nitrogen partial pressure of ~ 1 atm, or 3×10^{-3} atm if a closed system is assumed. For a specific β'-sialon composition containing a glass phase, it is clear that there must be one optimum gaseous atmosphere, as defined by the silicon monoxide, nitrogen, aluminium vapour and silicon vapour partial pressures, if maximum densification is to be attained. For compositions containing initially an excess of aluminium nitride, and therefore no glass phase, densification is unlikely unless compositional changes occur, leading to the formation of grain-boundary glass.

Acknowledgement

The financial support of the Science Research Council in the form of a Research Grant, and a Research Studentship to M. Benn, is acknowledged.

References

1. K. H. JACK, *Trans. Brit. Ceram. Soc.* **72** (1973) 376.
2. *Idem, J. Mater. Sci.* **11** (1976) 1135.
3. M. H. LEWIS, B. D. POWELL, P. DREW, R. J. LUMBY, B. NORTH and A. J. TAYLOR, *ibid* **12** (1977) 61.
4. I. K. NAIK, L. J. GAUCKLER and T. Y. TIEN, *J. Amer. Ceram. Soc.* **61** (1978) 332.
5. M. BENN, M. KUWABARA and F. L. RILEY, "Science of Ceramics', Vol. 9, edited by K. J. de Vries (Ned. Keramische Vereniging, Stoke-on-Trent, 1977) p. 119.
6. *Idem,* Proceedings of the International Symposium "Factors in Densification and Sintering of Oxide and Non-Oxide Ceramics", Hakone, 3–6 October 1978, edited by S. Saito (in press).
7. L. J. BOWEN, R. J. WESTON, T. G. CARRUTHERS and R. J. BROOK, *J. Mater. Sci.* **13** (1978) 341.
8. C. GRESKOVICH and J. H. ROSOLOWSKI, *J. Amer. Ceram. Soc.* **59** (1976) 336.
9. D. R. MESSIER and G. E. GAZZA, *ibid* **58** (1975) 538.
10. J. P. TORRE and A. MOCELLIN, in "Nitrogen Ceramics", edited by F. L. Riley, NATO Advanced Study Institute Applied Science Series No. 23 (Noordhoff, Leyden, 1977) p. 63.

Received 5 July
and accepted 27 July 1979

M. BENN
F. L. RILEY
Department of Ceramics,
University of Leeds,
Leeds, UK

Composite metallic glass wires

It is well documented that metallic glasses show an excellent high strength accompanying high ductility (capable of 180° bending without fracture) [1]. Focusing on such superior mechanical properties of metallic glasses, a reinforcement application has been of potential interest in practical use. For this purpose, the present study was conducted on a composite metallic glass wire (i.e. a conventional metal wire covered by a metallic glass) and its mechanical properties and fracture behaviour are reported.

$Fe_{78}Mo_2B_{20}$ metallic glass filaments were made by rapidly quenching from the molten alloy. The glassy nature of the resultant ribbon filaments, 48 μm thick and 1.05 mm wide, was carefully examined using X-ray methods. In order to make a composite metallic glass wire, an as-quenched metallic glass ribbon was first drawn through diamond dies with reducing die diameters until it became virtually tube shaped. The detailed sequential observations of the cross-sectional change by drawing have been reported [2]. Then, a tip of a conventional metal wire, i.e. a wire reinforced by metallic glasses, was stuck into the groove of the metallic glass tube thus made. Subsequently, both the metal and metallic glass were simultaneously drawn through dies in multiple passes until the metallic glass material completely wrapped the conventional wire. A typical resultant composite wire thus made is shown in Fig. 1. The figure shows the optical micrograph of the cross-section of a copper composite metallic glass wire (inside and outside materials are copper and metallic glass, respectively). The surface of the cross-section as shown is mechanically polished. In a similar manner, an aluminium composite metallic glass wire was also made.

In order to evaluate their mechanical properties, the composite wires thus obtained were pulled to failure using an Instron tensile machine with a strain rate $\dot{\epsilon} = 4 \times 10^{-4}\,\text{sec}^{-1}$ at room temperature. In comparison to the stress–strain curves of a virgin as-quenched $Fe_{78}Mo_2B_{20}$ metallic glass ribbon, those of the composite

0022–2461/80/020532–3$02.30/0

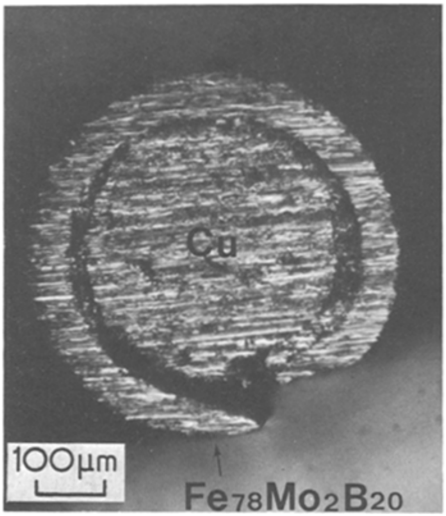

Figure 1 Optical micrograph of the cross-sectional area of a copper–$Fe_{78}Mo_2B_{20}$ composite metallic glass wire.

wires show a large deviation from elastic behaviour at a relatively low stress level before fracture, so that the composite wires tend to yield parabolically with incremental strain. This is also the case for all aluminium composite metallic glass wires. However, it is of interest to note that while the Al composite wires were fractured only at the metallic glass part at a fracture load, most of the copper composite specimens exhibit a large load drop corresponding to the failure of the inner copper wire just before entire fracture. Such a difference in the tensile deformations between Al and Cu composite wires may be interpreted in the light of the difference in elastic constants between the constituent materials. In fact, it should be noticed that comparing the value of Young's modulus of $Fe_{78}Mo_2B_{20}$ metallic glass ribbon ($\sim 17 \times 10^3\,kg\,mm^{-2}$) [3] with those of Al ($7 \times 10^3\,kg\,mm^{-2}$) and Cu wires ($12 \sim 13 \times 10^3\,kg\,mm^{-2}$) [4], the difference between the elastic constants for the Al composite wires is much larger than that for the Cu composite wire. Thus, during tensile tests of the Al composite wires, any load applied seems to be supported mostly by the constituent metallic glass. As a result, only the metallic glass part tends to be broken at the moment of a fracture load. On the other hand, in the case of the Cu composite wires, an applied load seems to be fractionally sustained by both parts of the constituent copper and metallic glass due to the relatively small difference in their elastic constant values. Hence it can be expected that the inner Cu wire would be fractured if the fractional stress is high enough to reach the value of its own inherent fracture stress.

The tensile strengths of Al and Cu composite wires are listed in Table I: their values were calculated as L_F/S_O, where L_F and S_O are fracture load and original total cross-sectional area, respectively. For comparison, tensile data of Al and Cu metal wires and $Fe_{78}Mo_2B_{20}$ metallic glass ribbon, used here, are also given in Table I. All values listed are those averaged for ten specimens (including the standard deviations). From Table I, it appears that the Cu or Al metal wires are remarkably reinforced by $Fe_{78}Mo_2B_{20}$ metallic glasses in the form of the composite wire as shown in Fig. 1.

Fig. 2 shows a typical fracture profile of the Cu composite metallic glass wire. (a) and (b) exhibit opposing fracture segments with and without a copper wire, respectively. It is of interest to note that the macroscopic fracture of the metallic glass tube takes place perpendicular to the tube axis, but the fracture plane consists of a conical surface that rose at a certain angle to a tensile axis. It should be noted in (b) that vein and featureless patterns, corresponding to shear and tensile, and shear displacements, respectively [5], appear mostly on the inner and outer edges of the fractured surface. Such fracture morphology is, of course, opposite on the matching fracture surface as shown in (a).

Let us estimate a stress value loaded on the constituent $Fe_{78}Mo_2B_{20}$ metallic glass at the moment of fracture. From the right-hand photo of Fig. 2, the area of the fracture surface was measured to be 3.62×10^{-5} in.^{2}, with the corresponding fracture load of 16.2 lb. If all fracture loads were supported by a constituent metallic glass, the fracture stress is calculated to be 315 kg

TABLE I Tensile strength averaged over ten specimens

Sample	Tensile strength ($kg\,mm^{-2}$)
Cu wire	40 ± 1
Cu + $Fe_{78}Mo_2B_{20}$ wire	109 ± 4
Al wire	11 ± 0.7
Al + $Fe_{78}Mo_2B_{20}$ wire	99 ± 5
$Fe_{78}Mo_2B_{20}$ ribbon	311 ± 6

Strain rate $\dot{\epsilon} = 4 \times 10^{-4}\,sec^{-1}$ at room temperature.

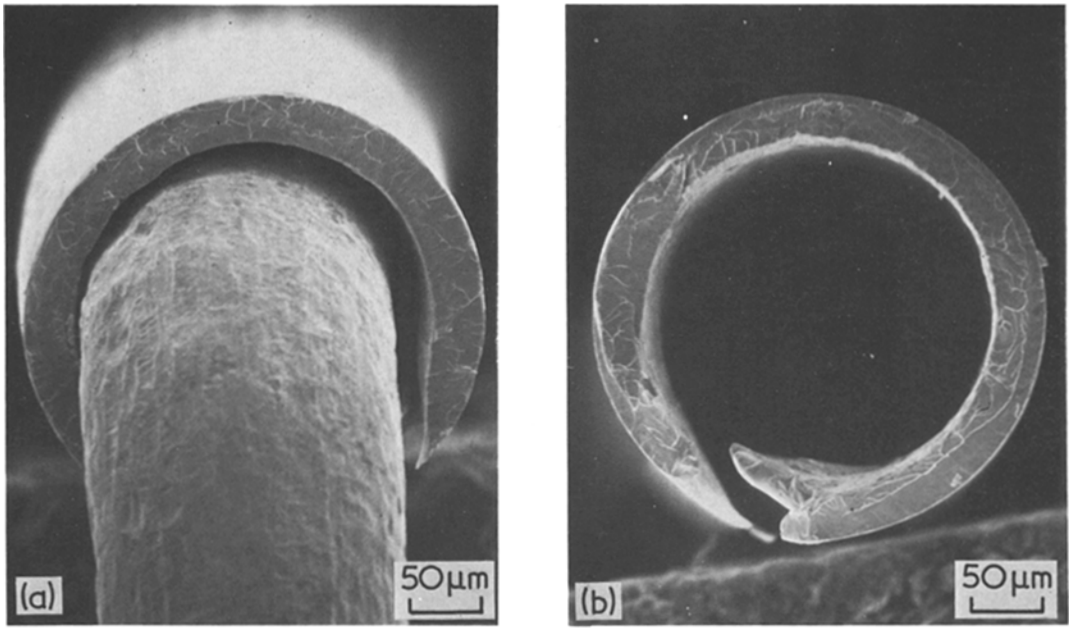

Figure 2 Scanning electron micrographs of the fracture profile of a copper–$Fe_{78}Mo_2B_{20}$ composite metallic glass wire: (a) fractography showing copper wire (inside) and $Fe_{78}Mo_2B_{20}$ metallic glass (outside) (b) fractography without copper wire.

mm^{-2}. This value is surprisingly close to that of the virgin as-quenched $Fe_{48}Mo_2B_{20}$ metallic glass ribbons (see Table I). Therefore, this calculation also supports the previous discussion in which the load applied to the composite wire is supported only by the constituent metallic glass at the moment of fracture.

Acknowledgement

This work was performed at the Materials Research Center, Allied Chemical Corporation, Morristown, New Jersey 07960, USA.

References

1. J. J. GILMAN, *Physics Today* **28** (1975) 46.
2. S. TAKAYAMA, *J. Mater. Sci.* **15** (1980) (in press).
3. *Idem,* private communication (1973).
4. S. P. TIMOSHENKO and D. H. YOUNG, "Elements of Strength of Materials" (Van Nostrand and Marazen, Tokyo, 1968) p. 342.
5. S. TAKAYAMA and R. MADDIN, *Phil. Mag.* **23** (1975) 457.

Received 11 July
and accepted 27 July 1979

S. TAKAYAMA*
R. G. FEHRMAN†
Department of Materials Science and Engineering,
University of Pennsylvania,
Philadelphia,
Pennsylvania 19104,
USA

---

* Present address: Central Research Laboratory, Hitachi Ltd, Kokubunji, Tokyo, Japan.
† Present address: Materials Research Center, Allied Chemical Corporation, Morristown, New Jersey 07960, USA.