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The preparation, properties and applications of some glass-coated metal filaments prepared by the Taylor-wire process

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The Taylor-wire method offers a versatile and intrinsically inexpensive route for the manufacture of glass-coated metal filaments a few micrometres in diameter in a single operation directly from the melt. The preparation by this process of a number of microcrystalline and amorphous microwires is reported. Materials investigated have included copper, four different Ni–Si–B alloys and a Co–Mo alloy. The resultant properties of the microwire products prepared from these materials are summarized. One potential application for microwire is in the area of composite materials and data are presented outlining the preparation directly from microwire of metal filament-reinforced glass-matrix composites. In conclusion, a number of alternative potential applications for microwire are briefly discussed.

1. Introduction

A process for the production of fine metal wire directly from the melt was first reported by Taylor [1] in 1924. In Taylor's inherently simple technique, subsequently known as the Taylor-wire or microwire process, the metal to be drawn is contained in a glass tube which is closed at one end. The metal is then melted and the end of the glass tube softened and drawn down to produce a fine glass-encapsulated metal filament. Since the early work by Taylor [1, 2], many different metals and alloys have been produced in microwire form using this basic method, with core diameters ranging from less than 1 μm to almost 100 μm (see [3]). One of the major attractions of the Taylor-wire process is that it enables metals and alloys to be produced in the form of microwire in a single operation directly from the melt and, therefore, unlike conventional die-drawing methods for producing fine filament, it offers an intrinsically inexpensive route for microwire manufacture.

Many microcrystalline metals and alloys have now been prepared by the Taylor-wire process, including elemental copper, silver, gold, iron, nickel, cobalt, palladium and antimony, together with alloys based on these metals and including stainless steel [3]. In addition, depending on the process parameters employed and the diameter of microwire obtained, very high cooling rates can be achieved using the Taylor-wire route, with estimates ranging from $4 \times 10^3\ \mathrm{K\,s^{-1}}$ for a core diameter of ≈100 μm, to 10^7–$10^8\ \mathrm{K\,s^{-1}}$ for a 1–2 μm diameter core [4–8]. These cooling rates are high enough in principle to enable the vitrification of a range of metallic alloys, and the process has indeed been employed successfully to produce microwire with an amorphous metal core, as first reported by Weisner and Schneider in 1974 for Fe–P-based alloys [9]. Further reports confirming the successful production of amorphous alloy microwires have been published by Goto for a range of iron- and nickel-based materials [10–12], by Miroshnichenko *et al.* [8] and Bashev [13] for a limited number of amorphous iron-based alloys, and by the present authors [14, 15] for nickel-based alloys.

The Taylor-wire route has therefore been demonstrated to offer an ideal method for preparing both microcrystalline and amorphous metal alloys in microwire form with diameters in the range ≈1–100 μm. Although the Taylor-wire produced materials are not generally available commercially at the present time, their unique properties coupled with their low intrinsic cost make them attractive materials for the future. Production of microwire directly from the melt in this size range is not feasible by any other current route, with the exception of the melt-spinning into-rotating-water method, first described by Ohnaka et al. [16], which has been used to produce wires with diameters down to around 80 μm (but these are not glass-coated). The cooling rate for this latter process has been estimated [17] to be of the order of $10^5\ \mathrm{K\,s^{-1}}$ for wire of diameter ≈100 μm and a limited number of amorphous alloys based on iron [16], cobalt [16], palladium [17] and Cu–Zr [18] have been successfully prepared using this method, as reviewed by Ohnaka [19]. Some of these amorphous wires are available commercially [20] in diameters down to 20 μm, having been drawn through dies from an as-quenched diameter of ≈130 μm. Other techniques for manufacture of related products have been reviewed recently [21].

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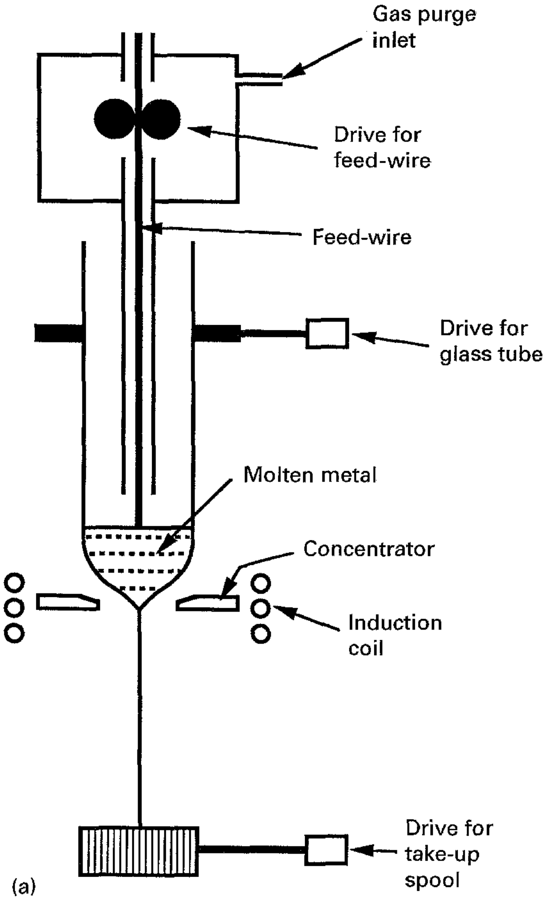
There are many potential application areas for microwire, including their use in electrical and electronics applications, e.g. connecting wires for printed circuit boards, miniature electrical components, etc. (copper, silver or gold). In addition, microwire offers potential for use as a reinforcing phase in polymer or ceramic composites. The fact that microwire is prepared with a thin glass coating also offers the possibility of manufacturing metal filament-reinforced glass-matrix composites directly by the hot pressing of suitable microwire tows [15, 22–24].

In the present contribution we outline and discuss the preparation and properties of a number of microcrystalline copper microwires, together with some Ni–Si–B-based microcrystalline and amorphous alloys and a Co–Mo alloy, all produced by the Taylor-wire route. The Ni–Si–B system was chosen for detailed study due to its well-established glass-forming characteristics, as reported by Donald and Davies [25] for chill-block melt-spun material. We also consider some applications for microwire materials, including their use as composite materials, and we outline the preparation and properties of some model composite systems.

2. Experimental procedure

2.1. Production of microwire

Microwires were prepared from precursor materials using the apparatus shown in Fig. 1, employing Corning 7740 borosilicate Pyrex glass as the drawing medium. In the present system, the microwire was collected on to a suitable take-up spool contained on a cassette of interchangeable spools. Spools of microwire are shown in Fig. 2. Although the Taylor-wire process is an inherently simple technique, there are a number of interrelated variables over which careful control is required. Using standard material parameters (i.e. a given glass tube diameter and wall thickness), the main variables are the drawing temperature and the drawing speed. In the present method, melt temperature was controlled by varying the position of the melt within the r.f. concentrator, whilst the filament diameter was controlled by varying the drawing speed, higher rates producing finer filaments. Another factor in achieving a consistent product is the ability to maintain a constant melt size. In the present technique this was achieved by the continuous addition of more metal using a metal feedstock wire which was fed into the melt at a pre-determined rate. As metal and glass were used up, the glass tube was also continuously lowered using a motor drive in order to maintain the same relative position of the melt within the r.f. concentrator. Temperature measurement was carried out employing a two wavelength optical pyrometer via a back surface mirror sited under the melt. It was generally possible to produce consistently uniform long lengths of microwire (up to 2.5 km per spool) by monitoring the process parameters (temperature, drawing speed and filament diameter) automatically, and adjusting them as appropriate by the use of a microprocessor-controlled drawing system.



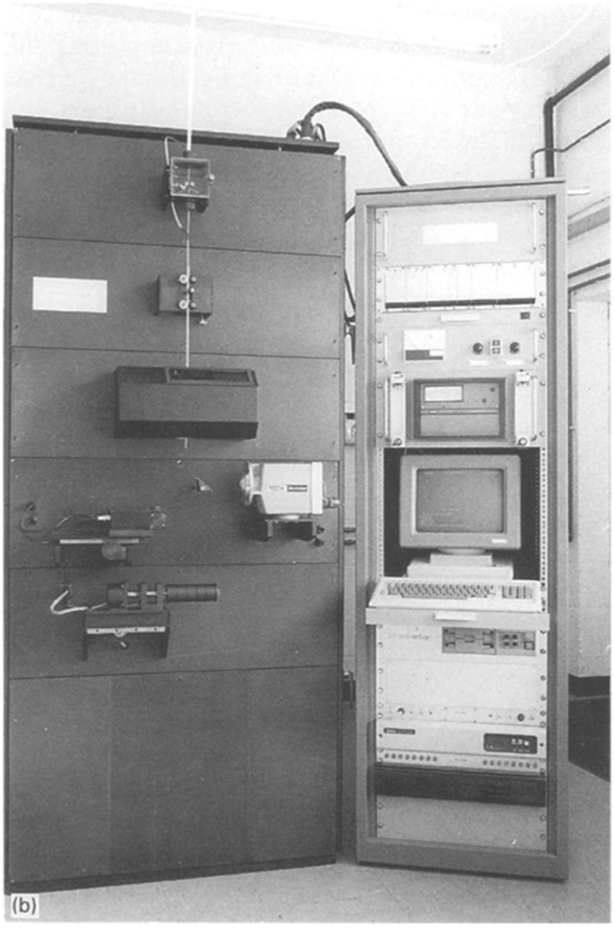


Figure 1 The Taylor-wire process for the preparation of microwire: (a) schematic representation; (b) photograph of a production machine.

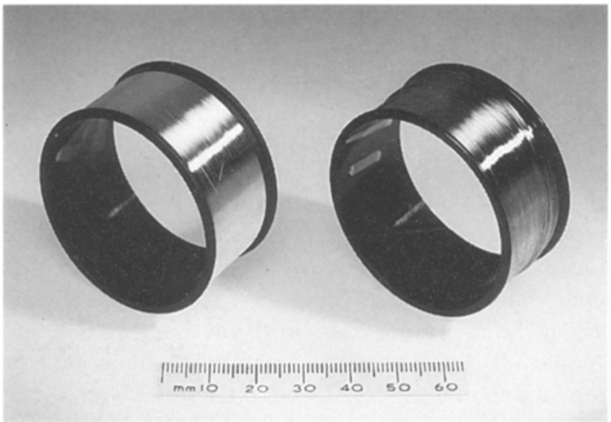


Figure 2 Photograph of representative spools of copper and Ni–Si–B alloy microwire.

In the manufacture of copper microwire metal pellets machined from high-purity copper were employed, together with 500 µm diameter high-purity copper wire. At the start of each run a single pellet weighing ≈0.7 g was placed in the glass tube, which had previously been sealed at the bottom by fusing the glass in a gas flame. For the nickel-based alloys, bulk alloy ingots were prepared by melting the elemental materials in a boron nitride crucible under argon; from the resulting ingots small pieces weighing around 1 g were subsequently used as starting material. Melt-spun alloy tape of the same nominal composition was employed as the feed wire in this instance (supplied by Sheffield University). Similarly, for the preparation of the CoMo microwire, small pieces of alloy were used as starting material. Melt-spun alloy tape could not, however, be used as a feed wire in this instance due to the extreme brittleness of the Co–Mo tape. Attempts were also made to produce microwire from CuZr alloy and from elemental nickel and cobalt. In the present process, a melting temperature of 1130–1430 °C was employed, together with a nominal drawing rate in the range 0.83–2.90 m s^{-1}.

2.2. Determination of phases present

As-drawn samples were examined by X-ray diffraction, employing a Philips PW 1710 diffractometer using CuK$_\alpha$ radiation from $2\theta = 30°$–$100°$.

2.3. Measurement of mechanical properties

The mechanical properties of the microwire were determined in tension using single fibres in accordance to ASTM D3379-75 with a 50 mm gauge length. The glass cladding was not removed prior to testing, and therefore the results obtained are those for the composite fibres. A minimum of 10 fibres was tested for each material.

2.4. Microstructures

Fractured microwire samples were examined by scanning electron microscopy (SEM) employing a Cambridge S360 SEM. The samples were coated with Au–Pd alloy prior to examination.

2.5. Preparation and characterization of composites

Unidirectionally aligned Pyrex matrix composites were prepared directly by the hot pressing of copper and Ni–Si–B alloy microwire tows obtained by cutting and removing microwire from a number of take-up spools. The tows were laid up in a graphite mould and hot pressed under a nitrogen atmosphere at 930° C for 5 min at a pressure of 1 MPa. Composite plates measuring 50 mm × 50 mm × 1 mm thick were produced by this method. These plates were subsequently cut into samples 5 mm wide for mechanical testing in three-point bend, employing a span of 40 mm and a crosshead speed of 0.5 mm min^{-1}. Flexural strength and work of fracture were calculated from a knowledge of the specimen dimensions, the maximum load and the crosshead displacement. Fracture surfaces were examined using SEM. Polished samples were also prepared for optical examination of microstructures.

3. Results

The properties of the microwires produced in the current work are summarized in Table I. Long continuous lengths (>1 km) of copper microwire could be produced consistently in the range of sizes given in Table I. Smaller and larger filament diameters could

TABLE I Details of microwires produced

Core	T_{liq} (°C)	Filament diameter (µm)	Core diameter (µm)	Phases present	UTS (MPa)	Young's modulus (GPa)
Cu	1069	16.8	7.8	fcc Cu	1096	47.2
Cu	1069	27.7	13.0	fcc Cu	611	44.5
Cu	1069	41.4	12.0	fcc Cu	579	45.7
$Ni_{78}Si_{10}B_{12}$	1034	13.1	9.0	Unidentified	1017	94.7
$Ni_{78}Si_{10}B_{12}$	1034	22.4	9.4	fcc Ni + Ni_3B	418	57.4
$Ni_{75}Si_8B_{17}$	1093	13.0	6.0	Amorphous	938	80.7
$Ni_{75}Si_8B_{17}$	1093	18.7	16.2	Amorphous	1393	74.8
$Ni_{70}Si_{10}B_{20}$	1022	16.1	9.1	fcc Ni	626	72.6
$Ni_{42}Fe_{28}Si_{10}B_{20}$	–	15.5	10.7	Amorphous	643	95.9
$Co_{73}Mo_{27}$	1340	14.0	3.6	Amorphous + Co_3Mo	1143	–

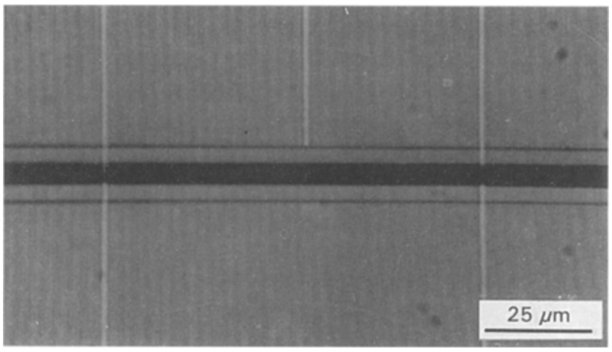
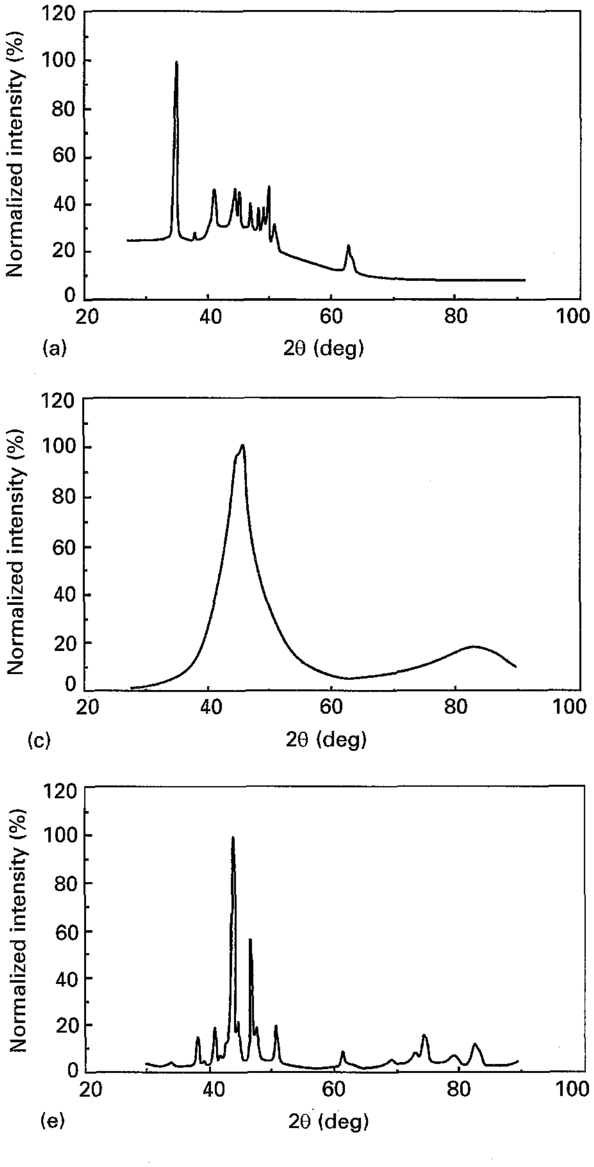


Figure 3 Optical micrograph of a representative copper microwire.

also be produced ranging from ≈13–75 μm, but only in shorter lengths. An optical micrograph of a representative copper microwire is shown in Fig. 3. Similarly, long lengths of microwire could also be produced consistently using the nickel-based alloys. Only short lengths of Co–Mo alloy were obtained, however, due in part to the unavailability of suitable feedstock material. It was not found possible to produce $Cu_{60}Zr_{40}$ alloy microwire (subscripts refer to atomic percent) due to chemical reaction between the alloy and the glass tube; and neither elemental nickel nor cobalt could be drawn successfully using Pyrex, due to the low viscosity of the glass at the temperature required to melt these metals.

Microwires that were produced were found to be either microcrystalline or amorphous, depending on the alloy composition and process parameters employed. X-ray diffractometer traces for a number of the materials are shown in Fig. 4. The copper was microcrystalline, consisting of fcc crystals aligned along the microwire axis. Both the $Ni_{78}Si_{10}B_{12}$ and $Ni_{70}Si_{10}B_{20}$ alloys were also microcrystalline, consisting of fcc nickel, Ni_3B and unidentified phases in various proportions. On the other hand, both the $Ni_{75}Si_8B_{17}$ and $Ni_{42}Fe_{28}Si_{10}B_{20}$ alloys were fully amorphous (within the resolution of the X-ray diffractometer). The $Co_{73}Mo_{27}$ alloy was found to be partially amorphous, consisting of an amorphous phase together with crystalline Co_3Mo. Fracture surfaces of microwires tested in tension are shown in Fig. 5. It was noted that some of the amorphous alloys occasionally exhibited partially hollow cores at their points of fracture (Fig. 5g and h). This effect was most probably caused by the presence of gas bubbles in the core during drawing.

Glass matrix composites were successfully prepared from both the copper and $Ni_{75}Si_8B_{17}$ microwires to yield volume fractions of metal filament of 0.15 and 0.20, respectively. Micrographs of the copper microwire composite are shown in Fig. 6. Typical load–displacement curves for the composites tested in three-point bending are given in Fig. 7. The composite



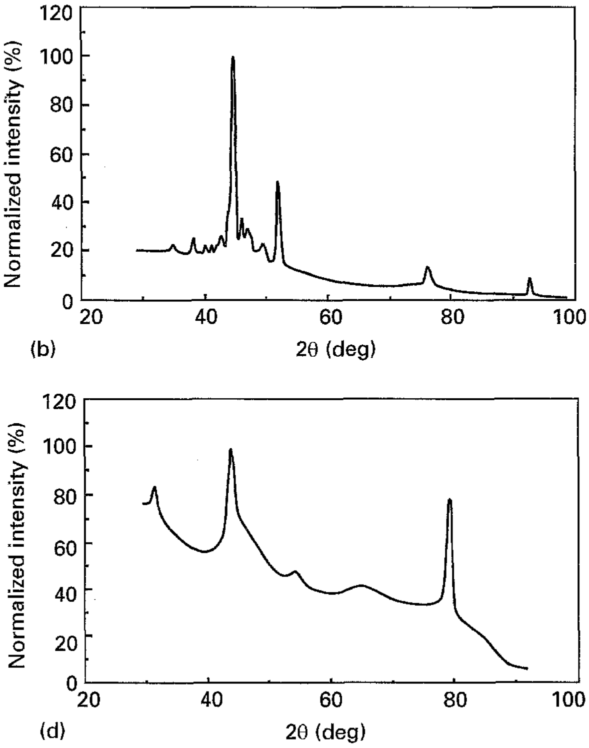


Figure 4 X-ray diffractometer traces for a number of Taylor-wire products: (a) microcrystalline $Ni_{78}Si_{10}B_{12}$ alloy; (b) microcrystalline $Ni_{70}Si_{10}B_{20}$ alloy; (c) amorphous $Ni_{75}Si_8B_{17}$ alloy; (d) partially amorphous $Co_{73}Mo_{27}$ microwire; (e) microcrystalline $Co_{73}Mo_{27}$ alloy melt-spun tape.

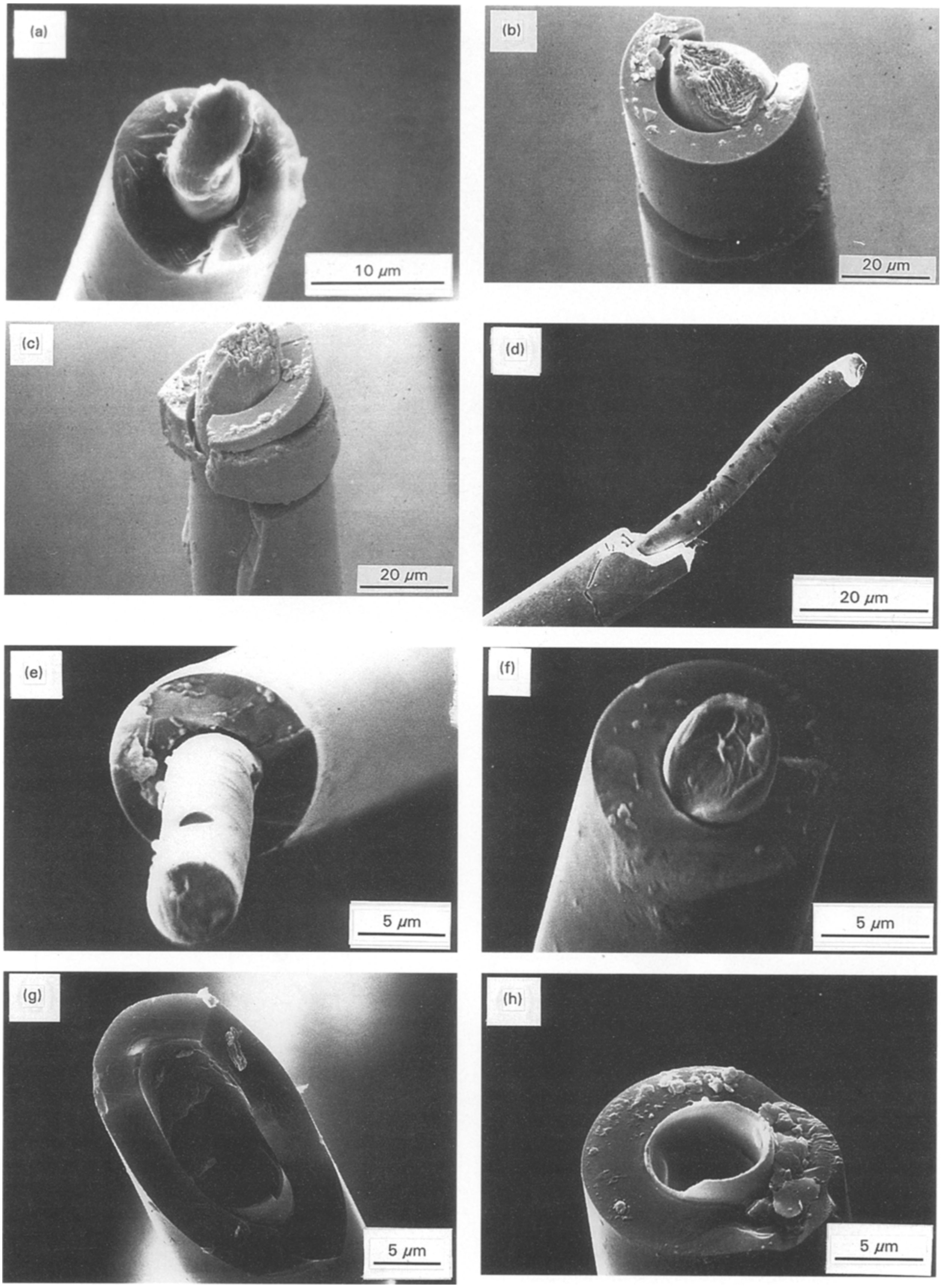
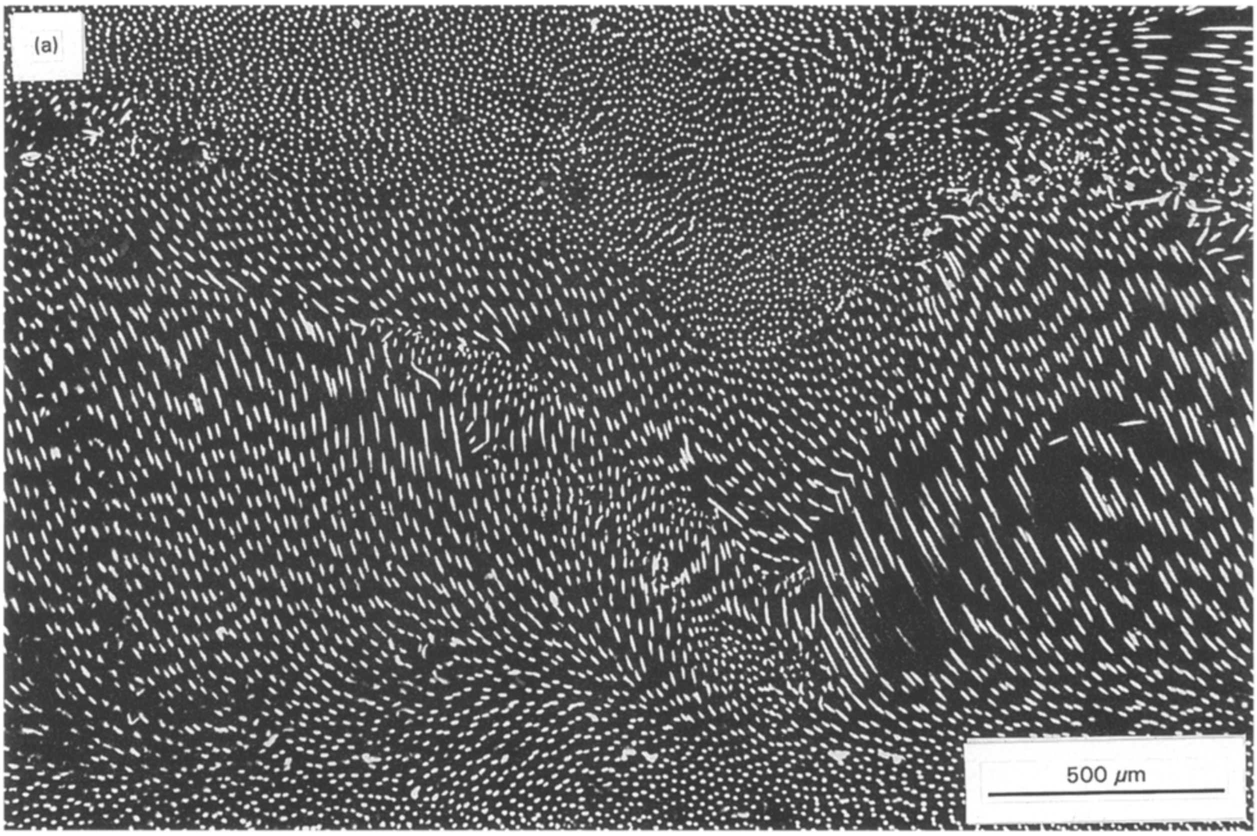


Figure 5 Fracture surfaces of microwires tested in tension: (a) small-core copper microwire; (b, c) large-core copper microwire; (d–f) amorphous $Ni_{75}Si_8B_{17}$ alloy microwire; (g, h) amorphous $Ni_{75}Si_8B_{17}$ alloy microwire exhibiting hollow core region.

prepared from the $Ni_{75}Si_8B_{17}$ microwire was the strongest, exhibiting a mean flexural strength of 255 MPa with a work of fracture of 1.8 kJ m^{-2}. The corresponding values for the composite prepared from the copper microwire were 111 MPa and 0.7 kJ m^{-2}, respectively. Micrographs showing the fracture surfaces of the copper microwire composite are shown in Fig. 8.



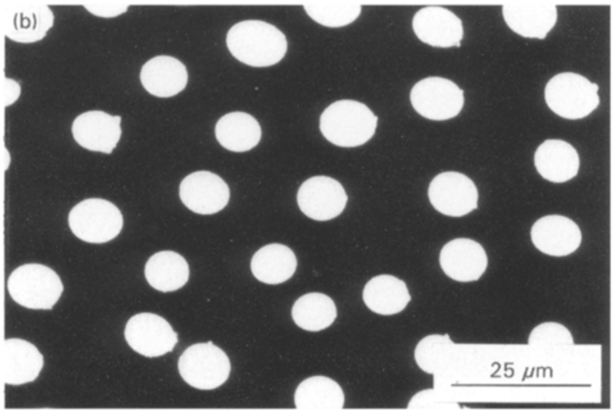


Figure 6 Optical micrographs of a copper microwire composite: (a) low magnification showing areas in which alignment of microwire is not uniform; (b) higher magnification of selected area.

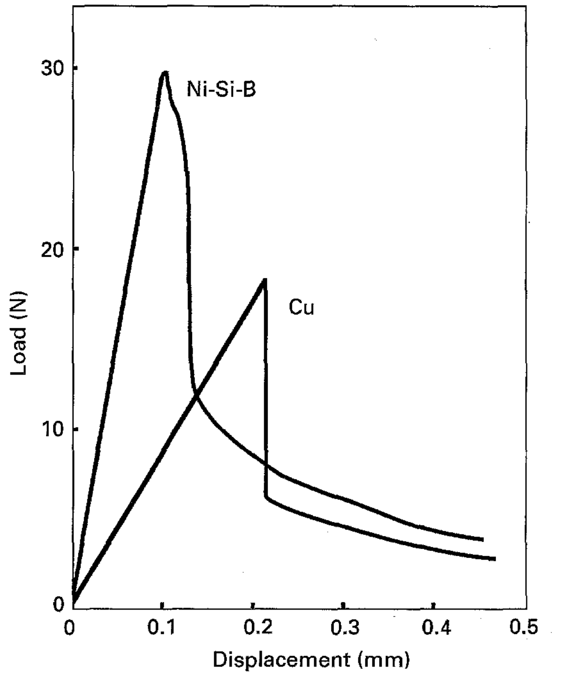
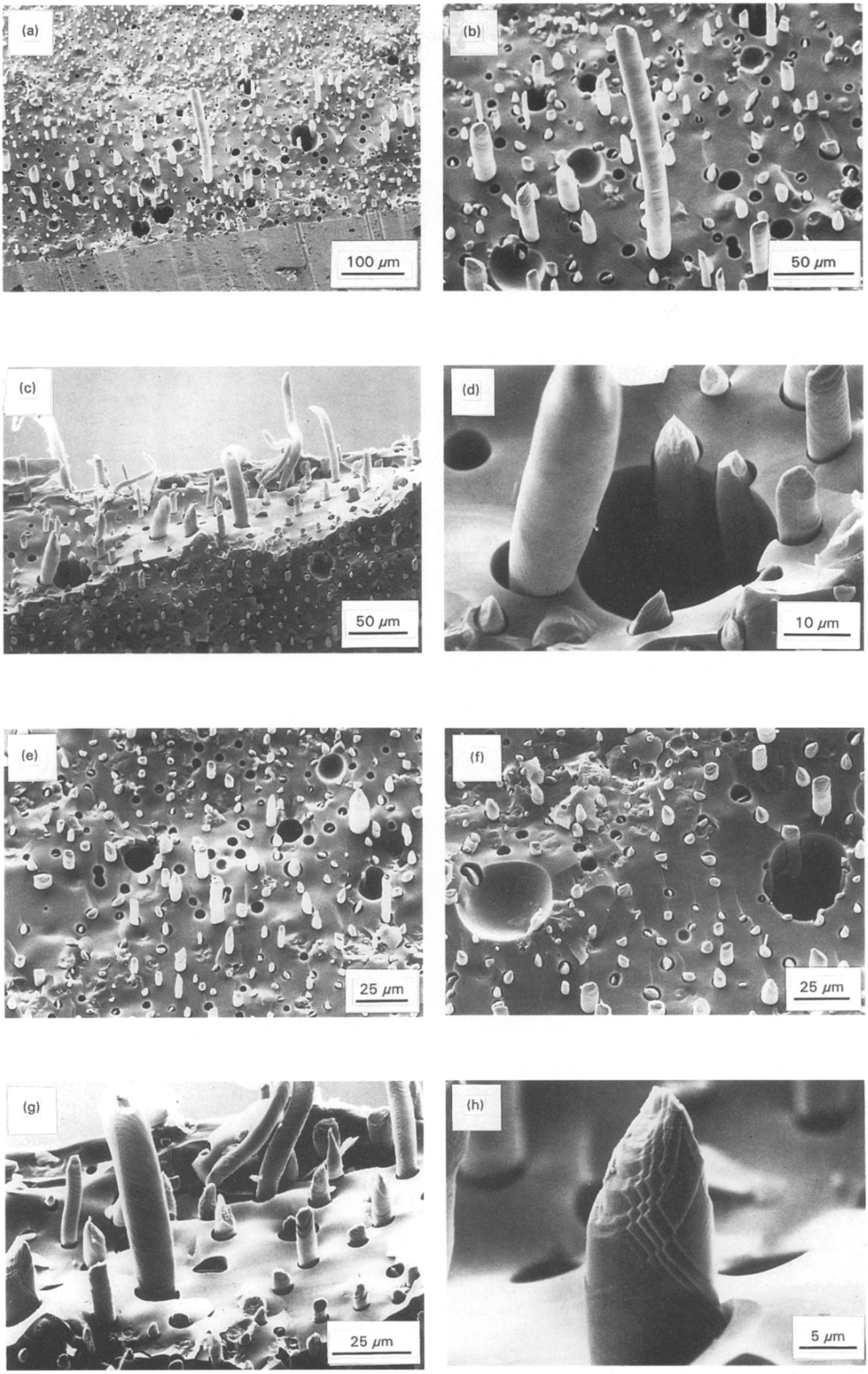


Figure 7 Load–displacement curves of copper and $Ni_{75}Si_8B_{17}$ alloy microwire composites tested in three-point bending.

4. Discussion

The Taylor-wire process is an ideal method for producing glass-coated metallic filaments of small diameter. It has been shown in the present work that copper microwire can be relatively easily drawn in a range of sizes using Pyrex glass, as can the Ni–Si–B alloys. The higher melting point Co–Mo alloy is more difficult to prepare as a microwire, although some success was noted, whilst elemental nickel and cobalt have proved impossible to prepare in microwire form due to the low viscosity of Pyrex glass at the temperature required to melt these metals. Neither was it possible to draw Cu–Zr alloy due to its high chemical reactivity with the Pyrex glass. The fact that Cu–Zr alloys can readily be prepared by chill-block melt-spinning employing fused silica nozzles, without serious chemical reaction, is due to the much shorter dwell times employed in this process.

Both the $Ni_{75}Si_8B_{17}$ and $Ni_{42}Fe_{28}Si_{10}B_{20}$ alloys were produced in an amorphous form in the present work, whilst the $Ni_{78}Si_{10}B_{12}$ and $Ni_{70}Si_{10}B_{20}$ alloys were microcrystalline. The fact that the $Ni_{70}Si_{10}B_{20}$ alloy could not be produced in an amorphous form is surprising in view of the relatively low critical cooling rate for glass formation predicted for this alloy


(a)
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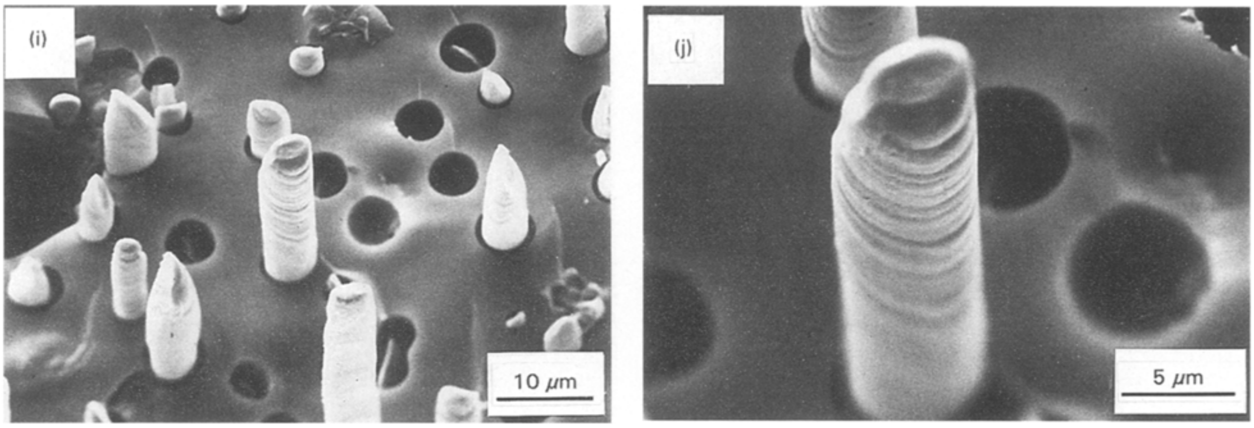


Figure 8 Fracture surfaces of copper microwire composites tested in three-point bending: (a,b) area close to an edge, note short pull-out length of metal filaments; (c, d) also close to an edge, note chisel-like fracture of filaments; (e, f) interior region, note porosity; (g–j) micrographs showing well-defined plastic slip markings on filaments.

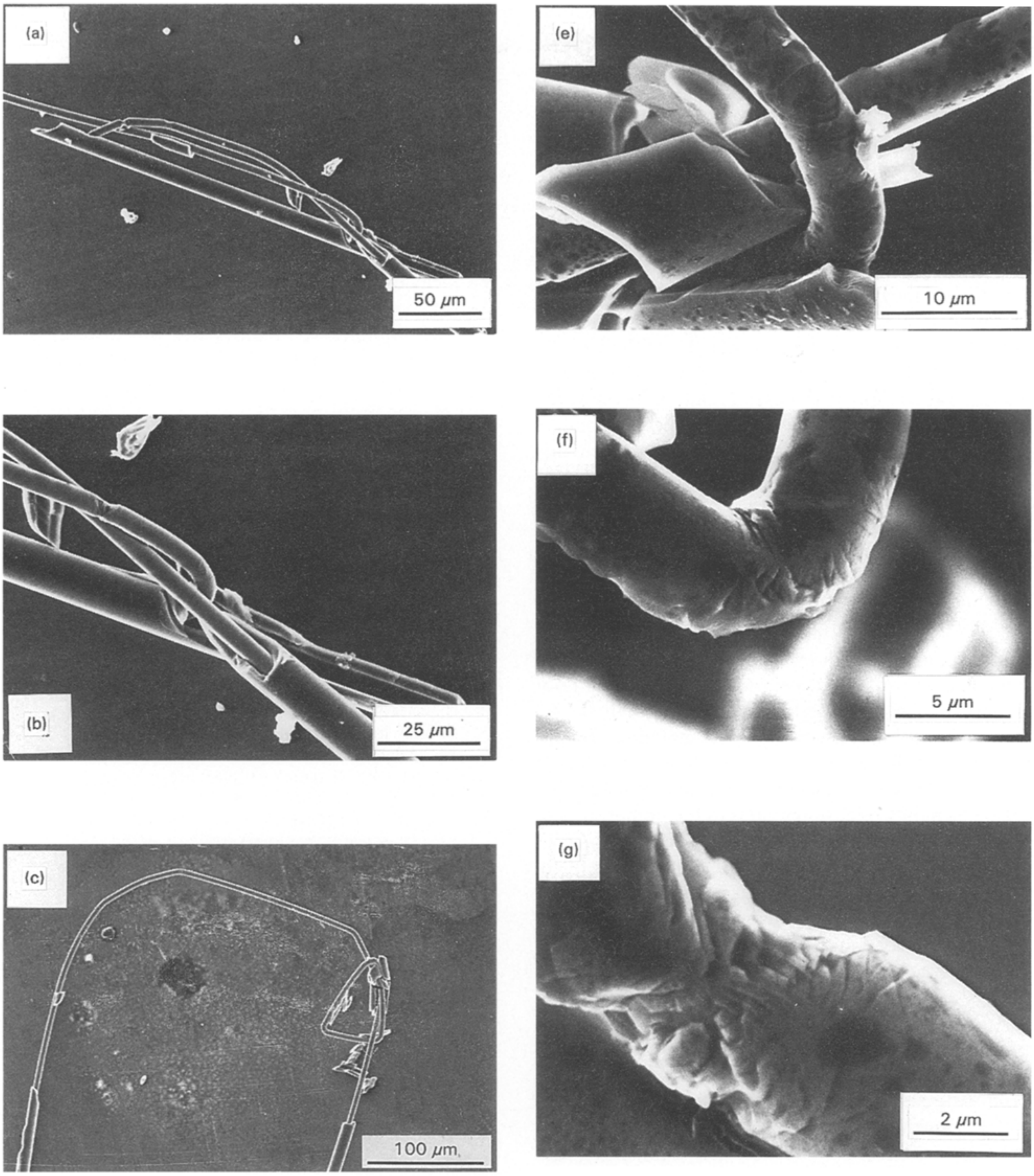
[25, 26], 10^3–10^4 K s^{-1}. This is lower than that for the $Ni_{75}Si_8B_{17}$ alloy, which was successfully produced in an amorphous form. The reasons may be connected with the lower melt temperature associated with the $Ni_{70}Si_{10}B_{20}$ alloy, this possibly resulting in a greater temperature differential being generated during solidification of the alloy from the melt. The $Co_{73}Mo_{27}$ alloy microwire was partially amorphous whilst the melt-spun material was microcrystalline. In this instance, however, the cooling rate achieved for the microwire is probably greater than 10^6 K s^{-1} (i.e. greater than that normally achieved during melt spinning) due to the very small diameter of the microwire core (<4 μm).

The microwires exhibit high mechanical strength, with the $Ni_{75}Si_8B_{17}$ alloy showing the highest strength of those tested (≈ 1400 MPa). The microcrystalline alloys exhibit conventional fracture behaviour (ductile failure for the copper and brittle failure for the Ni–Si–B alloys). The amorphous Ni–Si–B alloys, on the other hand, show fracture features characteristic of many metallic glasses, with well-defined vein patterns being apparent (Fig. 5f). These amorphous alloy microwires are also very ductile in bending. A simple test was employed to determine the relative ductility in bending by introducing a knot into a length of microwire and slowly tightening this until fracture occurred. The copper microwire could only be bent to a radius of ≈ 0.25 mm before failure occurred, whilst the glassy alloys could be tied into knots of very small radius, as shown in Fig. 9, without failure of the core. In this case, the Pyrex glass coating fractures and spalls off leaving the glassy metal filament to undergo extensive plastic deformation. Numerous slip markings are visible on the deformed portions of the wire, as noted in Fig. 9e–g.

It has been shown feasible in the present work to prepare metal filament glass matrix composites directly from Taylor-wire by hot pressing microwire tows. As illustrated in Fig. 6a, however, perfect unidirectional alignment of the metal filaments was not achieved. This was due to some difficulty in laying up the fine microwire tows accurately in the hot-pressing die without introducing some degree of twisting or other distortion of the tows. Alignment problems could undoubtedly be minimized, however, by more careful control over this laying-up operation.

The fracture surfaces of these composites are very interesting (Fig. 8), with copper filaments showing signs of extensive plastic deformation. Many slip lines are evident, with some evidence to suggest that the microwire is composed of single crystals aligned along the fibre axis. Only short filament pull-out lengths are noted and this, coupled with the relatively low volume fraction of filament, gives rise to the semi-brittle behaviour and relatively low values for the work of fracture noted for the composites reported in the present work.

Although the majority of recent work on glass and glass-ceramic matrix composites has concentrated on using the newer ceramic fibres as reinforcement, metal reinforcement does offer a number of advantages [22–24, 27]. These include, for example, a lower susceptibility to fibre damage during composite manufacture. At the present time, conventional die-drawn metal filaments are either of too large a diameter to promote useful strengthening, or the metals that are available in smaller sizes are prohibitively expensive or are only available in a limited number of metals and alloy compositions [27]. The Taylor-wire technique, therefore, offers a unique method for producing a range of small diameter metal and alloy microwires at realistic prices. Although the copper and Ni–Si–B Pyrex-matrix model composites prepared here are not very strong mechanically, it should in principle be possible to manufacture more practical composites using, for example, superalloy compositions prepared by the Taylor-wire technique. It may also be possible to prepare microwires with glass-ceramic precursor coatings by employing a suitable starting glass, although this must be available in the form of tube suitable for use in the Taylor wire process. In principle, the volume fraction of filament in a Taylor-wire produced composite could be controlled by controlling the thickness of the glass coating on the starting microwire. Higher volume fractions of filament than are noted in the present work should therefore be achievable.



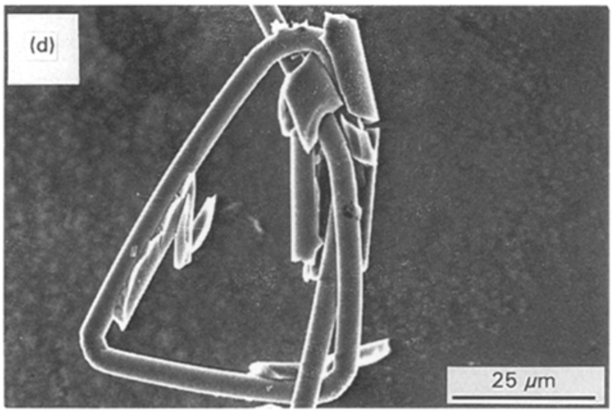


Figure 9 Micrographs illustrating the high ductility in bending of $Ni_{75}Si_8B_{17}$ amorphous microwire: (a–d) microwire has been tied into a knot; core has undergone extensive deformation whilst glass cladding has spalled off; (e–g) higher magnification micrographs showing the presence of extensive slip markings on amorphous filaments.

Recently, the Taylor-wire process has been modified for the preparation of fibres containing multiple (several hundred) sub-micrometre size discontinuous filaments [28], rather than the single filament produced in the conventional process. This offers further scope and versatility for the manufacture of randomly orientated and discontinuous filament-reinforced composites.

In terms of potential applications for microwire, it has been shown here that it is feasible to prepare metal filament-reinforced glass-matrix composite materials directly from microwire, as described above. In principle, the type, size and volume fraction of filament together with the inter-fibre spacing and the matrix material could be controlled by suitable choice of starting materials and drawing conditions. It may therefore be possible to tailor such composites for specific applications. Composites could find applications where high toughness and resistance to spalling are required, for example as ballistic protection materials. Alternatively, they may find applications where an intermediate temperature capability is required, in which case they could provide a useful extension to organic-based composites for applications requiring a higher temperature operating capability than is currently available using existing systems. In addition, microwire could provide a useful reinforcing phase for other composite systems, as first suggested by Nixdorf [29]. Some limited work has been reported in this area, with microwire being employed, for example, to reinforce a polymer matrix [30].

Other potential application areas for microwire could take advantage of their electrically insulating glass coating which is more refractory than conventional lacquer- or polymer-based wire insulation. For example, electrical connecting wires for printed circuit boards, miniature high-temperature wire-wound resistors, together with electric motors and related components with a higher operating capability than can be achieved when using conventional materials. Potential is also offered in the construction of miniature thermocouples and resistance thermometers. Another area which may offer potential is in the preparation of high-temperature ceramic superconductor filament if a compatible drawing medium can be identified. Finally, as microwire can, in principle, be produced from many different materials and in a range of sizes, it may provide a unique source of material suited for general research purposes.

5. Conclusions

1. The Taylor-wire process is an ideal method for producing glass-coated metallic filaments of small diameter. Depending on the starting composition and drawing conditions, both microcrystalline and amorphous alloys can be prepared in microwire form. In the present work, $Ni_{75}Si_8B_{17}$ and $Ni_{42}Fe_{28}Si_{10}B_{20}$ alloys have been prepared in an amorphous form, whilst $Co_{73}Mo_{27}$ alloy has been prepared partially amorphous. $Ni_{78}Si_{10}B_{12}$ and $Ni_{70}Si_{10}B_{20}$ alloys were microcrystalline as drawn, consisting of f c c nickel, Ni_3B and unidentified phases.

2. The use of a microwire precursor represents a simple, versatile and intrinsically inexpensive method for the manufacture of metal filament-reinforced glass composites. Both copper and Ni–Si–B alloy microwires prepared by the Taylor-wire route have been used successfully in the preparation of model unidirectionally aligned metal filament-reinforced glass matrix composites in the present work.

3. In addition to applications in the composites field, microwire may also find applications in the electrical and electronics areas where its small size and the presence of a heat-resisting insulating coating can be put to advantage.

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References

1. G. F. TAYLOR, *Phys. Rev.* **23** (1924) 655.
2. *Idem*, US Pat. 1793 529 (1931).
3. I. W. DONALD, *J. Mater. Sci.* **22** (1987) 2661.
4. G. MANFRÈ and D. VIANELLO, Ital. Pat. 930 409 (1972).
5. G. W. F. PARDOE, E. BUTLER and D. GELDER, *J. Mater. Sci.* **13** (1978) 786.
6. J. NIXDORF, *Drahtwelt* **53** (1967) 696, in German.
7. T. GOTO, *Sen-I Gakkaishi* **34** (1978) T237, in Japanese.
8. I. S. MIROSHNICHENKO, V. F. BASHEV, YU. K. POKROVSKIY and E. Z. SPEKTOR, *Russ. Metall.* **1** (1980) 105.
9. H. WEISNER and J. SCHNEIDER, *Phys. Status Solidi* **26** (1974) 71.
10. T. GOTO, M. NAGANO and N. WEHARA, *Trans. Jpn Inst. Metals.* **18** (1977) 209.
11. T. GOTO, *ibid.* **20** (1980) 219.
12. *Idem. Mater. Sci. Eng.* **59** (1983) 251.
13. V. F. BASHEV, *Phys. Met. Metall.* **55** (1983) 114.
14. B. L. METCALFE and I. W. DONALD, paper presented at the "UK Informal Conference on Rapid Solidification and Metastable Phases", University of Cambridge, 14–15 April, 1988 (unpublished).
15. I. W. DONALD and B. L. METCALFE, in "Advanced Structural Composites", edited by P. Vincenzini (Elsevier Science, Amsterdam, 1991) pp. 479–88.
16. I. OHNAKA, T. FUKUSAKO and T. OHMICHI, *J. Jpn Inst. Metals* **45** (1981) 751, in Japanese.
17. T. OHNAKA, T. FUKUSAKO, T. OHMICHI, T. MASUMOTO, A. INOUE and M. HAGIWARA, in "Proceedings of the 4th International Conference on Rapidly Quenched Metals", edited by T. Masumoto and K. Suzuki (Japan Institute of Metals, Sendai, 1982) p. 31.
18. A. INOUE, T. MASUMOTO and N. YANO, *J. Mater. Sci.* **19** (1984) 3786.
19. I. OHNAKA, *Int. J. Rapid Solid.* **1** (1985) 219.
20. "Unitika amorphous metal fibres", available from Metglas Products, Parsippany NJ, USA (1988).
21. L. A. JACOBSEN and J. MCKITTRICK, *Mater. Sci. Eng.* **R11** (1994) 355.
22. I. W. DONALD, B. L. METCALFE and A. D. BYE, *J. Mater. Sci. Lett.* **7** (1988) 964.
23. I. W. DONALD and B. L. METCALFE, in "New Materials and their Applications", Institute of Physics Conference Series 111, edited by D. Holland (IOP, Bristol, 1990) pp. 207–16.
24. I. W. DONALD, in "Key Engineering Materials", edited by G. M. Newaz, H. Neber- Aeschbacher and F. H. Wöhlbier, (Trans. Tech., Aedermannsdorf, 1995) in press.

25. I. W. DONALD and H. A. DAVIES, *J. Mater. Sci.* **15** (1980) 2754.
26. J. REEVE, H. A. DAVIES and I. W. DONALD, in "Proceedings of the 4th International Conference on Rapidly Quenched Metals", edited by T. Masumoto, (JIM, Sendai, 1982) pp. 221–24.
27. I. W. DONALD, *J. Mater. Sci.* **24** (1989) 4177.
28. J. D. AYERS, *ibid.* **28** (1993) 2337.
29. J. NIXDORF, *Proc. R. Soc.* **A319** (1970) 17.
30. T. GOTO and K. NISHIO, *J. Mater. Sci.* **22** (1987) 2357.

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