Edited by J.F. Nie, A.J. Morton and B.C. Muddle

On the Fatigue of Sintered Aluminium Alloys

G.N.Grayson[1], G.B.Schaffer[1], J.R.Griffiths[2]

[1]Division of Materials, School of Engineering, The University of Queensland, QLD 4072, Australia
[2]CSIRO Manufacturing and Infrastructure Technology, P.O. Box 883, Kenmore, QLD 4069, Australia

Keywords: Fatigue, Aluminium alloys, Powder metallurgy, Oxide films

Abstract

An understanding of the mechanisms of fatigue in sintered aluminium is required in order to improve properties. Here we examine and characterise the mechanisms of fatigue cracking in sintered aluminium. The fatigue strength of sintered Ampalloy 2712 in 3-point bending was found to be 150 MPa. Fatigue crack initiation occurred at surface or subsurface pores and pore clusters. Veins of oxide phase were observed on fatigue fracture surfaces and are believed to be pre-existing microstructural features the residue of the alumina coating on aluminium powder particles. The oxide phase is present on the fracture surfaces due to fatigue crack mechanisms.

1. Introduction

The use of sintered aluminium alloys and composites in automotive drive trains is an area of potential growth for the powder metallurgy industry [1-2]. A key property in such applications is fatigue and an understanding of the mechanisms of fatigue in these materials is required. Much research has been done on the fatigue behaviour of cast aluminium and the mechanisms and fracture mechanics of fatigue crack growth have been well documented [3-4]. However, this previous research is not particularly useful in regards to sintered materials, which have significantly different microstructures to cast or extruded material, particularly with respect to the type and distribution of intermetallic phases and the porosity.

As a first step in understanding fatigue in sintered composites, we need to examine and characterise the mechanisms by which sintered but unreinforced aluminium alloys undergo fatigue. This includes identifying the role played by porosity and the intermetallic particles which are a residue of the sintering liquid. Here we characterise the fatigue properties of unreinforced pressed-and-sintered aluminium alloys and examine aspects of fatigue crack initiation and growth.

2. Methods

The base powder was Ampalloy 2712 supplied by Ampal Inc. The composition is Al-3.8Cu-1Mg-0.7Si-0.1Sn with 1.5% Acrawax as a die-wall lubricant. Compacts were pressed at 200 MPa in a floating steel die to give rectangular bars measuring 55 x 10 x 6 mm. Sintering was carried out in a tube furnace under a controlled dry nitrogen atmosphere. The compacts were delubricated for 20 minutes at 300^{o}C and sintered at 600^{o}C for 30 minutes. The heating rate from the delubricating temperature to the sintering temperature was 20^{o}C /min. The compacts were then air cooled to room temperature. Fatigue testing was carried out on an Instron 1026 Servo-Hydraulic machine. Samples measuring 55 x 9 x 4 mm were machined from the sintered bars, polished to a 1 μm finish and tested in 3-point bending at a stress ratio, R = 0.1, and with a cyclic load frequency of 40 Hz. Tensile testing was performed using an Instron 4505 screw machine with a cross-head speed of 0.6 mm/min on machined samples with a nominal gauge length of 13.5 mm and a cross sectional area of 11.5mm^2. Fracture surfaces and microstructures were examined uncoated in a Phillips XL30 SEM, equipped with a LaB_6 filament, a back scatter detector and an Energy Dispersive Spectrometer (EDS).

3. Results and Discussion

The fatigue life properties of unreinforced Ampalloy 2712 are shown in Figure 1. The yield strength and tensile strength of the unreinforced 2712 alloy are 338 MPa and 355 MPa, respectively.

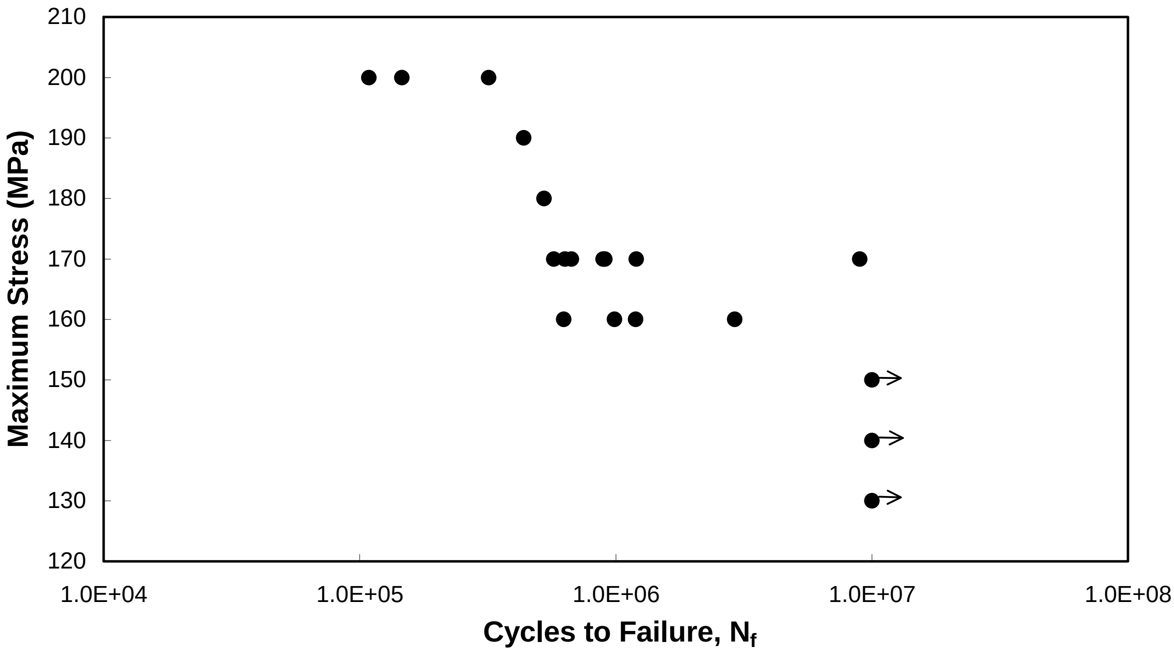


Figure 1: S-N curve for Ampalloy 2712 in 3 point bending with R = 0.1.

A typical fracture surface of the 2712 alloy is shown in Figure 2. Surrounding the initiation site, which in this case is a subsurface pore, is a region of fatigue crack propagation with the characteristic semicircular or 'thumbnail' form. Outside this region, the remainder of the sample has undergone fast failure by ductile overload. The regions are not discrete and there is no distinct line of transition from a fatigued appearance to a ductile overloading appearance. Instead, there is a gradual integration of one region into the other. The dotted line in Figure 2 is an indication as to the position of the region interface. The fatigued region of the sample has a relatively flat appearance. The area of the fracture surface outside the fatigue region defined in Figure 2 has the characteristic dimpled appearance of ductile failure by microvoid coalescence.

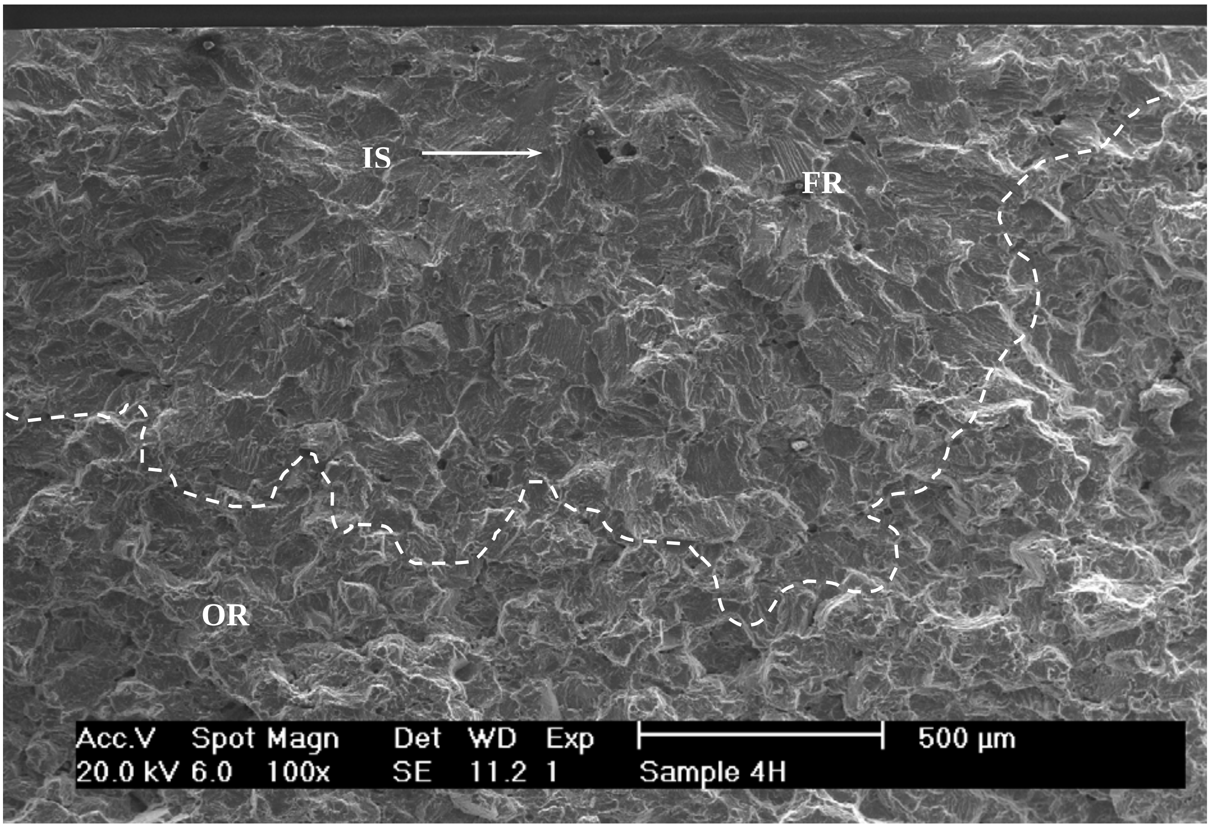
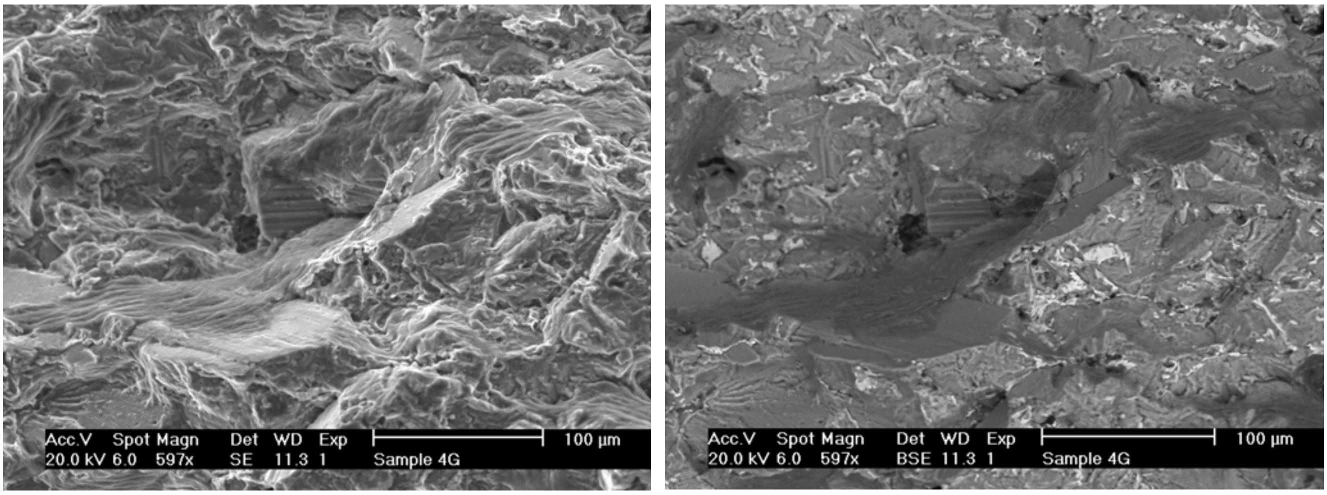


Figure 2: Typical secondary electron image of the fatigue fracture surface of a 2712 sample (R = 0.1), showing the initiation site, IS, the fatigue region, FR, and the overload failure region, OR.

Fatigue crack initiation in all the specimens examined was associated with porosity. In many cases a single, subsurface pore was found at the fatigue crack initiation site. This is in agreement with the findings of previous research on the initiation of fatigue in porous aluminium samples with polished surfaces although other authors also commonly report the importance of surface pores [5-6]. These pores act as stress concentrators, which leads to localised damage and eventually crack initiation. For samples in which fatigue crack initiation did not occur at a single subsurface pore, a cluster of relatively small pores was observed as the initiation site, at or near the surface. Initiation of fatigue cracking at pore clusters has been observed previously in research concerning the fatigue of sintered steels [9-10]. Initiation at pore clusters suggests that when small pores are close together they act as a single pore and therefore, that the mean pore spacing may be a significant factor in relation to fatigue crack initiation.

Examination of the fatigue fracture surfaces in back scattered electron mode revealed dark, vein-like markings running along the surface in the fatigued region, suggesting the presence of a different phase in these areas. A typical example is shown in Figure 3. The dark markings appear at grain boundaries and are associated with a distinctive serrated appearance. Chemical analysis of these dark markings reveal an extremely high concentration of oxygen. The magnesium concentration in these areas is also significantly higher than in the matrix.

The morphology and the composition of these ribbons suggest that they are an oxide phase, possibly spinel. Magnesium is added to the 2xxx series sintering alloys in order to solve the sintering problems associated with the passivating alumina layer on aluminum particles. During sintering, Mg reacts with the oxide layer, resulting in the formation of spinel and the elimination of sintering problem, not the oxide itself. [9-10] The oxide is merely transformed. However, this oxide has not been observed previously. The observation that spinel occurs on the fracture surfaces of all fatigue samples tested to date and not on tensile fracture surfaces or the overload region of fatigue specimens suggests that its presence on the fracture surface is a result of a fatigue mechanism. It is possible that, during cyclic loading, the brittle oxide phase located in the grain boundaries is cracked. These cracked grain boundaries may then act as a preferential crack path during propagation. If this hypothesis is correct, it would explain why the oxide rich regions appear in the form of veins on the fatigue surface.



(a) (b)

Figure 3: Typical (a) secondary and (b) backscattered SEM micrographs showing the presence of oxide veins on the fatigue fracture surface of 2712 specimens (R=0.1).

Three different regions of crack propagation can be defined on the fatigue fracture surfaces in terms of the observed oxide patterns. These are shown in Figure 4 which is the same field as shown in Figure 2 but in the backscattered mode. Region I includes the fatigue crack initiation site and early fatigue crack propagation. This region is very flat and contains much less of the oxide phase than Region II. Region II is also a fatigue crack propagation region but there is significantly more spinel phase than in RI. The difference between the oxide patterns in Regions I and II are primarily due to the crack propagation mechanisms taking place. Cracking in Region I is transgranular and as the oxide is located in the grain boundaries, very little is revealed as the crack travels through the grains. Transgranular crack propagation in this region also explains its flat appearance. The crack continues to propagate transgranularly until it intersects the surface of the specimen, at which point cracking becomes intergranular. The change of mechanism is presumably associated with the increased stress intensity factor as the crack breaks through to the free surface. The onset of intergranular cracking marks the start of Region II. In Region II the crack is traveling intergranularly, through the oxide veins in the grain boundaries, and therefore much more oxide is observed on the fracture surface. Region III is the fast failure region and, as noted above, this region does not contain any evidence of the oxide phase. This region is characterised by its dimpled, ductile failure appearance.

4. Summary

In as-sintered aluminium alloys, fatigue cracks initiate at sub-surface pores or pore clusters. Initiation at pore clusters suggests the importance of the mean pore spacing in fatigue of sintered materials. The fatigue crack initially propagates transgranularly until it intersects the free surface, at which stage it propagates in an intergranular fashion until overload occurs. Transgranular crack growth reveals the residue of the surface oxide films from the original aluminium powder particles. It has a vein-like nature and is only observed on fatigue surfaces. The pattern of the observed oxide phase on the fracture surface is directly related to the crack propagation mechanism.

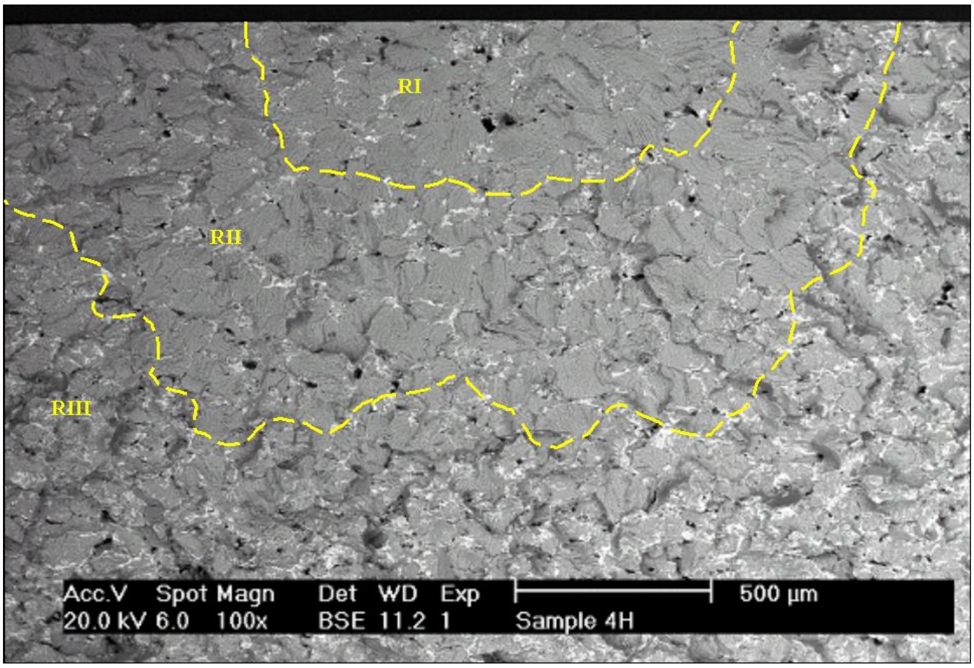


Figure 4: Backscattered SEM micrograph of a 2712 fracture surface showing the three crack propagation regions. See text for details.

Acknowledgements

This work was funded by Ampal, Inc. a member of the United States Bronze Powders Group, whose support is gratefully acknowledged.

References

[1] W.F. Jandeska and R.A. Chernenkoff, "Powder Metallurgy Aluminum and Light Alloys for Automotive Applications (proc. conf.),", Dearbon, MI, 1998.
[2] W.F. Jandeska and R.A. Chernenkoff, "Powder Metallurgy Aluminum and Light Alloys for Automotive Applications (proc. conf.),", Troy, MI, 2000.
[3] J.J. Lewandowski, "Fracture and Fatigue of Particulate MMCs," Comprehensive Composite Materials, vol. Volume 3 - Metal Matrix Composites, T. W. Clyne, Ed.: Elsevier, 2000, pp. 151-187.
[4] M.F. Horstemeyer, D.L. McDowell and Jinghong Fann, "From Atoms to Autos, Part 2: Cyclic Fatigue", Sandia Report SAND2000-8661, Sandia National Laboratories, California 94550, 2001.
[5] H. Jiang, P. Bowen, and J.F. Knott, "Fatigue Performance of a Cast Aluminium Alloy Al-7Si-Mg With Surface Defects," Journal of Materials Science, vol. 34, pp. 719-725, 1999.
[6] M.J. Couper, A.E. Neeson and J.R. Griffiths, "Casting Defects and the Fatigue Behaviour of Aluminium Castings", Fatigue and Fracture of Engineering Structures, vol. 13, pp. 213-227, 1990.
[7] K.V. Sudhakar, "Fatigue Behaviour of a High Density Powder Metallurgy Steel," International Journal of Fatigue, vol. 22, pp. 729-734, 2000.
[8] N. Chawla, T.F. Murphy, K.S. Narasimhan, M. Koopman, and K.K. Chawla, "Axial Fatigue Behaviour of Binder Treated Versus Diffusion Alloyed Powder Metallurgy Steels," Materials Science and Engineering, vol. A308, pp. 180-188, 2001.
[9] R.N. Lumley, T.B. Sercombe, and G.B. Schaffer, “Surface Oxide and the Role of Magnesium during the Sintering of Aluminum”, Metallurgical and Materials Transactions A, vol. 30A, pp. 457-463, 1999.
[10] G.B. Schaffer, T.B. Sercombe, and R.N. Lumley, “Liquid phase sintering of aluminium alloys”, Materials Chemistry and Physics, vol. 67, pp. 85-91, 2001.