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Scripta Materialia 67 (2012) 814–817

Scripta MATERIALIA

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Ultrahigh strength and high plasticity in TiAl intermetallics with bimodal grain structure and nanotwins

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Received 13 June 2012; revised 21 July 2012; accepted 23 July 2012
Available online 27 July 2012

Nanostructured intermetallics generally exhibit high strength but limited plasticity due to the covalent nature of their bonding. In this study, high-pressure torsion followed by annealing was used to produce TiAl intermetallics with two microstructural features: (i) bimodal microstructure composed of nanograins and submicrometer grains; and (ii) nanotwins. An exceptional performance, combining ultrahigh yield strength, ~2.9 GPa, and high strain to failure, ~14%, was achieved with micropillar compression tests. Twinning, dislocation slip and grain boundary sliding appear to be active under compressive stress.

Keywords: Nanostructure; High-pressure torsion (HPT); Severe plastic deformation (SPD), Stacking fault energy; Ductility

Intermetallics, which are ordered chemical compounds comprising two or more metals, are generally hard and brittle at room temperature. These mechanical features are a consequence of strong atomic bondings due to rather covalent than metallic bonding, which make dislocation motion through the crystalline structure difficult [1]. Although a number of approaches have been used to improve these materials' mechanical properties, such as grain refinement and addition of alloying elements, there is always a trade-off between strength and plasticity [2]. Although intermetallics refined to the nanometer level exhibit superior physical properties as well as high strength to weight ratios [3] and even superplasticity at elevated temperatures [4], their main weakness remains their brittleness at room temperature [1,2].

Previous studies have reported that the large fraction of grain boundaries acts as both dislocation sources and sinks so that dislocation accumulation, strain hardening and plasticity become limited in nanostructured materials [5,6]. In order to improve the ductility (plasticity under tensile stress), a number of strategies have been employed in metallic alloys, such as severe plastic deformation (SPD) [7–10], bimodal microstructure formation [11–13], introduction of nanotwins [14–16], gradient structure formation from coarse grains to nanograins [17], introduction of precipitates [18], introduction of nanotwins and lattice softening [19], etc. [20]. In this study, a combination of the two strategies mentioned above, namely bimodal microstructure and nanotwin formation, are applied to intermetallics and an ultrahigh strength and high malleability (plasticity under compressive stress) are attained in an TiAl intermetallic.

Disc samples (10 mm diameter, 0.8 mm thickness) of TiAl intermetallics were prepared from Al–50 mol.% Ti micropowder mixtures by SPD followed by annealing, using an approach developed in a previous study for AlNi [21]. Al (99.99%) powders had particle sizes less than ~75 μm and Ti (99.9%) powders had particle sizes less than ~150 μm. The powder mixtures were subjected to SPD using high-pressure torsion (HPT) [22,23] under a pressure of 6 GPa and concurrent rotation of 50 turns with a rotation speed of 1 rpm at 573 K. Following the HPT, Al was completely transformed into Al-rich intermetallics such as $TiAl_3$, $TiAl_2$ and TiAl, and a saturation

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http://dx.doi.org/10.1016/j.scriptamat.2012.07.030

of grain refinement [24,25] to the nanometer level was achieved throughout the discs. The HPT-processed samples were subsequently annealed at 873 K for 86.4 ks to complete the reactions and produce TiAl with bimodal microstructures and nanotwins.

The samples were evaluated by means of X-ray diffraction (XRD) analysis, differential scanning calorimetry (DSC), Vickers microhardness measurement, compression testing using square-shaped micropillars [26] (side length: 0.7–11.3 μm, height: three times the the length), electron back-scatter diffraction (EBSD) analysis, scanning electron microscopy (SEM) and scanning transmission electron microscopy (STEM).

The materials and processing parameters were selected carefully to produce several characteristic features as shown in Figure 1. First, the average grain size of sample reaches ∼20 nm after SPD (Fig. 1d), whereas the grain size of severely deformed metallic materials is usually larger than 100 nm [27,28]. Here, the grain refinement is enhanced by using the powder mixtures [24], by combining the solid-state reactions and SPD [29] and by strong atomic bonding of Al-rich intermetallics [25]. Second, in addition to ordinary and superlattice slip deformation modes, the TiAl exhibits deformation twinning [30]. Moreover, the stacking fault energy of TiAl is low, 100 mJ m^{-2} [31], and the materials exhibit nanotwin formation by annealing (Fig. 1a–c). The twin width ranges from few nanometers to ∼50 nm, with an average twin width of ∼9 nm (Fig. 1e). It should be noted that since only the twins with twin boundaries parallel to the incident electron beam are visible in TEM images, the real twin density should be much higher than the one seen in Figure 1. Third, the annealing temperature of 873 K is selected slightly higher than the temperature peaks appeared during DSC analysis of the HPT-processed samples (478, 652, 810 and 844 K) to ensure that all

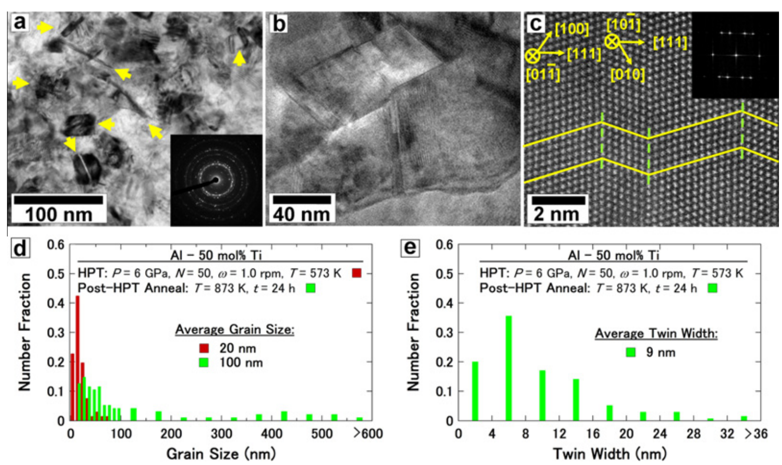

Figure 1. Microstructures of TiAl intermetallic. (a) TEM bright-field image and corresponding SAED pattern of nanograined structure with nanotwins indicated by arrows; (b) TEM bright-field image of a single submicrometer grain containing several twins; (c) STEM lattice image of nanotwins and corresponding diffractogram; (d) grain size distribution for HPT-processed samples before and after annealing; and (e) twin width distribution after annealing.

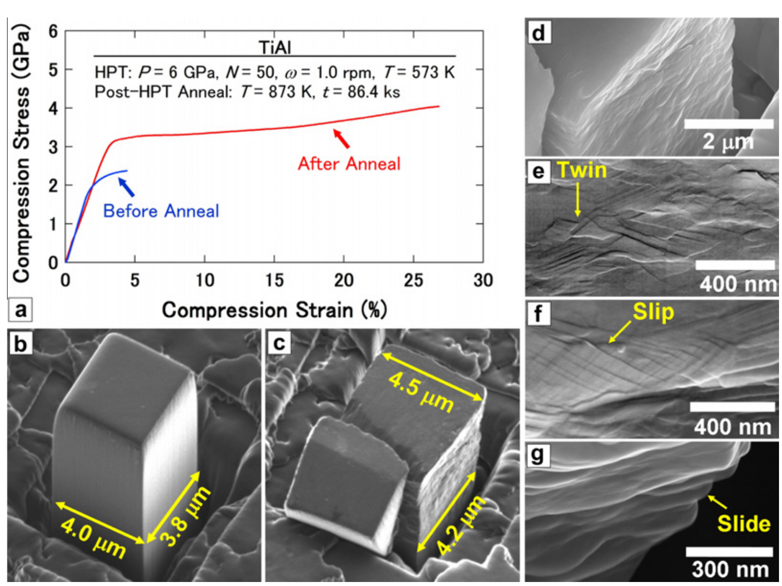

Figure 2. Micropillar compression test for TiAl intermetallic. (a) Nominal compression stress vs. nominal compression strain curves of HPT-processed samples before and after annealing, (b) appearance of pillar before compression, (c,d) appearance of pillar after compression, (e–g) SEM micrographs taken from pillar side surface and edge after compression.