Study of the Origins of Toughness in Amorphous Metals

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To my loving family,

Ronald, Linda, Allison, Brad, Evan, Anna

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ABSTRACT

Amorphous metals that form fully glassy parts over a few millimeters in thickness are still relatively new materials. Their glassy structure gives them particularly high strengths, high yield strains, high hardness values, high resilience, and low damping losses, but this can also result in an extremely low tolerance to the presence of flaws in the material. Since this glassy structure lacks the ordered crystal structure, it also lacks the crystalline defect (dislocations) that provides the micromechanism of toughening and flaw insensitivity in conventional metals. Without a sufficient and reliable toughness that results in a large tolerance of damage in the material, metallic glasses will struggle to be adopted commercially. Here, we identify the origin of toughness in metallic glass as the competition between the intrinsic toughening mechanism of shear banding ahead of a crack and crack propagation by the cavitation of the liquid inside the shear bands. We present a detailed study over the first three chapters mainly focusing on the process of shear banding; its crucial role in giving rise to one of the most damage-tolerant materials known, its extreme sensitivity to the configurational state of a glass with moderate toughness, and how the configurational state can be changed with the addition of minor elements. The last chapter is a novel investigation into the cavitation barrier in glass-forming liquids, the competing process to shear banding. The combination of our results represents an increased understanding of the major influences on the fracture toughness of metallic glasses and thus provides a path for the improvement and development of tougher metallic glasses.

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Chapter 1

INTRODUCTION

When engineers choose materials and design components for bridges, airplanes, and other applications where human lives are at risk, they no longer use the static strength of the material as the sole criteria for safety. Advances in fracture mechanics have shown that the best way to ensure the safety of a critical component is to design around the damage tolerance (the combination of yield strength and fracture toughness) of the material. Materials in the real world will always contain some potential flaw or crack, introduced during processing, regular use, or even mishandling. The important question to ask of a material is how much stress can this material withstand before any potential flaws cause it to fail quickly and catastrophically. This idea is the essence of fracture toughness, the measurement of a material's resistance to fracture. For metallic glass, even with an impressive strength, a lack of confidence in its fracture toughness, it will prevent it from being used for any but the least strenuous of applications (e.g., as excellent soft magnets).

M. F. Ashby and A. L. Greer have assessed both the strengths and weaknesses of metallic glasses as structural materials [1]. Naturally, the lack of a crystalline structure and its associated defects, i.e., dislocations and grain boundaries, is the source of both the most interesting advantages (high strength, high yield strain, high elastic energy storage, low damping, soft-magnetic properties, forming of the supercooled liquid) and deeply consternating disadvantages (zero tensile ductility, toughness values that can be as low as 5 MPa$\cdot$m$^{1/2}$ [2] and sometimes as high as 100 MPa$\cdot$m$^{1/2}$ [3], plastic zone sizes that range from microns [2] to a millimeter [3], and sometimes severe annealing embrittlement [4]) when comparing metallic glass to conventional crystalline engineering metals [1]. Ashby and Greer correctly conclude that given the circumstances one must identify applications where the disadvantages of metallic glass can be marginalized and the strengths can be maximized. However, the fracture toughness is such a crucial parameter for the wider adoption of metallic glass that we seek to shed light on the origins of its fracture toughness and identify the salient properties that control this important material parameter.

Specifically, in chapter 2 we address the fundamental source of toughness and thus damage tolerance in metallic glass, the development of the plastic zone in front of the crack tip. We introduce a Pd-based glass of excellent damage tolerance and show that the competition between extensive shear band growth and crack propagation via cavitation in the shear band lies at the heart of fracture toughness. In chapter 3 we explore the variability in the as-cast state of a highly processable Zr-based glass, and demonstrate that the fracture process of a pre-cracked specimen is a local process that is sensitive to the local environment of the crack. We show how annealing reduces the variability in toughness, and that toughness can be increased by increasing the potential energy of the glass. In chapter 4 we investigate the effect of minor alloying additions ($\leq 2\%$) on the configurational state and notch toughness of a Cu-based glass. In chapter 5 we present a study on the nucleation of cavities in glass-forming liquids due to the dynamic application of negative hydrostatic pressure. Glass-forming liquids are metastable to negative pressure on laboratory timescales, giving insight to the cavitation process that opposes shear band growth in metallic glass and thus plays an important role in limiting fracture toughness.

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