Changes in Microstructure during Primary Creep of a Ti-47Al-2Nb-1Mn-0.5W-0.5Mo-0.2Si Alloy

D.Y. SEO, T.R. BIELER, S.U. AN, and D.E. LARSEN

Cast gamma titanium aluminides are gaining acceptance as potential replacements for superalloy and steel components in many applications. One particular alloy with W, Mo, and Si additions has shown exceptional primary creep resistance. Quantitative microscopic comparisons were made between microstructures in undeformed and deformed regions in creep specimens deformed to strains between 0.1 and 1.5 pct strain, using optical microscope, scanning electron microscope (SEM), and transmission electron microscope (TEM) techniques. As-hot isostatically pressed ("hipped") and heat-treated (1010 °C for 50 hours) conditions were compared. The as-hipped specimen had a higher lamellar volume fraction, and it crept more than 100 times faster. The lamellar spacing in the lamellar grains systematically decreased by 15 to 35 pct, with increasing stress, during the first 0.1 to 2 pct strain. Precipitates containing W, Mo, and/or Si were observed in the deformed gage and undeformed grip sections of the heat-treated specimens. Precipitation is nucleated by heat treatment, but, during creep deformation, a more homogeneous and faster growth process occurs in the gage section than in the aged but undeformed grip section. The gage section had a 35 pct higher precipitate volume fraction, but their average size was smaller. A lower volume fraction of lamellar grains and the presence of precipitates account for the excellent creep resistance in the heat-treated alloy.

I. INTRODUCTION

The Ti-Al intermetallic alloys are potential replacements for superalloys in some high-temperature applications in heat engines, turbine engine blades, and aerospace and automobile components, since it has high specific strength at high temperatures. The microstructure is affected by composition and heat treatment, and creep properties are sensitive to microstructure. Gamma titanium aluminide can be heat treated to obtain four types of microstructure. The best creep resistance has been observed in fully lamellar microstructures. However, the duplex microstructure is preferred for many applications, because it provides a desirable combination of room-temperature ductility and toughness.

The additions of Cr, Nb, V, Mn, W, Mo, and Si in two-phase Ti-Al alloys affect many material properties. Additions of 1 to 3 at. pct of Cr, V, or Mn can improve the ductility of duplex alloys, but V generally reduces the oxidation resistance. Niobium greatly enhances the oxidation resistance and slightly improves the creep resistance. The addition of 0.5 to 1 at. pct Si enhances the creep strength, oxidation resistance, and room-temperature fracture toughness of 48 at. pct Al two-phase alloys. Silicon also increases fluidity and reduces the susceptibility to hot cracking. Molybdenum provides a good balance of strength and ductility in TiAl, having very fine equiaxed gamma grains with the αγ and β phase. The addition of W greatly improves oxidation resistance and enhances creep resistance. Most of these studies have focused on either room-temperature properties, minimum creep-rate conditions, or stress-rupture properties. However, primary creep resistance is important for practical applications. Gamma-based TiAl exhibits primary creep strains that are typical for metals, where the minimum is reached after about 1 pct strain. In an effort to decrease the creep rate during primary creep deformation, additions of W, Mo, and Si have significantly increased the time to reach 0.5 pct strain. A dynamic precipitation process has been indicated in References 13 and 24. Observations of lamellar refinement during primary creep suggest that a significant amount of mechanical twinning occurs parallel to lamellar interfaces as an easy mode of deformation, and this hardens the microstructure. In this article, we analyze microstructural changes during primary creep in a Ti-47Al-2Nb-1Mn-0.5W-0.5Mo-0.2Si alloy by characterizing the volume fraction of lamellar and equiaxed microstructures, the distribution of γ interface and αγ lath spacings, mechanical twinning, and the precipitates of various size, composition, and shape that interact with dislocations.

II. EXPERIMENTAL

The Ti-47Al-2Nb-1Mn-0.5W-0.5Mo-0.2Si alloy was investment-cast and hot isostatically pressed ("hipped") at 1260 °C for 4 hours at 127 MPa, in order to eliminate casting porosity, at Howmet Corp. (Whitehall, MI). The cast 16-mm-diameter test bars were heat treated in the two-phase αγ + γ field at 1010 °C for 50 hours and air cooled, to obtain a duplex microstructure, by the Howmet Corp. The heat treatment is illustrated on the binary phase dia-
Fig. 1—A Ti-Al phase diagram near the stoichiometric TiAl composition.

Tensile creep specimens with a 25-mm gage length and a 5-mm diameter were machined from the test bars, and creep tests were conducted at Howmet Corp. One creep specimen (000248) was deformed at 760 °C at 138 MPa and the other (012784) was deformed at 649 °C at 276 MPa. The specimens were loaded in a few seconds, and data acquisition of one datum point each 15 minutes started just after loading. The experiment was stopped when about 0.5 pct strain was reached, and the specimen was cooled under load.

Some additional 5 × 5 × 3 mm brick-shaped specimens were cut using electrodischarge machining (EDM) from an as-hipped slice of a 28-mm-square casting gate from a different casting for shear compression creep tests. The shear compression experiments were deformed on a 45 deg inclined stage in an INCONEL* 718 compression cage.*INCONEL is a trademark of INCO Alloys International, Inc., Huntington, WV.

The maximum shear stress is 45 deg from the principle stress state, and it has a value of 1.12 τ. The effective stress for this loading condition was computed to be σeff = 1.26 τ. Since the specimen has a compressive stress component with a magnitude equal to the shear stress, there may be some reduction in thickness due to deformation. Supposing that all the strain occurred due to compression, then the shape change indicated in Figure 2(b) would occur, and the magnitude of the compressive strain would be more than 6 times larger than the shear strain computed by assuming only simple shear (for the measured displacement). If a mixture of shear and compression strain occurred, the resulting shear strain would be very nearly the same as that obtained using the assumption of only simple shear, as illustrated in Figure 2(b). Consequently, the simple shear strain is a lower bound on the strain that occurred in the middle of the sample. In order to compare results with tensile experiments, the effective strain was estimated as εeff = γ/√2. Tests were stopped at shear strains of about γ = 0.2, 0.5, and 1.5 pct to measure microstructural changes in the middle of the specimen. With such small strains, mechanical measurement of the specimen shape change was not resolvable.

For microstructural analysis of the tensile creep specimens, slices were cut from the middle of the gage and the middle of the annealed TiAl specimens. The principle stresses were determined with Mohr’s circle, and they are illustrated in Figure 2. Some additional 5 × 5 × 3 mm brick-shaped specimens were cut using electrodischarge machining (EDM) from an as-hipped slice of a 28-mm-square casting gate from a different casting for shear compression creep tests. The shear compression experiments were deformed on a 45 deg inclined stage in an INCONEL* 718 compression cage.*INCONEL is a trademark of INCO Alloys International, Inc., Huntington, WV.

In order to compare results with tensile experiments, the effective strain was estimated as εeff = γ/√2. Tests were stopped at shear strains of about γ = 0.2, 0.5, and 1.5 pct to measure microstructural changes in the middle of the specimen. With such small strains, mechanical measurement of the specimen shape change was not resolvable.

For microstructural analysis of the tensile creep specimens, slices were cut from the middle of the gage and the middle of the annealed TiAl specimens. The principle stresses were determined with Mohr’s circle, and they are illustrated in Figure 2. Some additional 5 × 5 × 3 mm brick-shaped specimens were cut using electrodischarge machining (EDM) from an as-hipped slice of a 28-mm-square casting gate from a different casting for shear compression creep tests. The shear compression experiments were deformed on a 45 deg inclined stage in an INCONEL* 718 compression cage.*INCONEL is a trademark of INCO Alloys International, Inc., Huntington, WV.

In order to compare results with tensile experiments, the effective strain was estimated as εeff = γ/√2. Tests were stopped at shear strains of about γ = 0.2, 0.5, and 1.5 pct to measure microstructural changes in the middle of the specimen. With such small strains, mechanical measurement of the specimen shape change was not resolvable.

For microstructural analysis of the tensile creep specimens, slices were cut from the middle of the gage and the middle of the annealed TiAl specimens. The principle stresses were determined with Mohr’s circle, and they are illustrated in Figure 2. Some additional 5 × 5 × 3 mm brick-shaped specimens were cut using electrodischarge machining (EDM) from an as-hipped slice of a 28-mm-square casting gate from a different casting for shear compression creep tests. The shear compression experiments were deformed on a 45 deg inclined stage in an INCONEL* 718 compression cage.*INCONEL is a trademark of INCO Alloys International, Inc., Huntington, WV.

In order to compare results with tensile experiments, the effective strain was estimated as εeff = γ/√2. Tests were stopped at shear strains of about γ = 0.2, 0.5, and 1.5 pct to measure microstructural changes in the middle of the specimen. With such small strains, mechanical measurement of the specimen shape change was not resolvable.

For microstructural analysis of the tensile creep specimens, slices were cut from the middle of the gage and the middle of the annealed TiAl specimens. The principle stresses were determined with Mohr’s circle, and they are illustrated in Figure 2. Some additional 5 × 5 × 3 mm brick-shaped specimens were cut using electrodischarge machining (EDM) from an as-hipped slice of a 28-mm-square casting gate from a different casting for shear compression creep tests. The shear compression experiments were deformed on a 45 deg inclined stage in an INCONEL* 718 compression cage.*INCONEL is a trademark of INCO Alloys International, Inc., Huntington, WV.