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Thermoplastic Wire Drawing from Bulk Metallic Glass

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ABSTRACT

The low loss coefficient and high elastic energy storage of amorphous metals may provide novel opportunities in the design of stringed musical instruments. To produce prototypes for metallic glass music wire, bulk metallic glass pre-forms were reheated into the supercooled liquid region and stretched into wires. Investigations of these wires' geometrical, mechanical, and physical properties are reported. The process is relatively simple and could be practical for producing continuous wire. A theoretical analysis shows the importance of the interaction between heating power input, radiative and convective cooling, and area reduction in determining the wire's final properties.

INTRODUCTION

Bulk metallic glasses are here defined as amorphous metals which exhibited a glass transition upon cooling from the molten alloy, without detectable crystallization, in a shape with minimum dimension greater than 1 mm. By Fourier's law of heat flow, the maximum cooling rate that can be achieved in a bulk object is inversely related to the square of its minimum dimension, so this definition implies that the crystallization kinetics in bulk metallic glass-forming alloys are unusually sluggish. As a result, these materials exhibit a practically useful window of time and temperature in the supercooled liquid state above the glass transition temperature, where the shape obtained when the glass was made in the first cooling is only the starting point for easy deformation processes leading to much more complicated shapes. If flow of the material is unconstrained at the surface, particularly in uniaxial tensile testing, strains much larger than unity can be achieved [1,2]. In confined flow, much larger strain rate gradients are needed for large deformations, so the achievable strain is limited by a material formability parameter that takes into account the temperature dependence of viscosity and of crystallization kinetics [3,4]. Thermoplastic forming processes [5] that have been successfully carried out with bulk metallic glasses include imprinting [6-9], extrusion [10], injection molding [11], friction welding [2], manipulation with forceps [7], and blow molding [5].

Inspired by the similarities and differences between blow molding of bulk metallic glasses and the ancient art of glass blowing with silicate glasses, the possibility of fiber drawing by thermoplastic processing of bulk metallic glass was examined. The aim of the process is to reduce the diameter and increase the length of a cylindrical section of a bulk metallic glass casting, as a precursor to developing capabilities for more complex thermoplastic forming operations. Conventionally, the fiber drawing process would start from a high-temperature melt rather than a glass at room temperature. Thin wires, up to a few 100 µm, can be produced directly using rapid quenching methods. Using these methods, amorphous wires can be produced from even marginally glass-forming alloys [12,13]. Bulk metallic glass coil springs, with wire of 1-2 mm diameter, have also been produced by casting into a groove on a rotating copper mould [14]. In this work. The thermoplastic wire drawing technique allows to produce intermediate diameters as well. Metallic glasses could be of interest for novel stringed musical instruments, given their unique combination of high resilience and low intrinsic loss. However, it is by enabling design changes that make full use of the thermoplastic forming process that these materials generate real enthusiasm for innovation in musical instrument design. This work therefore examines the possibility of thermoplastically forming metallic glass wires.

EXPERIMENT

Method

$Zr_{55}Cu_{30}Al_{10}Ni_5$ bulk metallic glass specimens were prepared by copper mold casting. A 20 mm long segment was cut from a 7 mm diameter cylindrical section, and holes were drilled at each end. With the aid of some copper wire, these holes allowed the specimen to be suspended between a rigid support and a 1 kg weight, inside a glass tube with flowing helium gas. The assembled setup is shown inside the induction heating coil in figure 1a. The specimen was heated to the supercooled liquid region, between the glass transition temperature T_G and crystallization temperature T_X, where it deformed into a 0.5 m long wire, as shown in figure 1b.

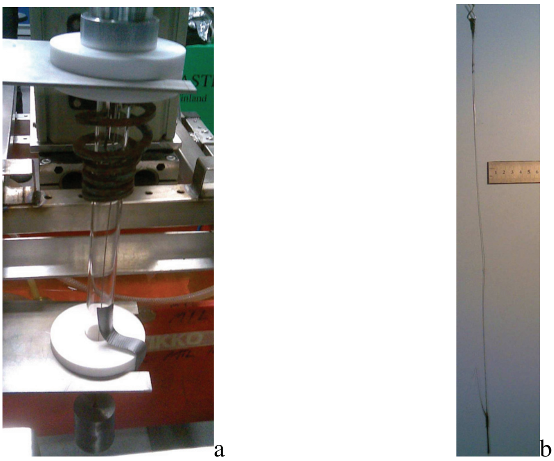

Figure 1. a) The assembled setup for wire drawing in the supercooled liquid region. b) the glassy wire produced using this setup.

Results

The microstructure of the drawn wire was determined to be glassy based on the X-ray diffraction (XRD) and differential scanning calorimeter (DSC) measurements, shown in figures 2 and 3. The mechanical properties of the produced wire were measured with instrumented indentation, and compared to those of a copper mold cast 10 mm diameter bar cross-section. Very similar hardnesses were measured from both, as is shown in Table 1. A somewhat smaller indentation modulus was measured from the wire cross-section than from the cast bar cross-section.

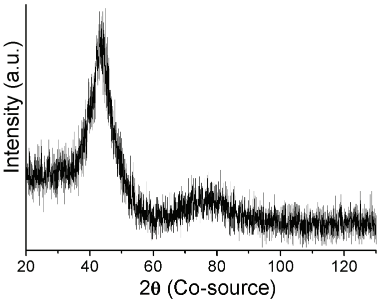

Figure 2. X ray diffraction (Co Kα) patterns of the supercooled liquid region stretched wire.

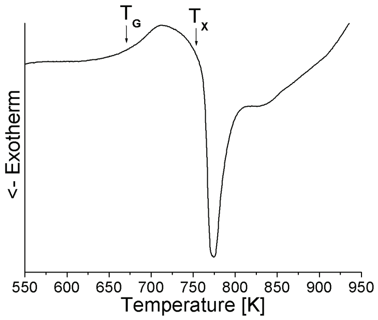

Figure 3. Differential scanning calorimeter (DSC) measurement of the supercooled liquid region stretched wire with glass transition T_G and crystallization T_X temperatures, 670.8 K and 754.3 K respectively.

	hardness [GPa]	modulus [GPa]
supercooled liquid region stretched wire, cross section	7.1 (0.14)	79.7 (1.0)
cast 10 mm rod, cross section	7.2 (0.27)	96.0 (2.7)

Table 1: Hardness and Young's modulus at initial unloading, with their standard deviations, as measured by instrumented indentation.

Modelling

The wire in figure 1b had a slightly elliptical cross-section, probably resulting from the bar heating also at the very ends, thus producing a non-circular cross-section during the super-cooled liquid drawing process. To evaluate, the focusing of the induction heating, a finite element model was created to evaluate, whether the heating of the specimen ends could be reduced by cutting the ends of the bar perpendicular to the drilled holes. The cuts effectively reduce the induced surface currents at the unwanted bar ends, as is shown in figure 4. To get a quantitative estimate of the power that is induced per length of the specimen, a linear line projection plot shown in figure 5 was calculated. This plot shows that the induction heating is focused at the center of the specimen, which gives the wanted round preform cross-section for the super-cooled liquid region wire drawing. This simulated result was verified with subsequent tests. Better understanding of the test conditions from simulations allowed a drastic reduction in the number of real tests.

CONCLUSIONS

Supercooled liquid region stretching with induction heating was successfully used to manufacture glassy wires from cylindrical cast glassy preforms. The microstructures of the drawn wires were verified with XRD and DSC measurements. The mechanical properties of the produced wires were tested with instrumented indentation to be very similar to those measured from a glassy cast specimen cross-section of the same composition $Zr_{55}Cu_{30}Al_{10}Ni_5$. Finite element simulation was used to better understand and optimize the process for producing circular cross-section wires. In theory, these produced wires can have novel acoustical properties, but more research is still needed to evaluate these possibilities.

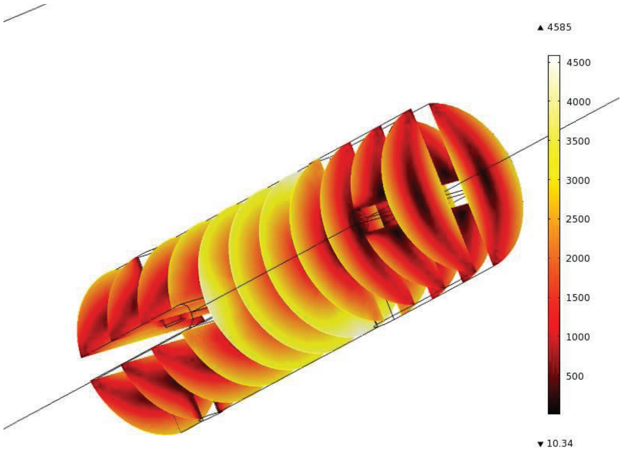

Figure 4. Finite element magnetic field simulation of induced current density in the 7 mm diameter, 20 mm long glassy wire drawing preform. The round holes are used to attach the preform during the drawing process. The longitudinal cut in each end of the specimen, help focus the inductive heating into the middle of the specimen, which is desirable for round cross-section wire drawing.

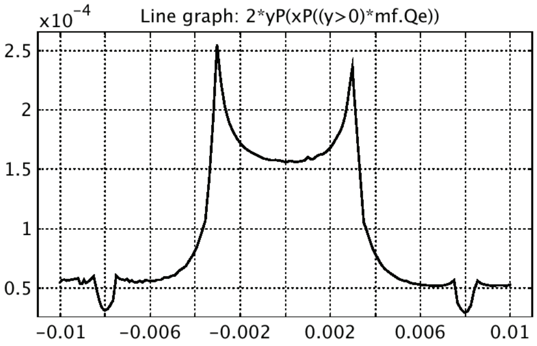

Figure 5. The calculated inductive heating power per unit length, in W/m, vs. distance, in m, along the longitudinal axis of the wire drawing preform. The dips in the curve at 2 mm from each end correspond to the holes through which the specimen is attached, and the spikes at 3 mm from the center result from concentrations in the current density at the edge of the slots cut into the sample. Approximately three times more power is delivered to the center of the specimen than to the ends, so the longitudinal slots cut into the ends seem to serve their purpose.

ACKNOWLEDGEMENTS

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REFERENCES

1 A. Inoue, "Stabilization of Supercooled Liquid and Opening-up of Bulk Glassy Alloys," *Proc. Japan Acad. B* **73**, 19-24 (1997).

2 Y. Kawamura and Y. Ohno, "Superplastic bonding of bulk metallic glasses using friction," *Scr. Mater.* **45**(3), 279-285 (2001).

3 J. Schroers, "On the formability of bulk metallic glass in its supercooled liquid state," *Acta Mater.* **56**(3), 471-478 (2008).

4 S. Bossuyt, "The Role of Friction in Measurement of the Formability of Bulk Metallic Glasses," *TMS Ann. meeting*, (2009).

5 J. Schroers,.Q. Pham, A. Peker, N. Paton and V. Curtis, "Blow molding of bulk metallic glass," *Scr.Mater.* **57**(4), 341-344 (2007).

6 Y. Saotome, K. Itoh, T. Zhang and A. Inoue, "Superplastic nanoforming of Pd-based amorphous alloy," *Scripta Mater.* **44**, 1541-1545 (2001).

7 A. A. Kundig, A. Dommann, W. L. Johnson and P. J. Uggowitzer, "High aspect ratio micro mechanical structures made of bulk metallic glass," *Mater. Sci. Eng. A* **375**, 327-331 (2004).

8 B. Zhang, D.Q. Zhao, M.X Pan, W.-H. Wang and A.L. Greer, "Amorphous metallic plastic," *Phys. Rev. Lett.* **94**(20), 205502 (2005).

9 G. Kumar, H.X. Tang and J. Schroers, "Nanomoulding with amorphous metals," *Nature* **457**(7231), 868-872 (2009).

10 Jan Schroers, "Processing of Bulk Metallic Glass," *Adv. Mater.* **22**(14), 1566-1597 (2010).

11 A. Wiest, "Injection molding metallic glass," *Scr. Mater.* 60 (3), 160-163 (2009).

12 T. Masumoto, I. Ohnaka, A. Inoue and M. Hagiwara, "Production of Pd–Cu–Si amorphous wires by melt spinning method using rotating water," *Scr. Metall.* **15**(3), 293-296 (1981).

13 T. Nagase, K. Kinoshita and Y. Umakoshi, "Preparation of Zr-based metallic glass wires for biomaterials by are-melting type melt-extraction method," *Mater. Trans.* **49**(6), 1385-1394 (2008).

14 K. Son, H. Soejima, N. Nishiyama, X.-M. Wang and A. Inoue, "Process development of metallic glass wires by a groove quenching technique for production of coil springs," *Mater. Sci. Eng. A* **449**, 248-252 (2007).