Fabrication of metallic glass wire or tube by drawing

Much interest has been stimulated in metallic glasses since Duwez and co-workers [1, 2] developed splat quenching methods for making an amorphous structure in alloys. In particular, metallic glasses show an excellent high strength (1300 to 3900 MPa) and ductility (180° bending without fracture). Hence by using superior mechanical properties, a large number of practical applications have been considered [3]. However, unfortunately, the shape of the metallic glasses product is still limited to ribbon or wire due to the necessity of having high supercooling although modern technology may remove this limitation in the future.

It is the purpose of the present work to remove the above limitation by making another shape of metallic glass from the original as-quenched ribbon. We will present the first report of the success in making a round cross-sectional wire from an as-quenched metallic glass ribbon with a semi-circular cross-section.

The metallic glasses, $Fe_{29}Ni_{49}P_{14}B_6Si_2$ (2826B METGLAS®), are prepared by a rapid quenching method from the molten alloys. The resultant ribbon filaments, 0.24 mm wide and 40 μm thickness, are drawn through diamond dies in several steps (0.152 to 0.076 mm in diameter). The continuous profile change of the cross-section in each step and the appearance of deformation bands are observed by optical microscope. The samples before and after being drawn to a final stage were pulled to failure at room temperature with a strain rate of $\dot{\epsilon} = 4 \times 10^{-4}\,\text{sec}^{-1}$ using an Instron tensile machine. The nature of the fracture surfaces was examined by scanning electron microscopy.

Focusing on the ductility of metallic glass, an as-quenched Ni–Fe base ribbon sample was drawn through diamond dies in several steps (0.152 to 0.076 mm in diameter). Fig. 1a to d shows the continuous micrographic observations of both cross-sections (left on the photos) and the corresponding side surfaces on the samples (right on the photos) during the drawing process. As expected, but surprisingly, the original semi-circular cross-section tends to be bent, continuously changing the shape itself and finally reaches a wholly round cross-sectional wire without a break.

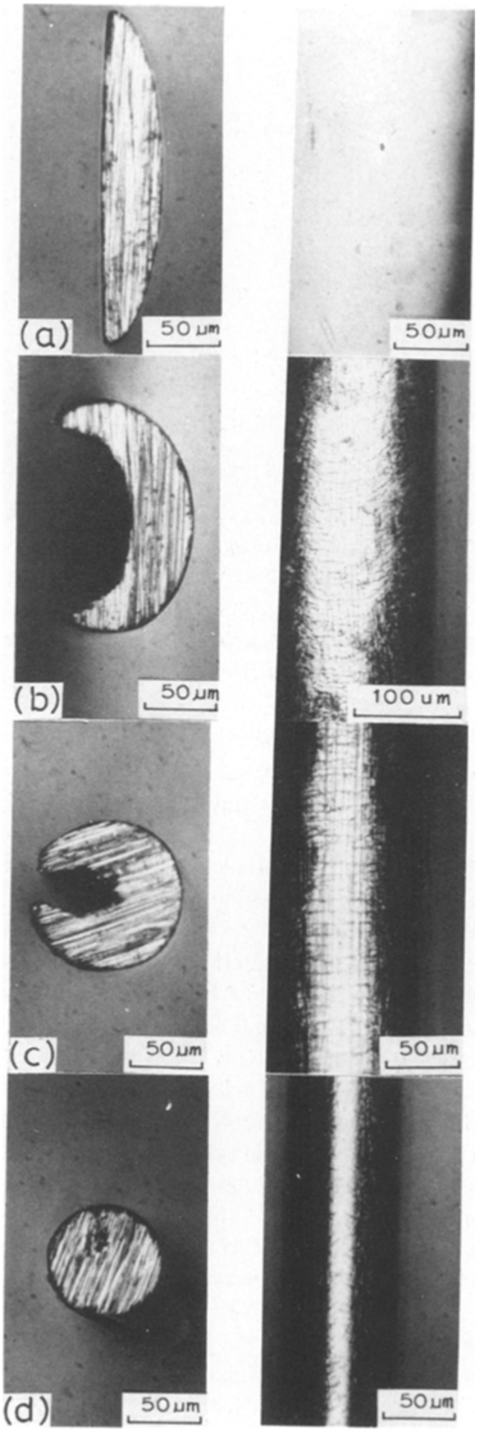

Figure 1 Sequential observations of both the cross-section (left) and the corresponding top surface (right) of a $Ni_{49}Fe_{29}P_{14}B_6Si_2$ metallic glass ribbon sample during drawing. The righthand photographs show the view from the right of the corresponding left photographs.

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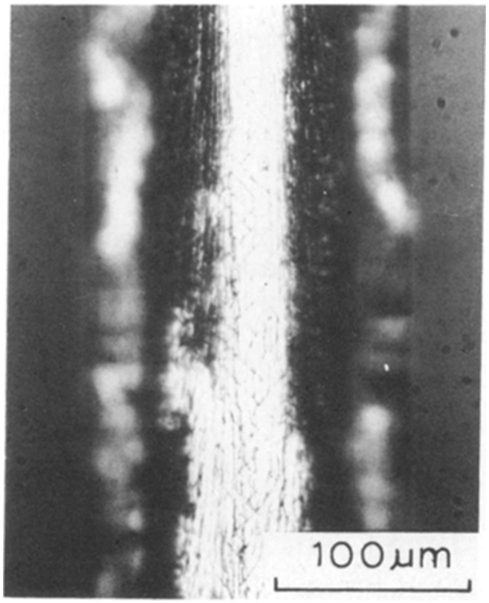

Figure 2 Optical micrograph of the inside groove corresponding to the view from the left Fig. 1b.

On drawing, firstly the ribbon sample was curled due to the residual stresses induced by an inhomogeneous deformation inside the dies. However, from Stage c in Fig. 1 the specimens tend to be straight and the cross-section formed a tube shape. For further drawing, the inside hole of the tube wire was squeezed out to be smaller, resulting in a smooth straight wire with a completely round cross-section (as shown in Fig. 1d). Accordingly, it appears more likely that from Stage c, an axially symmetric plastic flow [4] occurs during drawing, redistributing the residual stresses homogeneously within the sample. Hence in turn, it tends to straighten the drawing sample. In Fig. 1d both edges of the original cross-section of Fig. 1a are removed by mechanical polishing and appear to be connected to each other but actually they are slightly separated as shown later.

It should be noted here that there are two families of deformation bands, i.e. one showing vertical lines parallel to the drawing direction and the other inclining at a certain angle to the drawing direction. These deformation bands can be designated as a shear type slip line [4]. The former slip lines are, therefore, introduced so as to accomodate the bending strain around the longitudinal ribbon axis of a sample, while those of the latter accommodate the elongation during drawing. These two families of deformation bands are more clearly shown in Fig. 1b. The view of the inside of a groove (i.e. the view from the left on the cross-section in Fig. 1b) is shown in Fig. 2. Here, two families of slip lines are more clearly observed. The inclined slip lines in the photograph make an angle of 40° to 45° with respect to the longitudinal axis of the sample, which is close to the trace of the maximum shear plane under a uniaxial tension. It should be noted that many slip lines are terminated by contact with each other as shown in Fig. 2. This termination of the slip lines might indicate some difficulties for plastic flow in cutting through a predeformed area of a glassy structure. A detailed discussion of this subject is presented in [4–7].

The wires thus made above were pulled to failure at room temperature and their mechanical data were compared with those of unused as-quenched ribbons as listed in Table I. A stress–strain curve of the artificial wire shows a relatively large deviation from the elastic region before fracture. Such a deviation point is designated as an apparent yield stress and strain in Table I. It is worth emphasizing that the fracture stress of the artificially fabricated wire does not show any significant decrease compared with that of the unused as-quenched ribbon even though the apparent yield stress significantly decreases by 16%. This effect of no decrease of a fracture stress following heavy deformation has also been reported [4].

TABLE I Mechanical properties of $Ni_{49}Fe_{29}P_{14}B_6Si_2$ metallic glass averaged with seven samples

	Fracture stress σ_F (MPa)	Apparent yield stress σ_Y (MPa)	Fracture strain ϵ_F ($\times 10^{-2}$)	Apparent yield strain ϵ_Y ($\times 10^{-2}$)	Plastic strain ($\times 10^{-4}$)
Original as-quenched ribbon filaments	1942 ± 108	1265 ± 98	1.83 ± 0.14	1.17 ± 0.15	7.1 ± 2.0
Artificially fabricated wires	1971 ± 39	1108 ± 59	2.17 ± 0.06	1.06 ± 0.10	30.2 ± 2.5

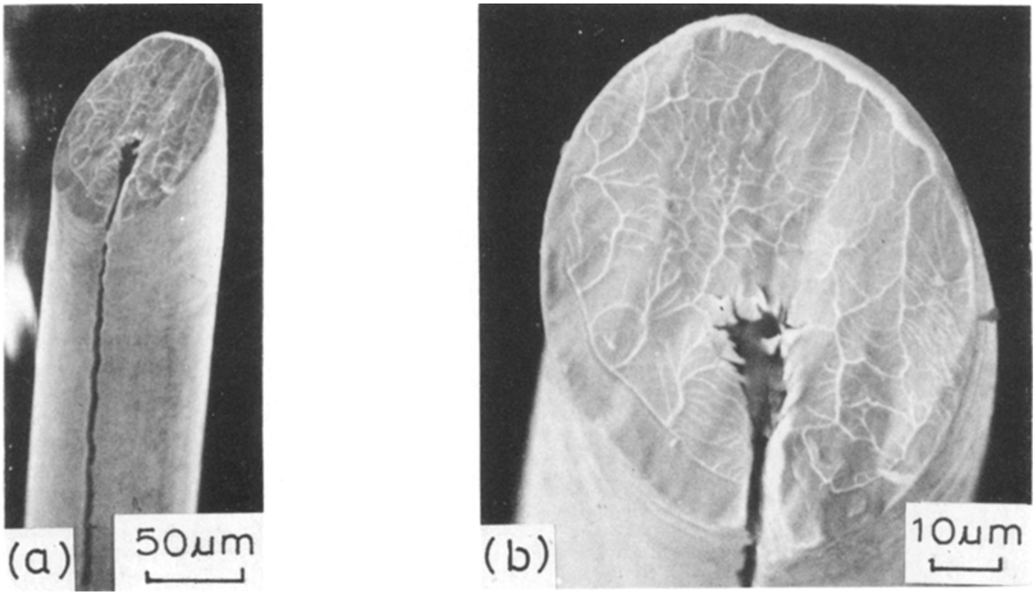

Figure 3 Scanning electron micrographs of the fracture surfaces of the round cross-sectional wire made by drawing.

It is of interest to note that such fabricated wires with a round cross-section are failed in a slant fracture, which is similar to those with an as-quenched metallic glass wire with a round cross-section [4]. The fractographs after drawing are shown in Fig. 3a and b. They show the scanning electron micrographs of the fracture surface for the drawn sample corresponding to Fig. 1d. Fig. 3b shows Fig. 3a at a higher magnification. Comparing with the fracture morphologies of as-quenched glassy wire [4], the wires made from a ribbon metallic glass, Fig. 3a and b, are fractured as if they do not contain any grooves or holes.

In summary, it is worth emphasizing that even metallic glasses can be plastically deformed so as to make a useful shape without losing their original superior mechanical properties.

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