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FRACTURE OF $\text{Al-Al}_2\text{O}_3$ ALLOYS: FRACTURE ANALYSIS OF THE COMMERCIAL SAP-TYPE ALLOY XAP-001

D.G. Harman

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COMMERCIAL SAP-TYPE ALLOY XAP-001

D. G. Harman T. A. Nolan

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FRACTURE OF Al-Al₂O₃ ALLOYS: FRACTURE ANALYSIS OF THE
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D. G. Harman T. A. Nolan¹

ABSTRACT

Fracture surfaces of XAP-001 dispersion-hardened aluminum were examined in the electron microscope using two-stage replication. The fracture surfaces were obtained from rod tensile specimens tested from -200 to 450°C or creep tested at 450°C. Three modes of ductile fracture are described and identified by fractography. High-temperature fractures are initiated at single oxide particles or groups of particles. Banding and stringing of oxide particles seriously affect the fracture process.

INTRODUCTION

Aluminum dispersion hardened with Al₂O₃ shows superior strength properties at elevated temperatures when compared with the strongest precipitation hardened aluminum alloys. Alcoa XAP-001 had 6-8% Al₂O₃ and shows a tensile strength greater than 10,000 psi at a temperature equal to two-thirds its melting point. This strength advantage, however, is accompanied by low ductility and elongation values of less than 5% are common.

Theoretical studies involving dispersion strengthened alloys have usually dealt with the strength of these materials but not their ductility. Work-hardening models have been developed but only for low plastic strains or for low temperatures where relaxation is not significant. In the few cases where the fracture of SAP-type alloys has been treated, it has been assumed to be brittle because of the low total elongation measured over the entire gage length.

¹Physics Department, Technical Division, Oak Ridge Gaseous Diffusion Plant.

The present study involves fractographic analysis over a wide range of testing conditions and describes three modes of ductile fracture and identifies some initiation sites for fracture.

EXPERIMENTAL PROCEDURE

Constant strain-rate tensile tests were conducted on 1/8-in.-diam, 1 1/8-in.-gage length buttonhead specimens that were machined from a 0.4-in.-diam extruded XAP-001 rod. Tests were conducted in liquid nitrogen, at room temperature, 300°C, and 450°C at strain rates of 0.0002 to 0.02 min⁻¹. A floor model Instron testing machine was used for the tensile tests. Creep-rupture tests were conducted at 450°C in air.

Replicas of the fracture surfaces were made by a two-stage polyvinyl alcohol-carbon technique. Two coats of 20 wt % PVA were applied to the fracture surface. The dried plastic replicas were then removed from the specimens and were shadowed with platinum at a 45° angle and with carbon in a vacuum evaporator. After the plastic was dissolved by complete immersion in water, the replicas were washed and mounted on electron microscope specimen grids. This technique yielded complete replicas over the entire fracture surface with few holes or folds in the carbon film. Large areas of the replicas were viewed and electron micrographs were made of representative fields for each mode of fracture found.

EXPERIMENTAL RESULTS AND DISCUSSION

Results of other investigations have shown that plastic deformation is a part of the ductile fracture process.^{2,3,4} This deformation culminates in the formation voids in the material, which usually occur at some discontinuity such as an inclusion or a second phase particle. Extensive

²E. Orowan, J. F. Nye, and W. J. Cairns, Strength and Testing of Materials, Pt. I, p. 127, H. M. Stationery Office, London, 1952.

³C. S. Smith and R. W. van Wagner, Am. Soc. Testing Mater. Proc. 36, 263 (1936).

⁴A. H. Cottrell, "Theoretical Aspects of Fracture," Proc. Conf. Fracture, Swampscott, Mass., 1959.

Fig. 1. Section Through the Neck of a Tensile Specimen of Copper.

void formation in the necked region of a tensile specimen of copper that was sectioned immediately before fracture is shown in Fig. 1 (ref. 4). These voids may link up to form a separation in the material such as shown in the center portion of Fig. 1. This process, generally called separation, usually occurs simultaneously at several sites throughout the material. The early stages of fracture for this mode of fracture initiation is shown schematically in Fig. 2. The intent of this and subsequent models is to show a mode of fracture that may, in fact, represent only a small fraction of the total volume of material. The figure shows that voids have

formed throughout the material and have linked up to initiate fracture in two regions. The model depicts a higher density of voids in the region near the fracture. The fractograph insert in this and subsequent figures shows the mode of fracture depicted in the model as it appears in the electron microscope.

If a material is loaded eccentrically, a "tearing" mode of fracture may be favored over separation. The model shown in Fig. 3 depicts the tearing mode of ductile fracture with the eccentric loading being indicated by the position of the force vectors. The fracture has initiated at the surface and is propagating through the material from left to right with the sectioned drawing showing the appearance of the fracture as it is propagating. The tearing process has been treated in some detail by A. Phillips et al.⁵ As will be shown later, ductile tearing results in matching features on both fracture surfaces that point toward the site of fracture initiation such as those shown on the lower half of the drawing (Fig. 3).

⁵A. Phillips, V. Kerlins, and B. V. Whiteson, Electron Fractography Handbook, Air Force Materials Laboratory Technical Report ML-TDR-64-416 (January 1965).

Fig. 2. Fracture Initiation by Separation. Voids have formed throughout the material and have coalesced to initial fracture in two regions. The voids now appear as equiaxed dimples on the fracture surface. The fractograph shows this fracture as it appears on the fracture surface.

Fig. 3. Fracture by Tearing. Eccentric loading has caused fracture to initiate at left hand surface and propagate into center region. The fracture surface shows somewhat elongated dimples. The fractograph shows this fracture as it appears on the fracture surface.

As was pointed out in the above figure, tearing results from an eccentric loading of the material and generally initiates at a free surface. A fracture that has been initiated by separation such as that shown in Fig. 2 often propagates by tearing. The separated region provides the free surface for the initiation of tearing and the material surrounding the separated region is, of course, eccentrically loaded. A fracture initiated by separation is shown in Fig. 4, as it is propagating through the material by tearing. Again, the fracture features point toward the initiation site.

Fig. 4. Tearing Fracture Initiated by Separation. Tearing fracture dimples point radially inward toward the separation region which initiated the fracture. The fractograph shows this fracture as it appears on the fracture surface.

A ductile material can fail by the shear mode of fracture at a sufficiently high stress. When such fracture occurs, the material fails along the direction of maximum shear stress, which is generally inclined about 45° to the tensile axis. The shear model illustrated in Fig. 5 shows the relative motion of the material along the plane of maximum shear stress. The surface features of a shear fracture are greatly elongated in the shearing direction and point in opposite directions on opposing fracture surfaces. Voids in the material adjacent to the fracture

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Fig. 5. Shear Fracture. The material fractures by shear at high stresses. The relative motion of the material along the plane of maximum shear stress causes the dimples to be greatly elongated on fracture surface. The fractograph shows this fracture as it appears on the fracture surface.

Fig. 6. Coalescence of Microvoids. A cross section of a dispersion strengthened material that has undergone local separation by the coalescence of microvoids formed at particles and aggregates.

of the oxide dispersion in commercial SAP alloys such as XAP-001; as suggested in the sketches, particles clustering is prevalent. Figure 6 shows a cross section of a dispersion strengthened material that has undergone local separation by the coalescence of microvoids formed at particles. These coalesced voids appear on the fracture surface as equiaxed dimples, as previously illustrated in Fig. 2.

are also elongated in this direction as is shown in Fig. 5. This model is in agreement with the observation of Beacham,⁶ and McMillan and Pelloux.⁷

A material that has suffered a significant loss of area from separation and tearing should ultimately fail by shear due to the high stress on the remaining material.

Particles dispersed in a ductile matrix are preferred sites for the initiation of the microvoids that eventually link up to form the fracture surface. Materials strengthened by internally dispersed particles should show a high density of these microvoids. The importance of the particle dispersion is demonstrated in Figs. 6 through 8. The random dispersion of particles depicted in these sketches is indicative

⁶C. D. Beacham, Electron Microscope Examination to Characterize and Identify Modes of Fracture, NRL Report 6293, U.S. Naval Research Laboratory (September 1965).

⁷C. McMillan and R.M.N. Pelloux, The Analysis of Fracture Surfaces by Electron Microscopy, Report 1-82-0169, Boeing Scientific Research Laboratories (May 1962).

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Fig. 7. Fracture Advancing by Tearing Through Voids. Increased stress in the region just ahead of the moving structure causes initiation and growth of voids at particle sites. The matching features (elongated dimples) of the two fracture surfaces are shown.

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Fig. 8. Material Fracturing by Shear. Cross section of a dispersion strengthened material shows void elongation caused by shearing action in region of fracture. Those voids actually involved in the fracture appear as elongated dimples pointing opposite directions on the two surfaces.

A dispersion strengthened material fracturing by the tearing mode is illustrated in Fig. 7. The fracture is shown tearing through the voids in the material immediately preceding the fracture. The increased stress in this region just ahead of the advancing fracture causes the initiation of new voids in addition to the growth of those that already exist. Figure 7 also illustrates the matching features on the opposing fracture surfaces. As was shown in Figs. 3 and 4, these features appear as slightly elongated dimples and point toward the fracture initiation site.

Figure 8 shows a dispersion strengthened material undergoing shear. Voids in the band of material undergoing shear deformation are shown to be elongated in contrast to the more rounded voids in the surrounding material. The voids involved in the fracture appear as elongated dimples on the fracture surface. These dimples are the features noted on the fracture surface in Fig. 5. Figure 8 shows the dimples to be pointed in opposite directions if viewed on opposing fracture surfaces.

A fracture surface of XAP-001 and other materials⁴⁻⁷ may show all three modes of ductile fracture discussed above. This is especially true of XAP-001 fractured at low stresses (e.g., high temperatures). As suggested by Fig. 4, the high-temperature fracture of XAP-001 generally initiates by separation. The material may then continue to fracture by tearing and finally fail by shear as the stress increases.

Figure 9 depicts an XAP-001 tensile or creep specimen that exhibited all three modes of fracture at a high temperature. The fracture initiated at the center of the test specimen and propagated radially by tearing. The tearing mode of fracture is shown to have extended to the left-hand surface of the sectioned specimen. The stress was then sufficiently high to shear the remaining portion of the specimen as shown on the right. Fractographs of various areas of the fracture surface are included in the figure.

A replica of an area such as the central portion of the specimen is shown in the upper left fractograph. This photograph shows the rounded dimples characteristic of the separation mode of fracture. The lower left fractograph shows evidence of tearing, and an area of separation bounded by tearing is shown in the upper right. As previously explained, the dimples point toward the initiation site. A shear surface is shown

Fig. 9. High-Temperature Fracture of XAP-001 Specimen. Fractographic analysis of a single fracture surface shows these typical fracture modes.

in the lower right. The black particles in some of the fractographs were identified as oxide flakes that adhered to the replica. These oxide particles were loosely attached to the fracture surface and were pulled off along with the plastic during replication.

In some cases the only obvious difference between separation, tearing, and shear is the degree of elongation of the dimple features on the fracture surface. In these cases the interpretation as to the mode of fracture can be influenced by such variables as shadowing angle and replica flattening.

Our observations of tensile fractures show separation and/or tearing at all test temperatures, but these modes are more prominent at higher temperatures (i.e., a greater portion of the cross section parted by this process before the high stress necessary for shear developed). Shear predominates at the lower test temperatures but occurs to some extent at all temperatures investigated. Typical fractographs resulting from the tensile tests are shown in Figs. 10 and 11.

Figure 10 shows fractographs of tensile specimens tested at temperatures of -200 to 450°C . The dimples are larger for the higher test temperatures; the dimples formed at -200°C are about $0.5\ \mu$; while those resulting from the 450°C test are about $5\ \mu$. Void growth during the high-temperature deformation could cause larger fracture dimples. Typical shear surfaces at high and low temperatures are shown in Fig. 11. Again dimple size increased with test temperature. In general, the position of the dimples corresponds to the location of oxide particles or groups of oxide particles as shown in Fig. 10.

Creep tests at 450°C also show the ductile modes of fracture even though the total measured creep elongations are less than 1%. The separation and tearing proceed very slowly with separation being predominant and is accompanied by essentially no necking of the specimen. The remaining portion of the specimen then shears at a very high strain rate giving rise to an appreciable reduction in area at the shear zone. Figure 12 illustrates this in a photograph of a specimen failed in creep. That portion of the specimen toward the bottom of the photograph (separation and tearing) shows no neck, while the upper portion (shear "lip") shows considerable necking. Examples of ductile creep fracture are shown in Fig. 13.

One characteristic of XAP-001 is its tendency toward segregation into oxide-rich and oxide-poor bands. The effect of this "banding" on the fracture is shown in Fig. 14. The lines running perpendicular to the direction of fracture in the oxide-poor zone are interpreted as Wallner's lines⁸ and result from an interference between a moving fracture and the elastic wave

⁸H. Schardin, "Velocity Effects in Fracture," Proc. Conf. Fracture, Swampscott, Mass., 1959.

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-200°C

25°C

300°C

450°C

Fig. 10. Fractographs of Short-Time Tensile Specimens Showing Ductile Separation and Tearing. Arrows point to Al₂O₃ flakes lying on the fracture surface. 4300X.

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J-500

25°C

450 °C

Fig. 11. Fractographs of Short-Time Tensile Specimens Showing Ductile Shear. 6500X.

Fig. 12. Creep Rupture of XAP-001 at 450°C Showing Local Necking at Shear Lip. No neck is evident on that portion that failed by tearing or separation.

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SHEAR

SEPARATION

Fig. 13. Fractographs of XAP-001 Creep Specimens. 6500X.

Fig. 14. Fractograph Showing the Effect of Oxide-Rich and Oxide-Poor Zones on the Fracture of XAP-001. Arrows indicate Wallner's lines in the oxide-poor zone. 6500X.

front that precedes it. This indicates a very rapidly moving fracture in this area. Another form of segregation is the stringering of the oxide in the extrusion direction. The fractograph of a tensile specimen showing unusually low ductility at 450°C, Fig. 15, shows the effect of severe stringering. Again a fast-moving fracture is indicated in those areas between the stringers.

CONCLUSIONS

This study has shown XAP-001 to exhibit ductile fracture over a range in temperature from -200 to 450°C. These ductile fractures occur in both short-time tensile tests and long-time creep tests.

High-temperature fractures initiated at single oxide particles or groups of particles by separation and then propagated by tearing and finally shear to the specimen surface. Lower temperature fractures were predominantly shear type.

Fractography showed the serious effects of oxide banding and stringering. Both tend to reduce the high-temperature ductility.

Fig. 15. Fractograph Showing the Effect of Oxide Stringing on the Fracture of XAP-001. Arrows show position of oxide stringers and Wallner's lines in oxide depleted zone. 6500X.

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