modification of microstructure through heat treatments and innovative thermomechanical processing schedules designed to promote attractive combinations of strength, ductility, fracture toughness, creep/stress rupture and fatigue resistance [10, 19, 22, 23]. Depending on the primary processing and heat-treatment conditions, the microstructure of the end-product can be fully gamma or equiaxed, duplex, fully lamellar and near lamellar. The duplex microstructure consists of equiaxed γ grains and the $\alpha_2 + \gamma$ lamellar grains. Earlier studies on the TiAl intermetallic have shown convincingly that duplex microstructures with optimum ratios of fine equiaxed γ grains and lamellar $\gamma + \alpha_2$ plates display the most desirable combinations of room-temperature strength and ductility [11, 24, 25]. The resultant mechanical properties exhibited by the γ TiAl intermetallic are

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strongly dependent on microstructure, which in turn is dependent on the concurrent and mutually interactive influences of alloy composition and the nature of processing.

The purpose of this paper is to report the tensile deformation and fracture behaviour of a two-phase gamma TiAl alloy containing chromium and niobium. The tensile behaviour of the intermetallic is discussed in terms of intrinsic microstructural effects, matrix deformation characteristics and macroscopic aspects of fracture.

2. Experimental procedure

2.1. Material

The γ-TiAl alloy used in this experimental study was provided by McDonnell Douglas Corporation (St Louis, MO). The actual composition of the alloy (Ti–48Al–2Cr–2Nb) is given in Table 1. Ingots with a diameter of 89 mm were canned in Ti–6Al–4V, was extruded with a reduction ratio of 10:1 at 1343 °C. The extrusion was carried out at the Air Force Materials Laboratory (AFML): Wright Patterson Air Force Base (WPAFB, Dayton, OH). The heat-treatment sequence was selected so as to investigate the stability of the microstructure produced by annealing treatment in the $\alpha_2 + \gamma$ phase field. The heat-treatment sequence consisted of a 24 h anneal at 815 °C superimposed on the heat treatment developed by Blackburn and Smith [26], namely, an anneal at 982 °C for 54 h and allowed to air cool (AC) coupled with an anneal at 704 °C followed by furnace cool (FC). The heat-treatment sequence facilitated long-term exposure of the intermetallic in the $\alpha_2 + \gamma$ phase field. Upon cooling to room temperature, the primary γ grains remain while the α particles undergo a eutectoid transformation to a lamellar structure of α_2 and γ phases. This processing schedule produces a nearly lamellar microstructure (Fig. 1). The addition and presence of the third alloying element (chromium) results in solid-solution strengthening and stabilization of the β phase. This is typically associated with improved ductility through the conjoint action of: (i) deformation-induced twinning [16, 27, 28], (ii) lower tetragonality [19], and (iii) decreased unit cell volume [19]. The presence of niobium in the γ intermetallic provides solid-solution strengthening and improves oxidation resistance [19, 25].

2.2. Experimental techniques

Test specimens were electro-discharge machined with the stress axis parallel to the extrusion direction and conformed to ASTM Standard for tension testing (ASTM E:8). The test specimens were smooth and cylindrical in the gauge section which measured 4.27 mm diameter and 17 mm long. Tensile tests were performed under ambient temperature conditions on a fully automated, closed-loop servo-hydraulic materials test system equipped with a 10 000 kg (98 KN) load cell. The specimens were deformed to failure at a constant strain rate of 0.0001 s^{-1}. The stress and strain, parallel to the load line, were recorded on an X–Y recorder equipped with a pen plotter.

Metallographic samples were cut from the as-received intermetallic, mounted in bakelite and wet ground on 320, 400, 500 and 600 grit silicon carbide (SiC) impregnated emery paper, using water as lubricant. The metallographic samples were then mechanically polished using a 1 μm alumina-based polishing compound. The polished samples were etched and then examined under an optical microscope using standard bright-field illumination techniques. Samples for TEM observation were prepared using jet polishing in a solution mixture of 4% perchloric acid, 35% butanol and 61% methanol (by volume) maintained at − 25 °C and 30 V. The thinned foils were examined in a Phillips electron microscope operating at 200 kV.

Fracture surfaces of the deformed tensile samples were examined in a scanning electron microscope to determine the predominant fracture mode, and to characterize the fine-scale topography and features on the fracture surface.

3. Results and discussion

3.1. Microstructure

The optical microstructure of the Ti–48 Al–2 Cr–2 Nb intermetallic is shown in Fig. 1. Electron microscopy observations of the three-stage annealed intermetallic revealed the microstructure to consist of: (a) regions of single-phase γ grains (allotriomorphs), (b) coarse twin-related γ lamellae with no α_2 present (the lamellae were around 1–2 μm across and these regions are termed as pseudo-allotriomorphic), and (c) fine lamellae of γ and α_2 (lamellar), Fig. 2. In the lamellar regions the width of the γ lamellae was between 0.3 and 0.5 μm, while the α_2 lamellae were an order of magnitude narrower. As the lamellae did not alternate, the volume fraction of the α_2 in the lamellar regions was between 5.0% and 7.5%.

3.2. Tensile properties

The ambient temperature tensile properties of the γ-TiAl intermetallic are summarized in Table II. Results are the mean values based on duplicate tests. The elastic modulus of the γ-TiAl intermetallic was provided as a print-out, as an output of the tensile stress programme, by the computer control CONSOLE unit of the Instron servohydraulic materials test machine. This value was cross-checked for both accuracy and consistency by measuring the slope of the initial

TABLE I Actual composition of the gamma titanium aluminide intermetallic (at %)

Ti	Al	C	O	N	H	S	Cr	Nb
Bal.	46.80	0.037	0.091	0.011	0.075	0.01	2.07	2.01

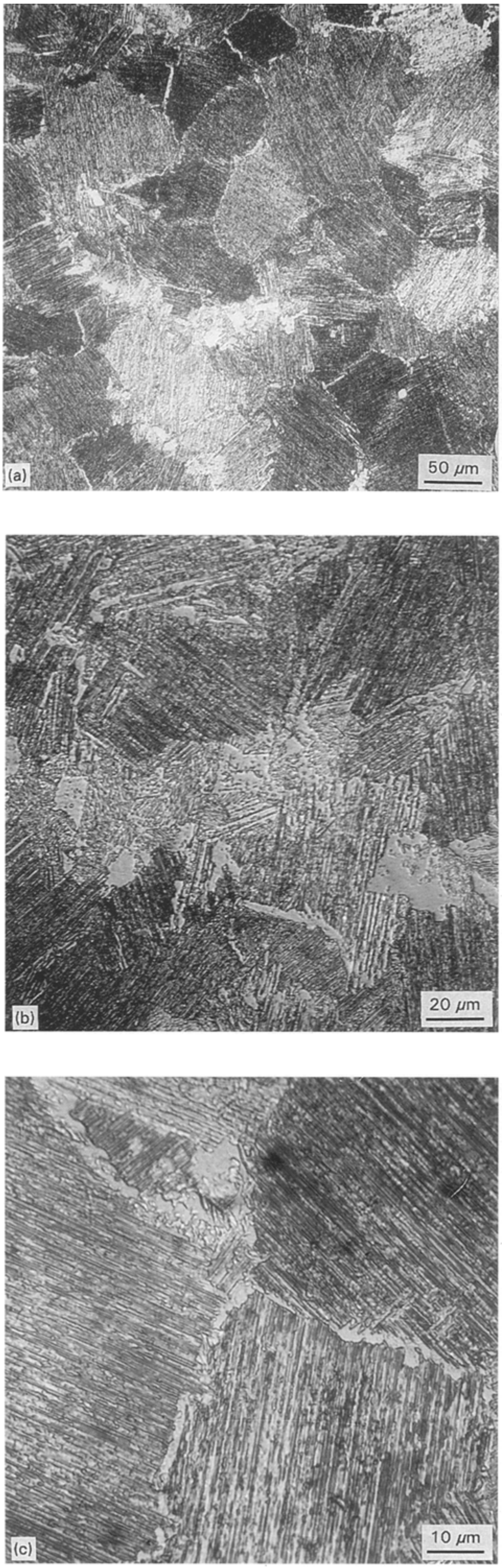

Figure 1 Optical micrographs showing lamellar microstructure of the Ti–48 Al–2 Cr–2 Nb intermetallic.

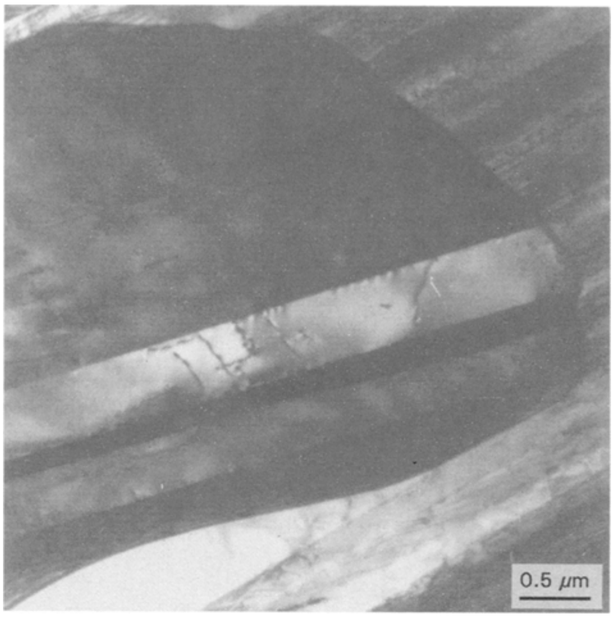

Figure 2 Bright-field transmission electron micrograph showing the pseudo-allotriomorphic and lamellar regions of the microstructure.

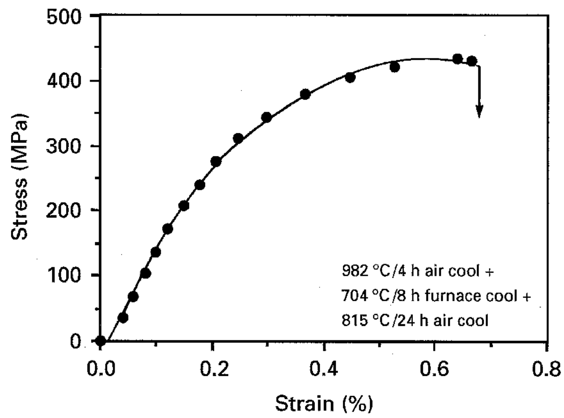

Figure 3 Engineering stress–strain curve of the Ti–48 Al–2 Cr–2 Nb intermetallic.

region of the stress–strain curve, below the elastic limit. The elastic modulus of the TiAl intermetallic is 161 GPa (23×10^6 p.s.i.). The yield strength of the intermetallic (defined as the stress required at a plastic strain of 0.2%) is 416 MPa. The increase in yield strength of this Ti–48 Al–2 Cr–2 Nb intermetallic alloy over the binary Ti–48Al counterpart is negligible. The ultimate tensile strength of the intermetallic is only marginally higher than the yield strength, indicating that the work-hardening rate past yielding is low. The ductility, as measured by tensile elongation over 12.7 mm gauge length, is low and only about 0.67%. The low ductility of the intermetallic is ascribed to the mutually competitive influences of the long-range ordering pattern (an ordered face-centred tetragonal, $L1_0$, crystal structure comprising of alternating planes of titanium and aluminium atoms) and a relatively high lamellar volume fraction [1, 29].

A typical engineering stress–strain curve is shown in Fig. 3. The tensile properties of this niobium containing γ-TiAl intermetallic are inferior to those of the binary [Ti–48A1] counterpart [23]. Thus, from the standpoint of strength and ductility, no appreciable

TABLE II Room-temperature tensile properties of the titanium aluminide intermetallic

Young's modulus, E		Yield stress		Ultimate tensile stress		True fracture stress		Plastic strain (%)	Elong. (%)
(10^6 p.s.i)	(GPa)	(10^3 p.s.i)	(MPa)	(10^3 p.s.i)	(MPa)	(10^3 p.s.i)	(MPa)		
23.3	161	60.4	416	63	440	62.6	431	0.40	0.67

[a] Tangency measurement based on extensometer trace.

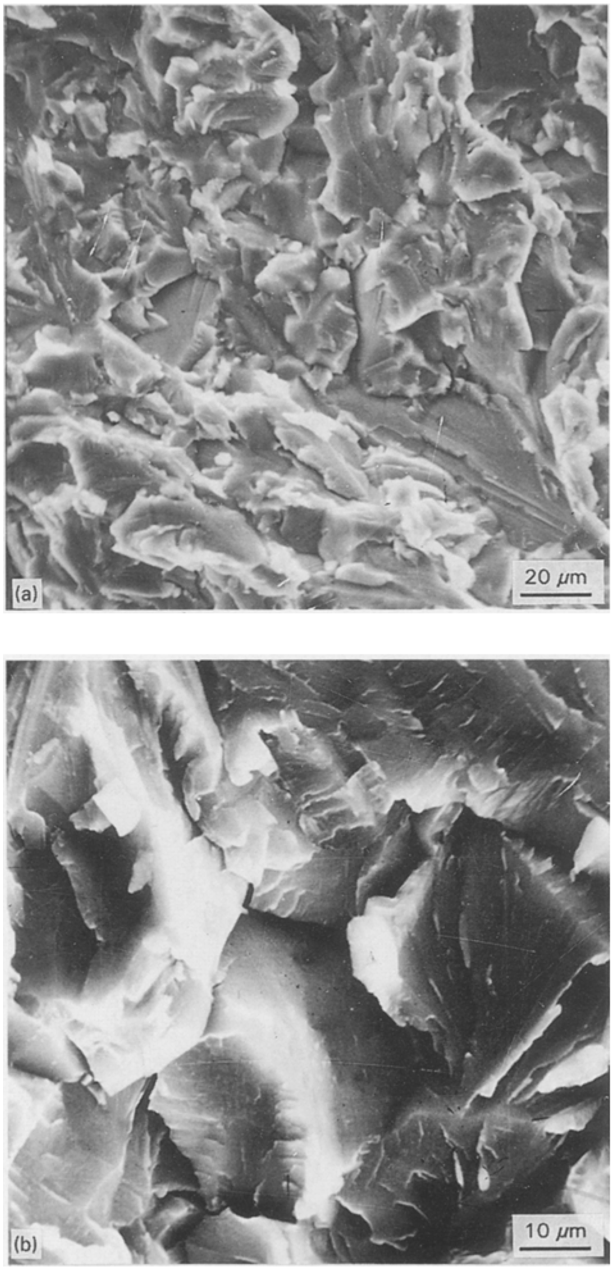

Figure 4 Scanning electron micrographs of the tensile fracture surface showing: (a) a mixture of cleavage and intergranular fracture, and (b) cleavage.

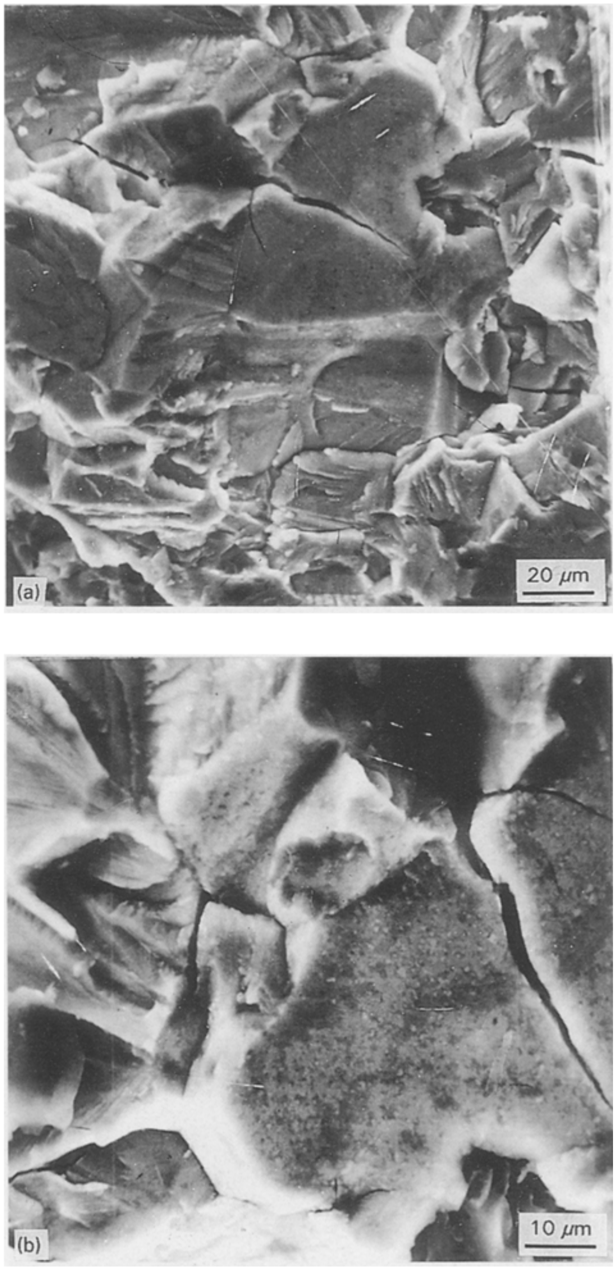

Figure 5 Scanning electron micrographs showing cleavage and intergranular cracking on the tensile fracture surface of the Ti–48 Al–2 Cr–2 Nb intermetallic.

advantage is obtained by adding niobium and chromium. Ternary alloying with niobium in Ti–49 Al–3.4 Nb has been shown to promote the formation of Nb_5Si_3 and α_2 precipitates after high-temperature annealing [23]. These have a detrimental influence on fracture resistance by favouring low-energy intergranular deformation. However, sole ternary alloying of Ti–48Al with 15.5 at% Nb can have a beneficial effect on tensile properties [25]. The limited strength of the quaternary Ti–48 Al–2 Cr–2 Nb alloy may therefore, be due to the competing influence of the above beneficial and detrimental effects.

3.3. Tensile deformation and fracture behaviour

The fracture surface features are useful in elucidating effects of microstructure on the tensile ductility and

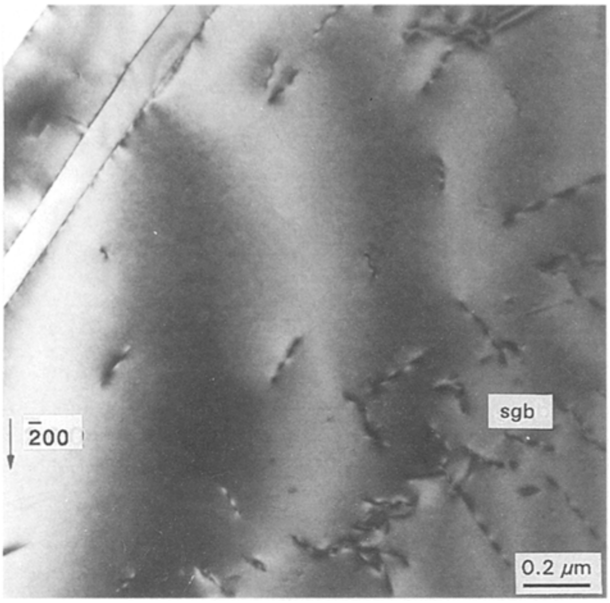

Figure 6 Bright-field transmission electron micrograph showing subgrain boundary (sgb) and isolated dislocations in the pseudo-allotriomorphic region.

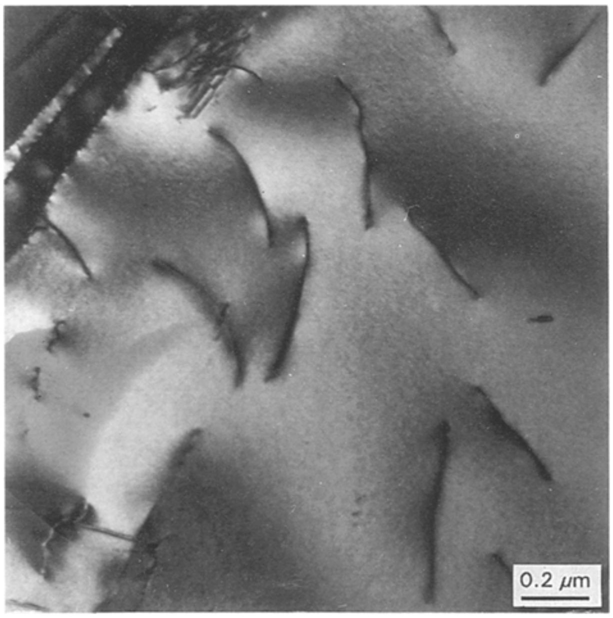

Figure 7 Bright-field transmission electron micrograph showing the 1/2 ⟨1 1 0⟩-type dislocations in the pseudo-allotriomorphic region.

fracture properties of the γ-TiAl intermetallic. On a macroscopic scale, ambient temperature tensile fracture surfaces revealed a mixture of cleavage and intergranular rupture (Fig. 4). The formation and presence of Nb_5Si_3 and α_2 precipitates upon high-temperature annealing degrades the fracture properties by favouring low-energy intergranular rupture (Fig. 5). The intergranular fracture results from the conjoint action of microcracking at grain boundaries due to the high dislocation densities in this region [30] coupled with the segregation of sulphur to grain boundaries [31]. While niobium addition was found to have a detrimental influence on tensile and fracture properties, it was found in an earlier study to provide desirable improvements in oxidation resistance [27].

Transmission electron microscopy observations revealed the presence of dislocations, as short, straight segments, in all three microstructural regions. In the pseudo-allotriomorphic region, some recovery occurred during heat treatment, thus promoting the formation of low-angle grain boundaries in addition to the formation of coherent twin boundaries between the γ lamellae (Fig. 6). The dislocation segments present were of the 1/2⟨1 1 0⟩ type, and they were more numerous in the pseudo-allotriomorphic regions than in the true allotriomorphic γ grains. The (number) density of twins was very low, and their distribution was highly inhomogeneous. The deformed tensile specimens also contained a low density of dislocations (Fig. 7), some of which were dislocation debris from processing. These may account for the generally large density of dislocations in the pseudo-allotriomorphic regions, compared with those in the allotriomorphic (recrystallized) and lamellar regions.

4. Conclusions

Based on a study of the tensile behaviour of the gamma titanium aluminide intermetallic, the following observations are made.

1. The low ductulity of the intermetallic is ascribed to competing influences of long-range ordering and a relatively high lamellar volume fraction in the microstructure. The tensile properties are inferior to those of the binary Ti–48Al counterpart.
2. Tensile fracture at room temperature occurred by a mixture of cleavage, intergranular failure and microcracking at the grain boundaries. The occurrence of intergranular fracture is attributed to the presence of Nb_5Si_3 and α_2 precipitates. Intergranular fracture may also be promoted by high dislocation densities at the grain-boundary regions, and the segregation of sulphur to the boundaries.
3. Transmission electron microscopy observations revealed the presence of dislocations as short straight segments. These dislocations were predominantly the 1/2 ⟨1 1 0⟩ type. The number density of the twins was low and they were distributed inhomogeneously.

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