JOURNAL OF MATERIALS SCIENCE 19 (1984) 2488–2492

Fabrication of fibre composites using an aluminium superplastic alloy as matrix

D. J. LLOYD
Alcan International Limited, Kingston Laboratories, PO Box 8400, Kingston, Ontario, K7L 4Z4, Canada

An aluminium superplastic alloy has been used as the matrix for a variety of fibre reinforcements. It is shown that, by hot pressing in the superplastic regime of the alloy, a number of different reinforcements can be incorporated into the matrix. Tensile tests on composites with up to 25 vol % of reinforcement showed good agreement with the rule of mixtures.

1. Introduction

Aluminium matrix composites have received considerable attention over the last decade in attempts to develop a light, high-strength structural material. Monolithic fibres, such as high-strength wires and boron, and fibre tows have been incorporated into aluminium using various fabrication routes, but final consolidation is usually achieved by hot pressing [1–3]. To achieve optimum consolidation during solid-state hot pressing, it is necessary to have an alloy with very high ductility at the hot-pressing temperature. The high ductility then enables the matrix to flow around the fibres and incorporate them into the matrix. In addition, the alloy has to be able to bond to itself under the consolidation pressure and achieve the large strains without any tendency for voiding. Aluminium alloys which should be good candidates as matrix materials for hot-pressed composites are the aluminium superplastic alloys. Several such alloys [4] have been developed in the last few years and in this paper one of them [5] has been investigated as a matrix alloy for a variety of reinforcements.

2. Experiment

The superplastic alloy Alcan-08050, which is nominally Al–5 wt% Ca–5 wt% Zn, was rolled to different foil gauges (0.0125 to 0.025 cm). The foil was degreased and then placed on a stainless-steel mandrel in a lathe and the reinforcement wound over the foil and subsequently covered by a second foil layer. This monotape could then be consolidated by hot pressing and a monolithic composite fabricated by a second hot pressing of several monotapes. Alternatively, a multi-layer lay-up could be wound directly and consolidated in a single consolidation step. Both routes gave comparable results and no distinction between single and duplex consolidation routes will be made. Hot pressing was carried out in air at 773 to 783 K for 30 min at pressures of up to 70 MPa. Composite coupons of (10 × 10 × 0.2) cm were used as blanks for machining tensile specimens with a (2.5 × 1.25 × 0.2) cm gauge length. The reinforcements used, together with their mechanical properties, are given in Table I.

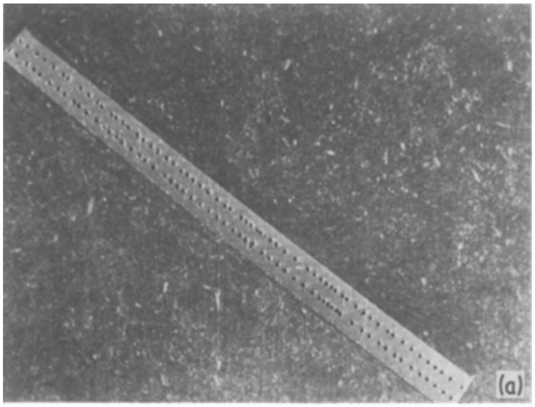
3. Results and discussion

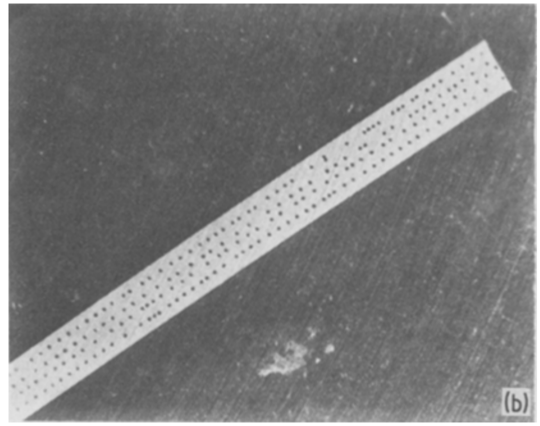
Preliminary experiments showed that good fibre alignment could be achieved only with volume fractions up to 25%, and fibre volume fractions greater than this were not investigated. Typical cross-sections through lower volume fractions of

TABLE I Mechanical properties of the reinforcement and matrix used in the composites

Reinforcement	Yield strength (MPa)	Ultimate strength (MPa)	Tensile elongation (%)
Eutectoid steel wire	1282	2458	2
Stainless steel wire	207	879	32
Chromel wire	496	938	24
Tungsten wire	1724	2599	1.0
Boron fibres	2460	–	–
Matrix	116	170	21

0022–2461/84 $03.00 + .12





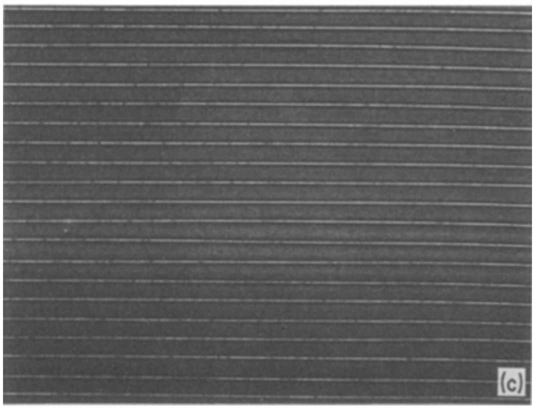


Figure 1 Sections of some typical composites: (a) two-layer composite, (b) four-layer composite, (c) fibre alignment (× 6.2).

two-layer and four-layer steel composites are shown in Fig. 1, together with a planar section after etching away the aluminium from one side. The fibre spacing and alignment is satisfactory for the present study.

If the superplastic alloy is to be viable as a matrix material it must be able to flow adequately around the fibres and also diffusion-bond to itself. To assess the extent of plastic flow during hot pressing the superplastic foil was anodized prior to fibre winding and hot pressing. During plastic flow the anodized layer breaks up and acts as a marker. Fig. 2 shows a cross-section through a steel composite after consolidation at 773 K. Clearly, extensive break-up of the anodized film has occurred, as expected, but two further points are of note. The breaks in the two anodic films correspond, so that there is nearly always anodic film in contact with anodic film. This is probably due to the stress concentration associated with a crack in one anodic layer nucleating a crack in the other layer. The second point of interest is that the spacing between cracks in the anodic layer immediately in contact with the fibres is much smaller than the spacing between cracks in the inter-fibre region. Thus the greater part of the plastic flow is occurring in the inter-fibre regions. There is, however, no evidence of voiding or lack of bonding in the consolidated composites.

Obviously, the degree of bonding will depend on the temperature of consolidation, since at low

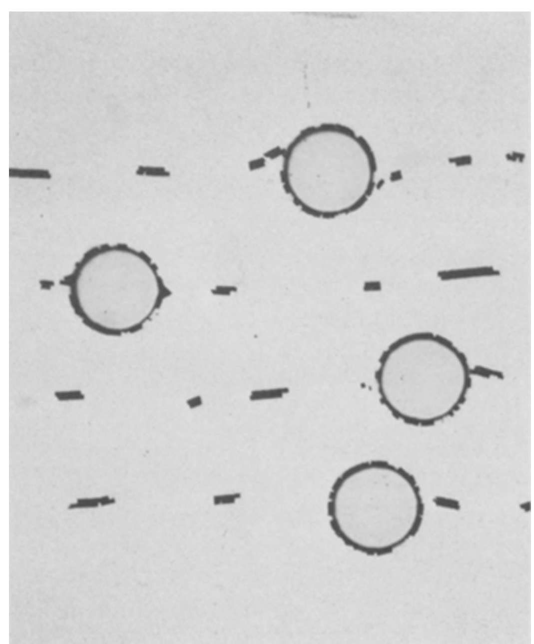


Figure 2 Section through a composite with anodized foil (× 40).

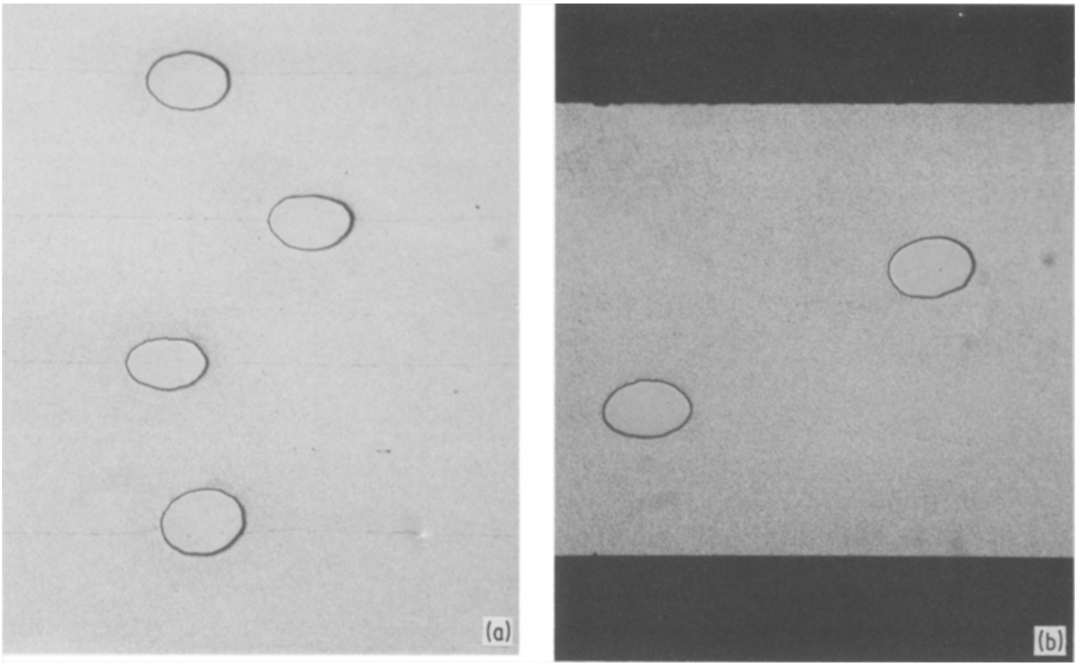


Figure 3 Sections through chromel wire-reinforced composites consolidated at (a) 740 K and (b) 773 K (×40).

temperatures the alloy will not exhibit sufficient superplasticity to incorporate the fibres and diffusion bonding will be limited. The same comments apply for the consolidation pressure. Fig. 3 shows cross-sections through chromel-wire composites consolidated at (a) 740 K and (b) 773 K under a pressure of 70 MPa. In the composite consolidated at the lower temperature the interfaces between the individual foil layers can be seen, whereas they are not apparent for the higher temperature. Poor bonding results in extensive fibre pull-out and delamination along the foil interfaces during fracture of the composite. An extreme example of this is shown in Fig. 4 for a boron-monotape composite consolidated at 725 K and 70 MPa. However, a boron monotape consolidated at 773 K and 70 MPa pressure fractures with very limited fibre pull-out and there is no evidence of delamination; Fig. 5.

In addition to adequate bonding between the matrix layers and the fibres, it is desirable to limit any interaction layer formation at the fibre–matrix interfaces [6]. Amongst the reinforcements investigated the steel reinforcement

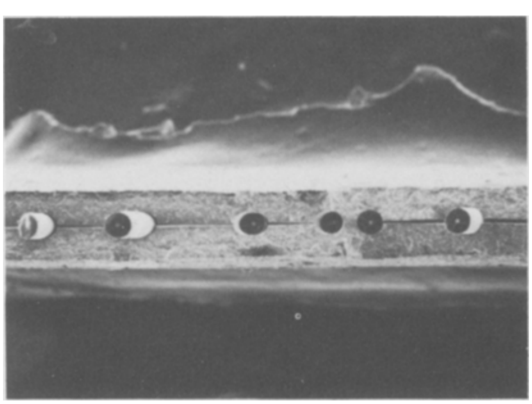


Figure 4 Poor bonding and extensive fibre pull-out in a boron-reinforced monotape consolidated at 725 K (×30.4).

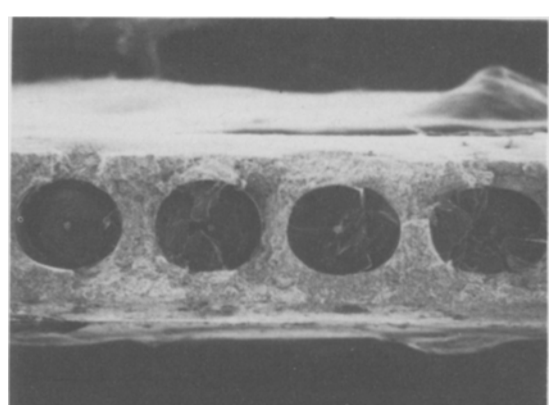


Figure 5 Good bonding in a fractured boron-reinforced monotape consolidated at 773 K (×60.8).

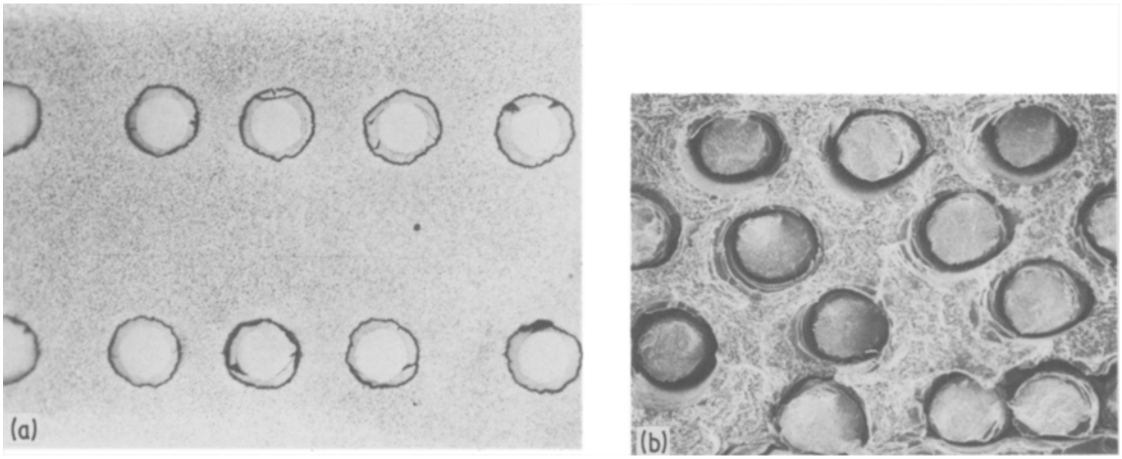


Figure 6 Section through a eutectoid-steel-reinforced composite showing (a) interfacial reaction layer, (b) fracture surface (× 68).

was the only one which formed a significant interaction layer. Fig. 6a shows the Al–Fe interaction layer formed after hot pressing at 773 K. The Al–Fe intermetallic is extremely brittle, as can be seen from the cracking associated with the intermetallic layer in the micrograph. Surprisingly, the fracture surface of the eutectoid-steel-reinforced composites did not show extreme fibre pull-out (Fig. 6b).

The tensile strengths of the composites are given in Figs. 7 and 8 together with the strength levels expected on the basis of the rule-of-mixtures (ROM) relationship

$$\sigma_C = \sigma_F V_F + \sigma_{UTS}(1 - V_F) \quad (1)$$

where σ_C is the strength of the composite, σ_F is the strength of the reinforcement, σ_{UTS} the ultimate strength of the matrix and V_F the volume fraction of the reinforcement.

This equation assumes that the matrix undergoes sufficient strain to work-harden it to the ultimate strength. With ductile reinforcement, such as chromel and low-strength stainless steel, this is a reasonable assumption, but may overestimate the strength for brittler fibres. This is probably the reason for the eutectoid-steel and boron-fibre composite strengths falling below the ROM line at low-volume fractions of reinforcement in Figs. 7 and 8. However, the results show that the composite strengths increase linearly with the volume fraction of reinforcement, as expected from the rule of mixtures.

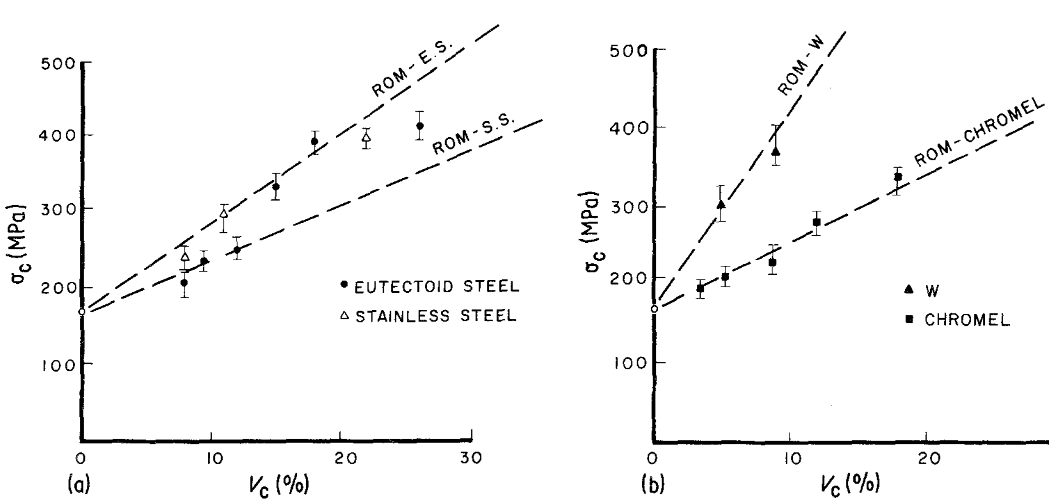


Figure 7 The variation in tensile properties with volume fraction of reinforcement, and the expected rule-of-mixture (ROM) behaviour.

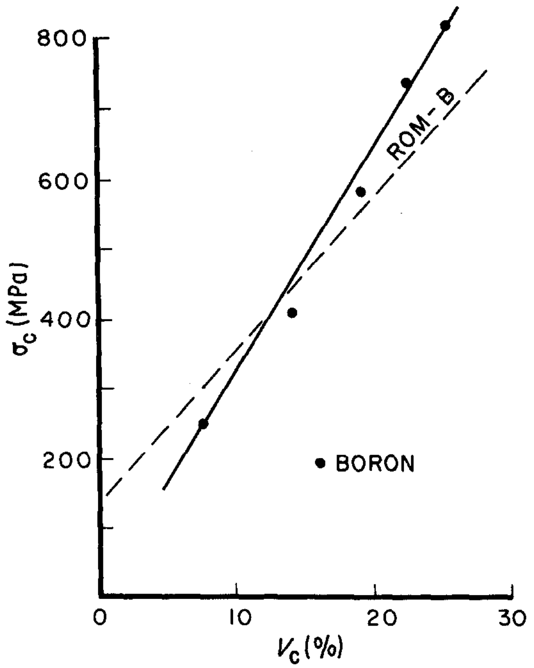


Figure 8 The variation in the tensile properties with volume fraction of boron fibres and the rule-of-mixture (ROM) behaviour.

4. Summary

The experiments have shown that the superplastic Alcan-08050 can be used for consolidating a wide range of fibre composites, for fibre contents of up to 25 vol%. No attempt has been made to optimize a fabrication schedule and it is encouraging that high-strength composites were achieved without resorting to vacuum or inert-atmosphere hot pressing. This alloy has quite a large window of superplasticity, in terms of strain rate and temperature [4, 5], so that other hot pressing conditions may enable the time for consolidation to be reduced. In practice the reinforcement content should be 40 vol% or greater to achieve as high a strength as possible. The highest strength achieved in the present study was 840 MPa with boron fibres. While this is significantly higher than the 550 MPa typically achieved with the highest-strength commercial aluminium alloys, it is obviously desirable to maximize the fibre content and hence the strength of the composite. The present alloy should allow a high volume-fraction of reinforcement to be achieved since it is superplastic and has a high resistance to cavitation.

Acknowledgements

The author is grateful to Alcan International Limited for permission to publish this work and to D. R. Lewis and C. M. Gabryel for technical assistance.

References

1. K. M. PREWO, ICCM-1, Proceedings of the 1975 International Conference on Composite Materials, Vol. 2, edited by E. Scala, E. Anderson, I. Toth and B. R. Noton (The Metallurgical Society of AIME, New York, 1976) p. 816.
2. W. H. PFIEFER and M. A. KINNER, ICCM-2, Proceedings of the 1978 International Conference on Composite Materials, edited by B. Noton, R. Signorelli, K. Street and L. Phillips (The Metallurgical Society of AIME, New York, 1978) p. 153.
3. A. P. DIVECHA, C. R. CROWE and S. G. FISHMAN, *ibid.*, p. 209.
4. D. J. LLOYD and D. M. MOORE, "Superplastic Forming of Structural Alloys", edited by N. E. Paton and C. H. Hamilton (The Metallurgical Society of AIME, New York, 1982) p. 147.
5. D. M. MOORE and L. R. MORRIS, *Mater. Sci. Eng.* 43 (1980) 85.
6. S. OCHIAI and Y. MURAKAMI, *J. Mater. Sci.* **14** (1979) 831.

Received 27 September and accepted 4 October 1983