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MECHANICAL AND MICROSTRUCTURAL RESPONSES AND MICROCRACK FORMATION IN TITANIUM ALUMINIDES AT A WIDE RANGE OF STRAIN RATE AND TEMPERATURE

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Significant progress has been made in the development of titanium aluminide alloys for high temperature and high performance applications in the last decade. An extensive database on the mechanical and microstructural responses of titanium aluminides under various quasi-static loading conditions has been developed. However, knowledge of the mechanical and microstructural responses of titanium aluminides under dynamic loading conditions remains poorly understood. A systematic investigation of the strain rate and temperature effect on mechanical and microstructural responses, microcrack nucleation and microcrack propagation in three titanium aluminide alloys, a polysynthetically twinned (PST) TiAl crystal, a duplex γ-TiAl alloy and a polycrystalline Ti_3Al-based alloy, was carried out in this study.

The PST crystal was grown at Kyoto University, Japan, using an optical floating zone furnace. The nominal composition of the PST crystal was Ti-49.3Al (at.%). The duplex microstructure of a γ-TiAl alloy with a nominal composition of Ti-46.5Al-2Cr-3Nb-0.2W (at.%) was obtained by a two-step forging process followed by a heat treatment at UES, Inc., Dayton, Ohio. The average grain size of this γ-TiAl alloy was ~10 μm. The investment cast Ti_3Al-based alloy, Ti-25Al-10Nb-3V-1Mo (at.%), was made by Howmet Corporation, Whitehall, Michigan. The equiaxed α_2 grain size was ~400 μm. Compressive tests were performed at strain rates of 0.001 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1}, 35 s^{-1}, 2000 s^{-1} and 3000 s^{-1} and at temperatures ranging from -196 °C to 1200 °C for the polycrystalline alloys and at a strain rate of 2500 s^{-1} and temperatures of 25 °C and 800 °C for PST crystals. The low strain rate (0.001 s^{-1} to 35 s^{-1}) tests were carried out using an Instron screw-driven test machine and a hydraulic MTS machine. The high strain rate (2000 s^{-1} to 3000 s^{-1}) tests were conducted using a Split-Hopkinson Pressure Bar. Deformation microstrucutres and microcrack nucleation and propagation were characterized using optical, scanning and transmission electron microscopes.

The flow stress of PST crystals at 2500 s^{-1} exhibited a strong dependence upon the lamellar interface tilting angle (Φ), similar to those observed at quasi-static strain rates. However, the absolute flow stress values at 2500 s^{-1} were larger than those at 0.0002 s^{-1} by ~200 MPa (Fig. 1 (a)). The deformation of individual domains was found to be dominated by mechanical twinning or the $\frac{1}{2}$<110] ordinary dislocation slip, which was dependent on the domain orientations.

The temperature dependence of yield and flow stresses of the duplex γ-TiAl alloy was found to be dependent upon the strain rate (Fig. 1 (b)). At strain rates of 0.001 s^{-1} and 0.1 s^{-1} (below 1 s^{-1}), the yield stress decreased with increasing temperature with a plateau between 200 °C and 800 °C. At strain rates above 1 s^{-1}, the yield stress exhibited a positive temperature dependence at temperatures above 600 °C. The strain hardening rate decreased dramatically with temperature in the low and high temperature regions with a plateau occurring at the intermediate temperatures at all strain rates. As the strain rate increased the strain hardening rate plateaus were seen to extend to higher temperatures. The strain rate sensitivity was found to increase slightly with temperature but the rate sensitivity was less than 0.1 for strain rates above 0.001 s^{-1}. At 0.001 s^{-1}, a dramatic increase in the strain rate sensitivity with temperature was observed. At temperatures ≥1100 °C, the rate sensitivity was larger than 0.3. Accordingly, the mechanical response of this fine grained γ-TiAl alloy was characterized into three distinct regimes as follows: (i) the stage-II hardening at low temperatures, (ii) the stage-III hardening at intermediate temperatures and (iii) superplasticity at high temperatures. The temperatures at which one of these mechanisms dominated were observed to increase as strain rate increased. The deformation microstructures were found to be dominated by mechanical twins and ordinary dislocations similar to those observed in PST crystals.

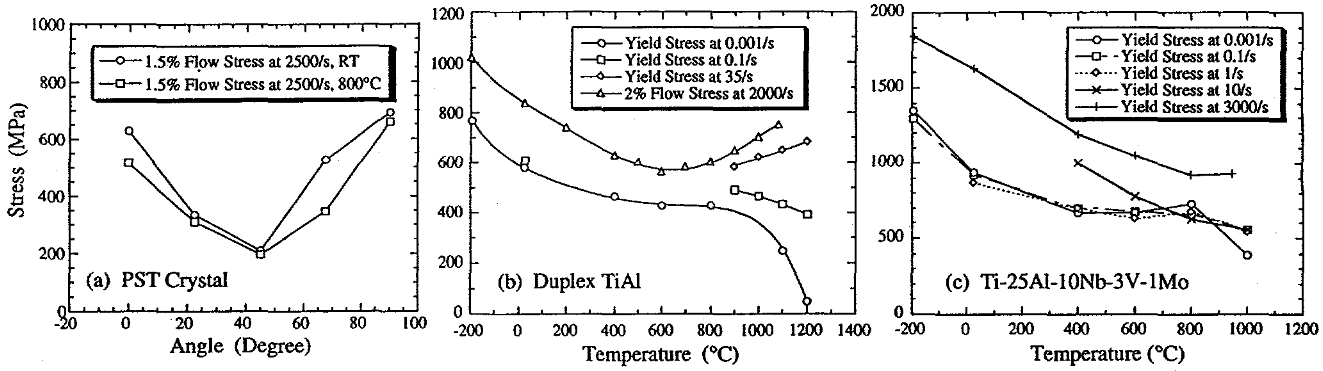

Fig. 1 Stress-temperature dependence of titanium aluminides

The strain rate effect on the anomalous stress-temperature dependence in the polycrystalline Ti_3Al-based alloy (Fig. 1 (c)) was seen to be opposite to that in the γ-TiAl alloy (Fig. 1 (b)). The anomalous stress-temperature dependence occurring at 800 °C was observed only at low strain rates (below 1 s^{-1}). The anomaly decreased with increasing strain rate and was not existent at strain rate above 1 s^{-1}. The work hardening rate also showed an anomalous temperature dependence at 800 °C and at strain rates ≤1 s^{-1}. No apparent strain rate dependence of the work-hardening rate was observed within the range of strain rate and temperature studied except at 800 °C. The stress-strain response of Ti_3Al-based alloys was found to be controlled by the stage-II hardening at low temperatures and by the stage-III hardening at temperatures ≥1000 °C. The deformation microstructural characterization of the Ti_3Al-based alloy is in progress and will be included in the manuscript.

Microcrack nucleation and propagation was found to be strongly dependent upon the deformation of individual domains in PST crystals. Two types of microcrack formation modes were observed (Fig. 2): (i) Microcracks nucleated at lamellar interfaces and propagated along the interfaces by a shear displacement due to the large strain mismatch between domains on the interfaces; (ii) The translamellar microcracks were formed by a tensile stress component imposed by the external loading and the local stress state caused by the strain mismatch of domains. The habit plane of translamellar microcracks was accordingly defined depending on the domain orientations. The translamellar microcracks were easily deflected at lamellar interfaces particularly at the interface where the other side domain was deformed primarily by parallel twinning. A TEM study of microcrack propagation in PST crystals showed no preferential crack propagation along α_2/γ interfaces. A zigzagged path of microcrack propagation within an α_2 lath was observed. Mechanical twinning as a primary deformation mode accommodated mismatch strains between domains such that mechanical twinning depressed the nucleation of microcracks at small strains. However, it was also observed that microcracks propagated along the mechanical twin interfaces at large strains. Microcracks in the duplex γ-TiAl alloy were observed to be formed by the shear displacement along the maximum shear stress planes in equiaxed γ grains. Microcracks in the Ti_3Al-based alloy were observed to form primarily at the α_2/β phase interfaces and grain boundaries.

The mechanical behavior observed in these three alloys will be interpreted based on the characterized deformation microstructures. Microcrack nucleation and propagation mechanisms will be discussed in detail in terms of the observed mechanical and microstructural responses of these alloys.

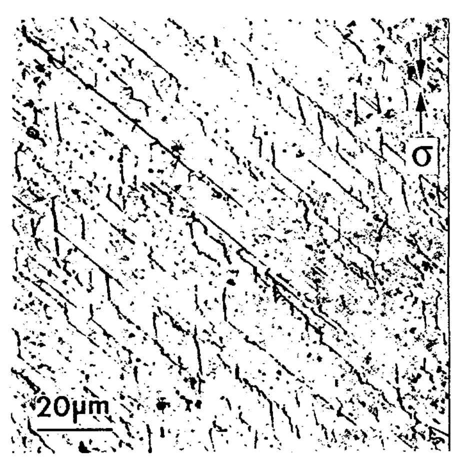

Fig. 2 Microcracks in a PST crystal