7.2 EFFECTS OF ION IRRADIATION ON BAM-11 BULK METALLIC GLASS —

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OBJECTIVE

The goal of this study is to investigate the radiation behavior of the bulk metallic glass BAM-11 and to determine if it is a viable candidate for high-radiation structural applications in fusion applications.

SUMMARY

Preliminary microstructural and nanoindentation examinations have been performed on BAM-11 (Zr-17.9%Cu-14.6%Ni-10%Al-5%Ti) bulk metallic glass (BMG) irradiated with 3 MeV Ni^+ ions to 0.1 and 1 dpa at room temperature and 200°C. Transmission electron microscopy (TEM) examination indicated the unirradiated and irradiated BMG samples were all fully amorphous with no evidence of nanoscale crystals. The hardness in the ion irradiated region of the BMG samples decreased by nearly 20% after irradiation at room temperature to 0.1 and 1 dpa, and decreased by ~25% and ~10%, respectively after irradiation at 200°C to 0.1 and 1 dpa. The elastic modulus of the irradiated samples decreased by ~10% after irradiation at room temperature to 0.1 and 1 dpa, and increased by ~10% and ~5%, respectively after irradiation at 200°C to 0.1 and 1 dpa. These results suggest that the BAM-11 bulk metallic glass may not have high intrinsic resistance to radiation-induced atomic rearrangements, i.e., the glass may not be in an optimized short-range order configuration for radiation damage stability.

INTRODUCTION

Metallic glasses are of potential interest for structural applications in fusion energy due to their good thermal conductivity, high strength, good ductility, good corrosion resistance, and the potential to be cast into near net shape geometries [1-3]. In addition, metallic glasses may provide unique advantages in terms of radiation resistance due to their lack of crystalline structure. Although particle irradiation can produce point defects and macroscopic changes in amorphous materials in a manner somewhat analogous to what happens in crystalline materials, there is some evidence that the amount of retained displacement damage can be significantly less in amorphous materials [4]. In addition, bulk metallic glasses may possess high helium permeability due to a larger free atomic volume and lack of grain boundaries that can act as helium traps; this would improve resistance to cavity swelling and tritium retention compared to crystalline materials [4]. A key question is whether radiation-induced defects might serve as deep traps for helium in metallic glasses.

Over the past few decades, pronounced advances have been made in metallic glass fabrication that now allows for the creation of high-performance structural glasses in bulk form, thus vastly increasing their usefulness for structural applications [5,6]. However, there is practically no information available on the effects of displacement irradiation on these new metallic glasses (simple glasses such as SiO_2 have historically exhibited poor dimensional stability following exposure to irradiation, with accompanying reductions in strength) [7,8]. In this study, we report the results of an investigation of the effects of ion irradiation on the Zr-based metallic glass BAM-11 (Composition: 52.5%Zr-17.9%Cu-14.6%Ni-10%Al-5%Ti, T_g~390°C) [9].

Preliminary

Preliminary microstructural examination of unirradiated BAM-11 bulk metallic glass was performed on a twin jet-polished BAM-11 specimen. TEM showed a feature-free sample that was revealed by diffraction to be fully amorphous (Figure 1). A baseline electron energy loss spectroscopy (EELS) scan performed via TEM gave a composition of Zr-7Al-3.8Ti-6.9Cu-15Ni with oxygen the only major impurity. This matches fairly well with the expected composition of the BAM-11 alloy [9].

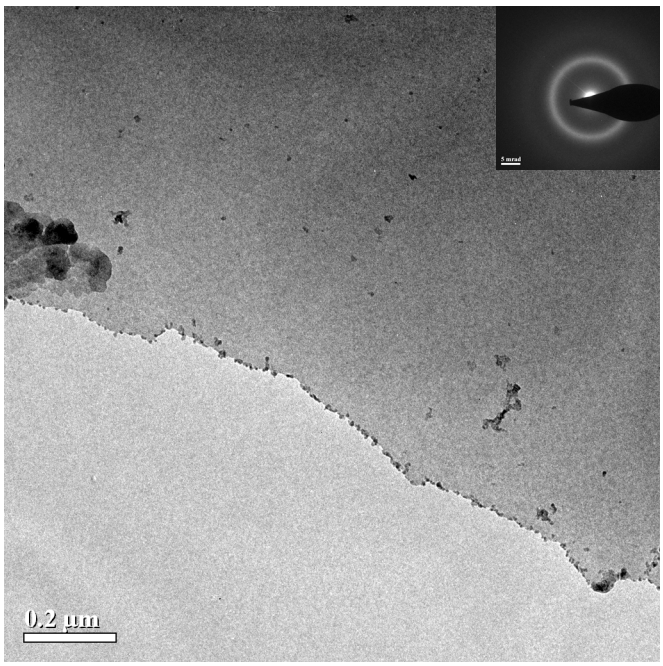

Fig. 1. TEM micrograph of the unirradiated BAM-11 alloy with DP inserted.

Irradiation

Ion irradiation experiments were performed at room temperature on BAM-11 specimens using 3 MeV Ni^+ ions. Samples were implanted to fluences of 4.2 x 10^{13} and 4.2 x 10^{14} ions/cm^2, or 0.1 and 1.0 dpa, respectively, at both room temperature and elevated temperature (200°C) at the University of Tennessee. Ion range and damage event profiles generated by the SRIM software are shown in Figure 2, using average displacement energy of 40 eV [10]. Additional samples are undergoing neutron irradiation in HFIR to doses of 0.1 dpa at temperatures of 70 and 200°C. Irradiation of the 70°C samples has been completed and post-irradiation examination will be performed in a few months.

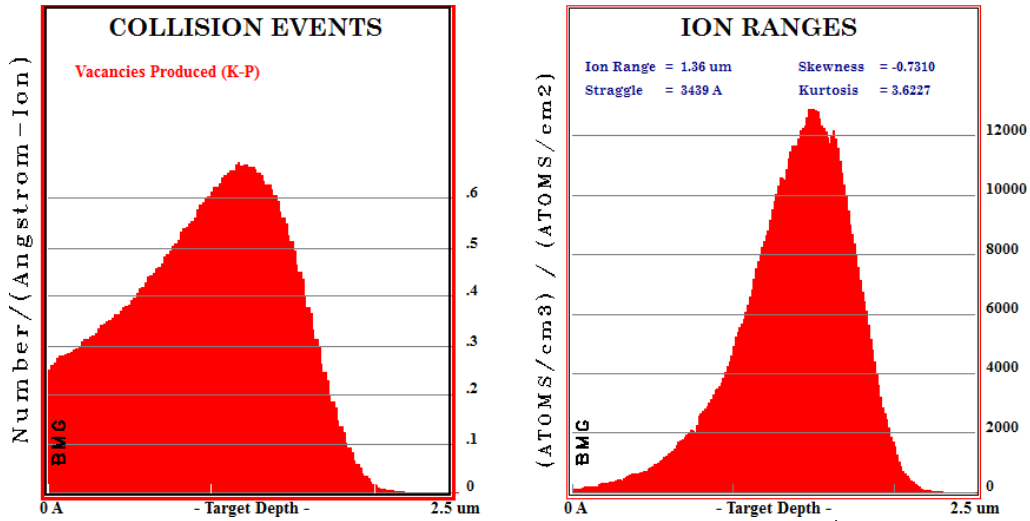

Fig. 2. SRIM plots of the vacancy production and ion range of 3 MeV Ni^+ ions in BAM-11.

Mechanical Properties

Mechanical properties were examined via microindentation using an MTS XP nanoindenter, with the indentations performed normal to the mechanically polished control and irradiated surfaces. All tests were performed in continuous stiffness measurement mode with a maximum load applied of 150 mN [11]. For statistical purposes, each sample was indented between 18 to 25 times and the average of the results is reported here. Hardness and elastic modulus were measured as a function of depth from the point of contact of the nanoindenter with the surface to a depth of about 1200 nm. Data generated within the first ~100 nm of the surface is unreliable and was thus discarded. The remaining data is shown as a function of indenter depth in Figures 3 and 4.

Considering the ~1 micrometer depth of the implanted ions and damage peaks and the fact that indentation properties are sensitive to substrate regions that are up to ten times the indenter depth [11], the behavior of the samples in the near-surface region is of the greatest interest. Average data is presented for an indenter depth of 200 nm in Table 1, which represents a compromise in depth to minimize surface effects while also minimizing contributions to the data from unirradiated regions.

Hardness and elastic modulus both dropped from the unirradiated condition for the room temperature irradiated conditions. Hardness decreased from about 8.0 GPa to about 6.5 GPa, and modulus decreased from about 111 GPa to about 101 GPa. Hardness and elastic modulus were comparable for both the 0.1 and 1.0 dpa conditions at RT, and collected data sets were very uniform.

In the samples irradiated at 200°C, somewhat dissimilar results were obtained. Both samples at 0.1 and 1.0 dpa showed reduced hardness. The 0.1 dpa sample displayed hardness of about 5.9 GPa while the 1.0 dpa sample showed hardness of about 7.1 GPa. Young's modulus, however, increased in both samples, to 123 GPa and 117 GPa in the 0.1 and 1.0 dpa samples, respectively. It should be noted that the standard deviations of the hardness and Young's

modulus data sets increased sharply for the sample irradiated to 0.1 dpa at 200°C. This particular sample will, after cleaning, be retested due to concerns during testing of the sample's surface cleanliness.

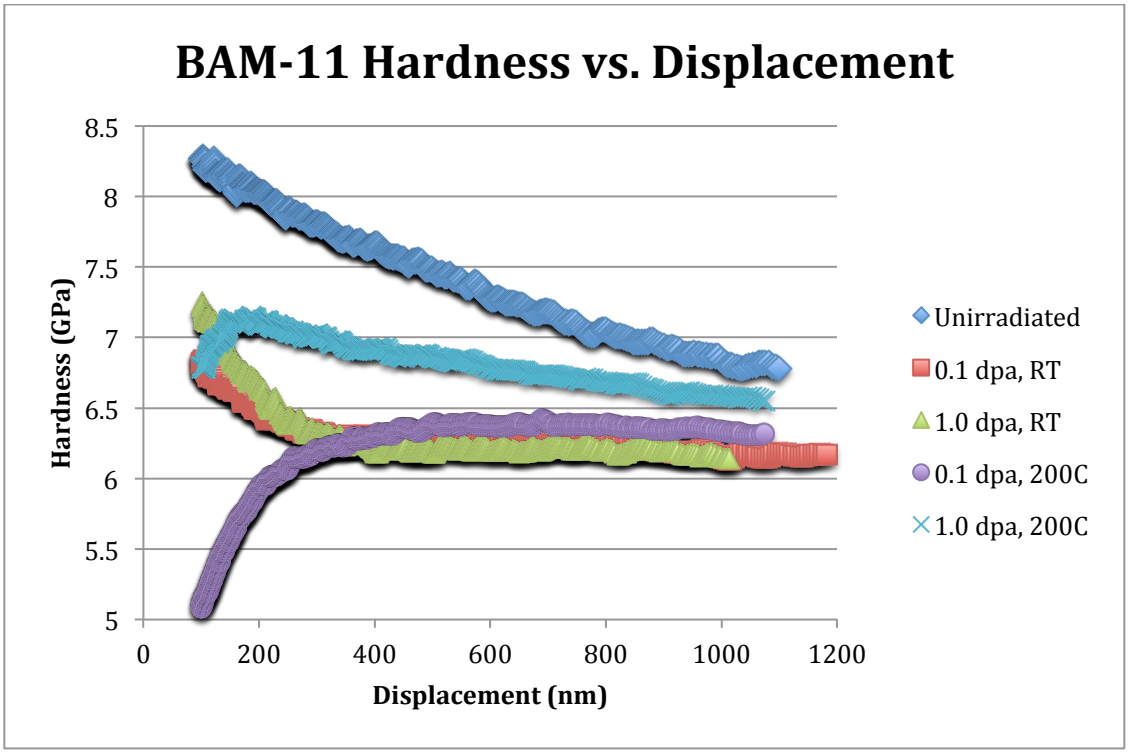

Fig. 3. Hardness as a function of indenter depth in the unirradiated and irradiated BMG specimens.

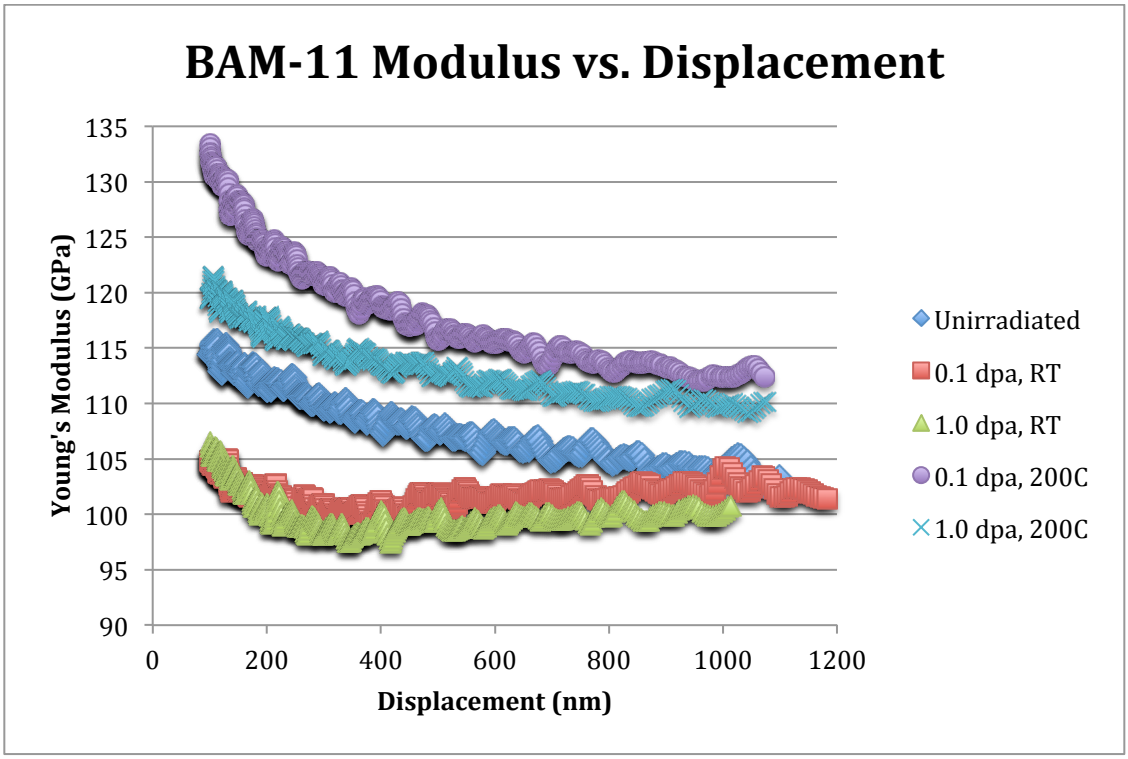

Fig. 4. Elastic modulus as a function of indenter depth in the unirradiated and irradiated BMG specimens.

Overall, however, the reduced hardness and young's modulus results suggest that the BAM-11 bulk metallic glass may not have high intrinsic resistance to radiation-induced atomic rearrangements, i.e., the glass may not be in an optimized short range order configuration for radiation damage stability.

Table 1. Summary of nanoindentation results on the BAM-11 specimens.

	Un-irradiated	0.1 dpa, RT	1.0 dpa, RT	0.1 dpa, 200°C	1.0 dpa, 200°C
Average Hardness* (GPa)	8.0	6.5	6.6	5.9	7.1
Std. Dev. Of Hardness	0.5	0.4	0.4	0.8	0.4
Average Young's Modulus* (GPa)	111.3	101.1	100.9	123.4	117.8
Std. Dev. Of Young's Modulus	4.1	4.1	4.4	7.3	4.1

* At depth of 200 nm

Microstructure

The BAM-11 samples irradiated at RT to 0.1 and 1.0 dpa did not show any real differences from the unirradiated condition. TEM revealed the samples to be feature-free and diffraction showed the samples to be amorphous. HRTEM confirmed that no crystallites were present in the sample. Additionally, no dislocations were visible upon tilting on two different axes in the TEM.

Similarly, samples irradiated to 0.1 and 1.0 dpa at 200°C also did not show noticeable differences from the unirradiated conditions. Samples were feature-free at differing tilt conditions, revealed amorphous diffraction patterns, and showed no evidence of crystallites in HRTEM mode. Figure 5 shows low-magnification, bright field images of each sample, as well as diffraction patterns and high-resolution phase contrast images of the BMG at each irradiation condition.

Analysis of the fast Fourier transform taken at a magnification of 135,000 times is underway, but should give some insight into the atomic spacing between atoms in the material. Electron energy loss spectroscopy (EELS) is planned to be performed in the TEM and should be able to give additional insight into changes in bonding conditions between the irradiated and unirradiated samples.

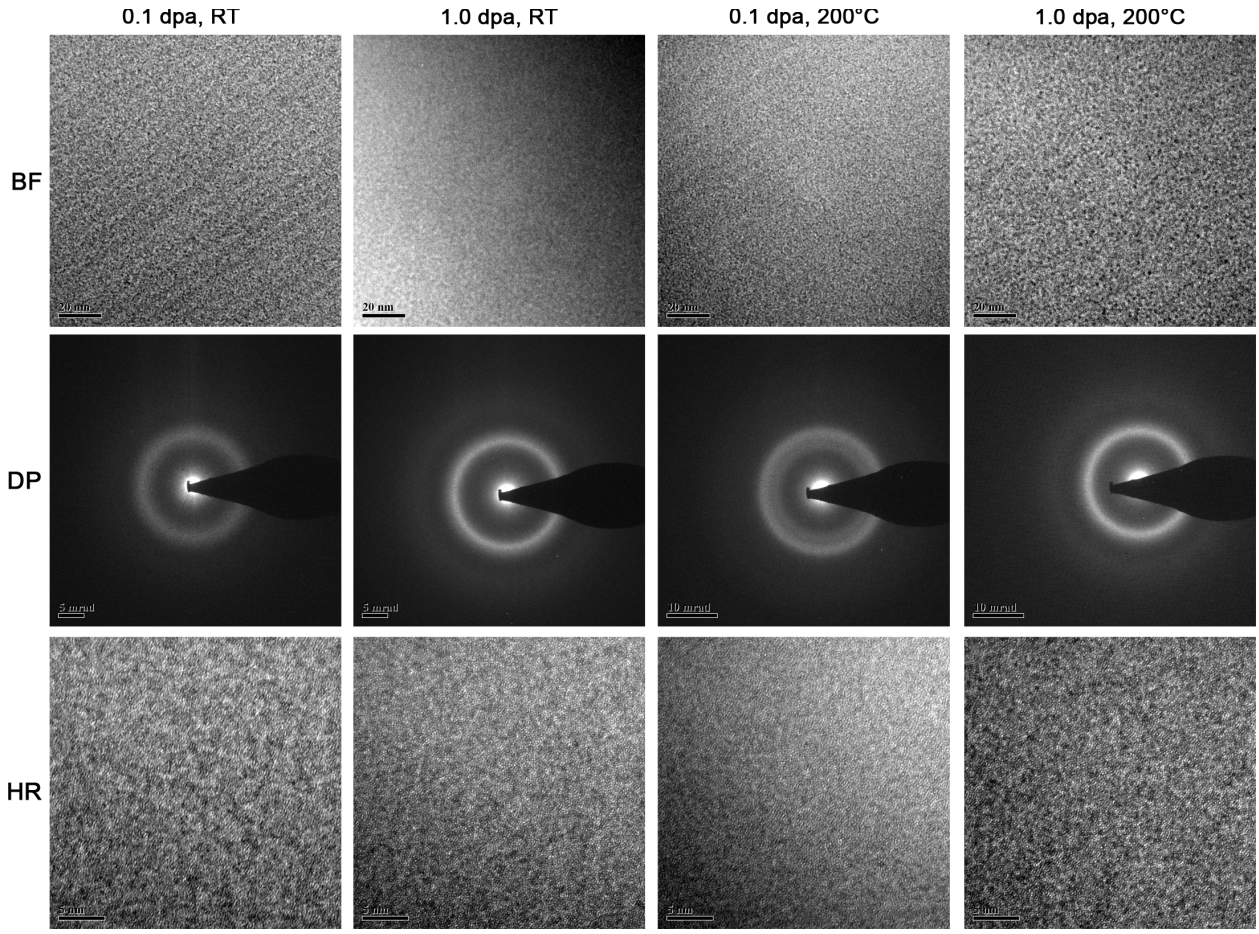

Fig. 5. TEM image showing bright field images at 135kx, diffraction patterns, and high resolution images at 580kx of ion-irradiated BAM-11 irradiated to 0.1 and 1.0 dpa at room temperature and 200°C.

Future Work

Some TEM experimentation and analysis is ongoing (EELS spectroscopy, FFT analysis). Additional mechanical testing and microstructural evaluation will need to be performed on the neutron-irradiated materials once the irradiations are complete and the samples are cool enough to handle. Further discussions will center on the viability of BAM-11 as a radiation-resistant bulk metallic glass based on the current results.

REFERENCES

[1] R. W. Cahn, *Nature (London)* **341**, 183 (1989).
[2] P. Chaudhari and D. Turnbull, *Science* **19,** 11 (1978).
[3] A. L. Greer, *Science* **267,** 1947 (1995).
[4] W. J. Weber, R. C. Ewing, C. A. Angell, G. W. Arnold, A. N. Cormack, J. M. Delaye, D. L. Griscom, L. W. Hobbs, A. Navrotsky, D. L. Price, A. M. Stoneham, and M. C. Weinberg, *J. Mater. Res.* **12**, 1946 (1997).

[5] A. Inoue, *Acta Mater.* **48**, 279 (2000).
[6] W. L. Johnson, *MRS Bulletin* **24**, 42 (1999).
[7] L. F. Curtiss, *Nature (London)* **120**, 406 (1927).
[8] E. P. EerNisse, *J. Appl. Phys.* **45**, 167 (1974).
[9] C. T. Liu, L. Heatherly, D. S. Easton, C. A. Carmichael, J. H. Schneibel, C. H. Chen, J. L. Wright, M. H. Yoo, J. A. Horton, and A. Inoue, *Metall. Mater. Trans. A* **29A**, 1811 (1998).
[10] James F. Ziegler, SRIM Software, retrieved 1 July 2013, from http://www.srim.org/.
[11] W. C. Oliver and G. M. Pharr, *J. Mater. Res* **7**, 1564 (1992).