Effects of Temperature and Loading Rate on Mechanical Behavior of Calcium Based Bulk Metallic Glass

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ABSTRACT

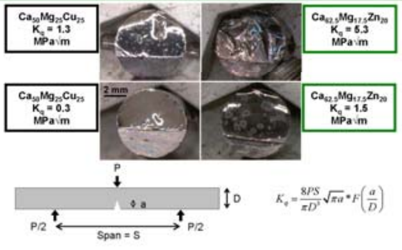
Calcium based bulk metallic glass has desirable properties for the aerospace industry including high strength and elasticity in addition to low density. These properties are due to the amorphous structure of the glass and low atomic weight constituents. Near the glass transition, extreme softening is exhibited, facilitating deformation processing of the amorphous alloy into different shapes. Two compositions were investigated: $Ca_{50}Mg_{25}Cu_{25}$ and $Ca_{62.5}Mg_{17.5}Zn_{20}$. X-ray diffraction was used to verify the amorphicity of the cast alloys before and after exposure to elevated temperatures. Vickers' microhardness tests at room and elevated temperatures were used to characterize the strength of the alloys at temperatures near the glass transition. Finally, hot compression experiments were performed near the glass transition of these alloys.

MATERIALS & METHODS

The two compositions were received in rod form approximately 6 mm in diameter and 5 cm long. Samples were cut and notched for 3pt bend tests using a 200μm wire saw while other samples were cut for Vickers' hot hardness. Hot hardness tests were performed using a Nikon QM hardness tester with attached furnace and vacuum chamber. Sample surfaces were prepared by lubricating with methanol and grinding with 800 and 4000 grit SiC paper. X-Ray diffraction spectra were recorded using a Scintag-X1 diffractometer. Hot compression tests samples were prepared from both compositions. Compression tests were performed on an MTS servo-hydraulic frame with metal platens. Room temperature Vickers' tests were performed with a Buehler indenter at 200gf and 1000gf loads. Optical images of hardness indents were taken at 400x with a Nikon optical microscope. Density was calculated from mass and cylinder volume (AS REC) and by weight in ethanol (after hot compression). Ultrasonic measurement was performed to determine the moduli and Poisson's Ratio of samples before and after hot compression.

Figure 1: Results of 3pt bend toughness tests on two compositions of Ca-based bulk metallic glass. The $Ca_{62.5}Mg_{17.5}Zn_{20}$ glass has a macroscopically rougher fracture surface than the $Ca_{50}Mg_{25}Cu_{25}$ which indicates a higher toughness [1].

Sample	Notched	Diameter [mm]	Length [mm]	a [mm]	a/w	Span [mm]	P_{max} [N]	P_{max} [lbs]	K_q [Mpa √m]	Average K_q
$Ca_{50}Mg_{25}Cu_{25}$	200 μm	6.36	30.0	2.00	0.31	11.5	172	39	1.3	0.7
		6.35	30.9	2.55	0.40	11.5	57	13	0.6	
		6.34	28.9	2.51	0.40	11.5	78	18	0.8	
		6.32	26.1	2.60	0.41	11.5	30	7	0.3	
$Ca_{62.5}Mg_{17.5}Zn_{20}$	200 μm	6.33	33.0	1.89	0.30	11.5	623	140	4.6	3.5
		6.36	30.0	1.52	0.24	11.5	836	188	5.3	
		6.35	31.7	1.59	0.25	11.5	224	50	1.5	
		6.33	15.0	2.52	0.40	11.5	243	55	2.4	



$$K_q = \frac{8PS}{\pi D^3}\sqrt{\pi a} * F\left(\frac{a}{D}\right)$$

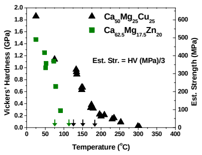


Figure 2: Results of Vickers' hot hardness tests on the two glass compositions. The dramatic drop in hardness and estimated strength begins at a temperature close to the glass transition [2]. The arrows along the x-axis indicate the temperatures which were chosen for hot compression tests.

$Ca_{50}Mg_{25}Cu_{25}$

Figure 3: Optical images of cylindrical samples before (a) and after (b) hot compression at temperatures listed. The engineering strain rate was $1x10^{-3}$ s-1 for all tests. The samples were held at temperature for 10 min prior to the start of testing which lasted approximately 8 min.

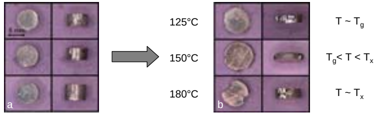


Figure 4: Results of hot compression tests (a) and XRD before and after compression tests (b). The dramatic change in flow behavior (a) is indicative of a material passing through the glass transition with possible crystallization (180°C). The XRD patterns show a generally diffuse peak corresponding to an amorphous structure. Some crystal structure may be present at 180°C.

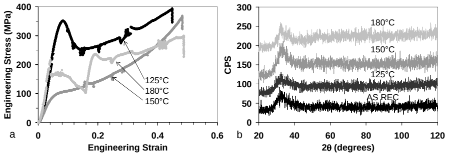


Figure 5: Results of room temperature Vickers' hardness tests (a and c) and corresponding indentation toughness [3] values (b) at 1000gf and 200gf load for samples before and after hot compression. The toughness appears to drop with hot compression.

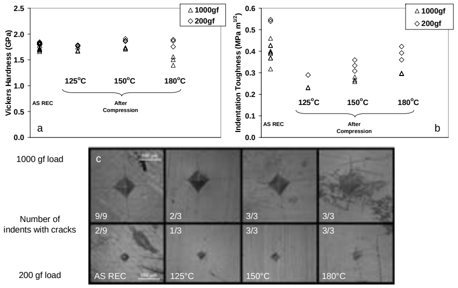
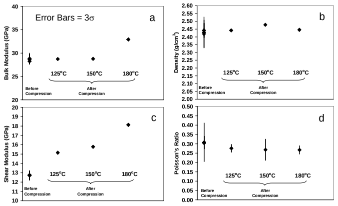


Figure 6: Results of elastic constant measurements (a and c) show an increase in moduli with hot compression. Density (b) may increase slightly with hot compression and Poisson's Ratio (d) may decrease slightly.



$Ca_{62.5}Mg_{17.5}Zn_{20}$

Figure 7: Optical images of both cylindrical samples before (a) and after (b) hot compression at temperatures listed. The engineering strain rate was $1x10^{-3}$ s-1 for all tests. The samples were held at temperature for 10 min prior to the start of testing which lasted approximately 8 min.

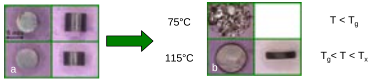


Figure 8: Results of hot compression tests (a) and XRD before and after compression tests (b). The dramatic change in flow behavior (a) is indicative of a material passing through the glass transition. The XRD patterns show a generally diffuse peak corresponding to an amorphous structure.

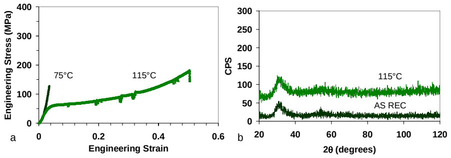


Figure 9: Results of room temperature Vickers' hardness tests (a and c) and corresponding indentation toughness [3] values (b) at 1000gf and 200gf load for samples before and after hot compression. No indents cracked after hot compression; the toughness may increase in this case.

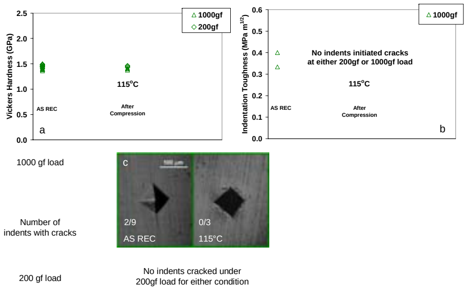
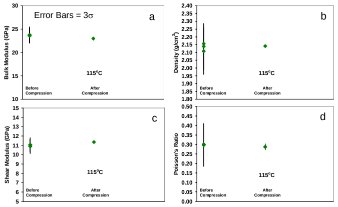


Figure 10: Results of elastic constant measurements (a and c) relatively no change in moduli with hot compression. Density (b) may increase slightly with hot compression and Poisson's Ratio (d) may decrease slightly.



RESULTS SUMMARY

- In the as-received condition, the Ca-Mg-Zn glass has a higher 3pt bend notch toughness than the Ca-Mg-Cu glass.
- The glass transition of the Ca-Mg-Zn glass is lower than the Ca-Mg-Cu glass.
- Compression test behavior varies greatly at temperatures near the glass transition.
- XRD shows an amorphous structure for samples before and after hot compression.
- Hardness for the Ca-Mg-Cu composition drops with hot compression while the hardness for the Ca-Mg-Zn composition remains relatively constant.
- Indentation toughness decreases for the Ca-Mg-Zu composition but seems to increase for the Ca-Mg-Zn composition.
- After hot compression, elastic constants for Ca-Mg-Cu increase but they remain relatively constant for Ca-Mg-Zn.
- The density of both alloys increases slightly with hot compression and the Poisson's Ratio decreases.

CONCLUSIONS

- Hot compression between the glass transition and the crystallization temperature appears to improve the toughness for $Ca_{62.5}Mg_{17.5}Zn_{20}$ but not $Ca_{50}Mg_{25}Cu_{25}$. Thus, the former composition is more suitable for further deformation trials than the latter.
- Care must be taken in proper thermal exposure of metallic glass alloys for deformation as evidenced by the different hot compression stress-strain behavior.
- Indentation toughness is a suitable technique for probing the variation of toughness with hot compression tests and can be combined non-destructively with elastic moduli and density measurements.

REFERENCES

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2. Senkov, O; Miracle, D; Keppens, V; and Liaw, P. "Development and Characterization of Low-Density Ca-Based Buld Metallic Glasses: An Overview." Met. Trans. A, 2007.
3. *Hess, P; Poon, S; Shiflet, G; and Dauskardt, R. "Indentation Fracture Toughness of Amorphous Steel." J. Mater. Res., Vol. 20, No. 4, Apr. 2005.*

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