Final Report

Laser Shock Peening of Bulk Metallic Glasses

MSE 516: Mechanical Metallurgy

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1 Introduction:

Bulk Metallic Glasses (BMG) constitute a relatively young class of materials, which came into existence in 1960. Klement et al. [1] first demonstrated through their rapid-quenching experiments the development of Au-Si based amorphous alloys. Since then, there has been a great progress in understanding and developing different types of amorphous alloy systems. BMGs have a unique combination of mechanical properties which put them in a special class of materials [2]. BMGs are multi-component alloy system that retains the amorphous structure after solidification, which is the reason for their phenomenal mechanical properties. Many amorphous alloy systems have been studied so far based on Fe, Ni, Co, Mg, Ln, Zr, Pd-Cu, Pd-Fe, and Ti [3]. Although BMGs have exceptional mechanical properties but they suffer low tensile ductility. The problems associated with BMGs are “work softening” and “shear localization” that limit their tensile ductility [2, 4]. Hence, this problem limits the usage of BMGs in various applications.

Zhang et al. [4] reported the tensile ductility improvement of BMG Vitreloy 1 by shot peening process using fused-silica beads. Commercially, the shot peening process is used to induce compressive stresses on metallic components that undergo severe cyclic loading and are prone to fail by fatigue failure. The compressive stresses thus generated act against the tensile stresses under loading to annihilate their effect, and thus protects the component from failing during service. The tensile ductility improvement of BMG Vitreloy 1 by shot peening gives the idea that the compressive stresses on the surface assist in controlling the work softening and shear localization. It gives the insinuation that any process which is capable of inducing compressive stresses on the surface of BMG should be able to improve its tensile ductility. One such process is Laser Shock Processing, which is stronger in effect than the conventional shot peening process.

Laser shock peening (LSP) is a surface treatment process designed to improve the mechanical properties and fatigue performance of materials [5, 6]. LSP is primarily conducted on metallic components. The principle of LSP is to use a high intensity laser and suitable overlays to generate high pressure shock waves on the surface of the workpiece. An increase in fatigue strength is accomplished by the creation of large magnitudes of compressive residual stresses and increased hardness which develop in the subsurface. The maximum compressive residual stress is often formed at the surface of the workpiece and decreases in magnitude with increasing depth below the surface. The transient shock waves can also induce microstructure changes near the surface and cause high density of dislocations to be formed. The combined effect of the microstructure changes and dislocation entanglement contribute to an increase in the mechanical properties in the near surface.

During LSP (Fig. 1), the surface of the test specimen is usually first coated with a thin layer of material such as black paint which is opaque to the laser beam. This opaque layer acts as sacrificial material and is converted to high pressure plasma as it absorbs energy from a high intensity laser (1–10 GW/cm2) for very short time durations (<50 ns). If the specimen surface is also submerged in a transparent media such as water, the rapidly expanding plasma cannot escape and the resulting shock wave is transmitted into the specimen subsurface. These shock waves can be much larger than the dynamic yield strength of the material (>1 GPa) and cause plastic deformation to the surface and compressive residual stresses which can extend to a deep depth in the subsurface [5]. The pressure of these shock waves at any point and time can be calculated as:

$$P(r,t) = P(t)\exp(-\frac{r^2}{2R^2 t})$$

Due to the high strains/strain rates that the material undergoes, there can also be significant microstructure changes thus causing the mechanical properties such as hardness, tensile strength, and fatigue strength to be improved. Because thermal rise in the specimen is nearly eliminated by the water overlay, LSP is a primarily a mechanical process. In order to make the improved material properties more uniform, massive LSP zones must be created. It may also be advantageous to perform multiple LSP passes in order to create larger magnitudes of residual stress and hardness.

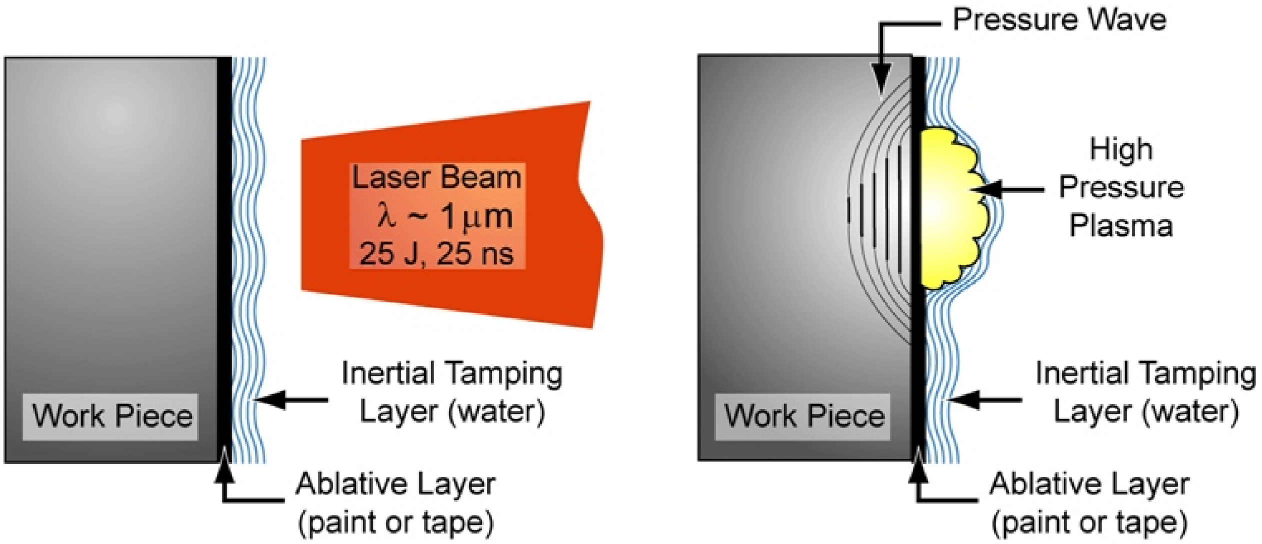

Figure 1

The objective of our work is to laser shock process a copper based bulk metallic glass and fathom its effect with respect to mechanical properties using X-ray diffraction, microhardness, and three-point bend test.

2 Experimentation:

For laser shock processing of Cu-based BMG, we used a 308 nm wavelength excimer laser with FWHM of 10 nm and energy per pulse of 10 mJ. The fluence delivered was around 25 J/cm^2 in a beam spot of 250 microns. It is a tunable pulse laser whose repetition rate can be varied. In order to make sure that the set-up is capable of doing LSP, trials were conducted on a titanium alloy Ti-6Al-4V and compared with the known results from literature. First, titanium sample was mounted in bakelite and ground to expose the surface, and then polished to grit size 600 in order to remove the major surface irregularities. After the sample was polished, it was ultrasound cleaned and then painted with a black paint (Rustoleum). The thickness of the paint after drying was found to be around 200 microns. The sample was then laser shock processed in the set-up made (Fig. 2) under the laser processing conditions mentioned above. The set-up consisted of an excimer laser which delivered laser beam in horizontal plane, a high reflectivity mirror (Melles Griot), a biconvex lens, a glass container with distilled water, and the sample under study. A mirror was placed a 45 degrees in the horizontal path of laser beam to reflect it by 90 degrees and convert it to vertical path. A biconvex lens was used to converge the laser beam and focus it to a tight spot size in order to obtain the required fluence. The sample under study was kept inside a glass container filled with distilled water; distilled water acts as a confinement to prevent the high pressure plasma from escaping. The spacing between the water surface and the sample surface was maintained at 1-2 mm. The assembly of mirror, biconvex lens and water container with sample was housed on a manual traverse capable of moving in X-Y direction; however, only one direction had the Vernier scale which could measure the movement while the other was a free movement.

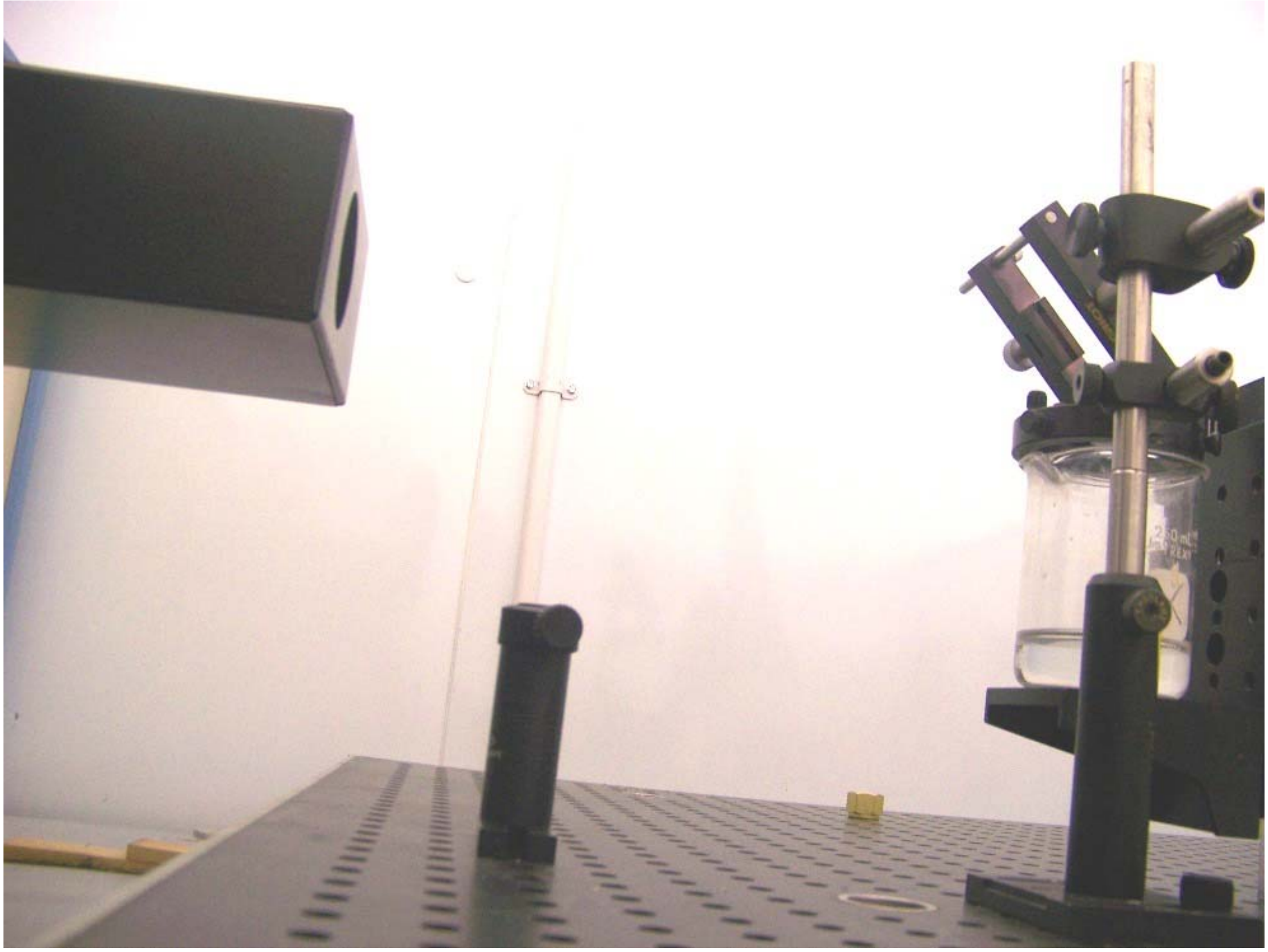

Figure 2

3 Results & Discussion:

The trial laser shock processed titanium sample was characterized using a LECO LM 300AT microhardness tester, integrated with LECO AMH32 software, under a load of 100 gf for 15 seconds using Vickers indenter. Microhardness measurements were taken across the thickness of the sample and compared with that of the unprocessed titanium sample to see the effect. Results show that there is no significant change in the hardness of the processed and unprocessed titanium trial samples. The average hardness of the unprocessed titanium sample (Fig. 3) was found to be 352 VHN with a standard deviation of ± 14 VHN. The average hardness of the laser shock processed titanium sample (Fig. 4) was found to be 351 VHN with a standard deviation of ± 24 VHN. Although there is no change in the average hardness values, results show an increase in the value of standard deviation. This change in the standard deviation may be attributed to unsynchronized sample movement during laser shock processing. The sample movement should sync with the frequency of laser pulse in order to get a uniform effect.

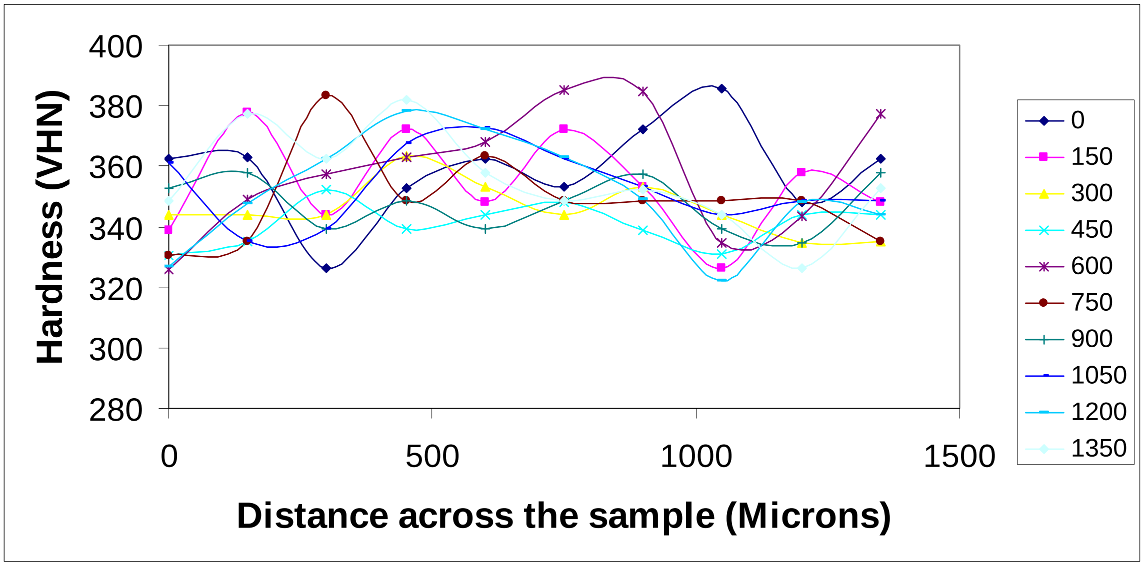

Figure 3

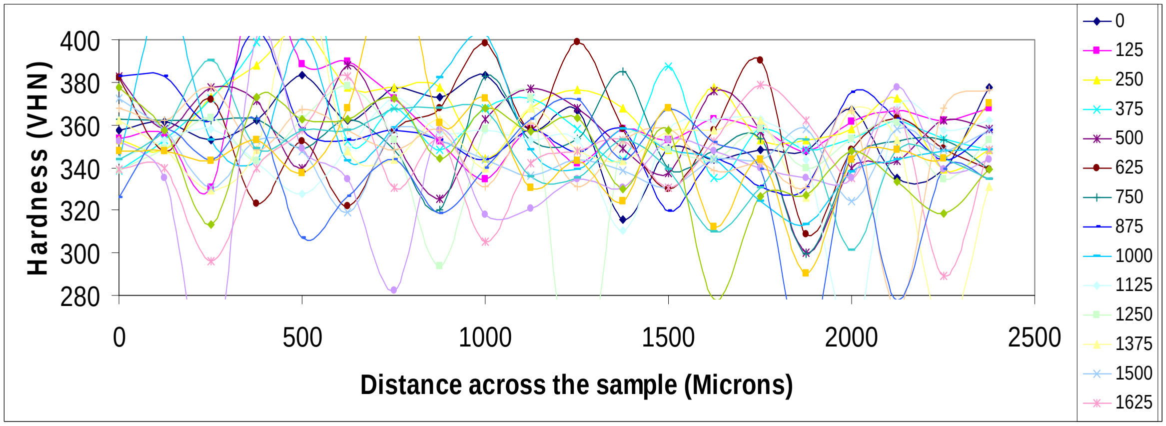

Figure 4

The expected hardness of the laser shock processed titanium sample was around 400 VHN, but the present set-up did not yield this result. Although the laser was capable of delivering the required fluence, there was no effect in the hardness of the processed sample. It indicates that the set-up requires a lot of modification.

4 Recommendations for future work:

Future work will be on modifying the experimental set-up prior to laser processing. The modifications will focus on computerized synchronization of laser pulse repetition rate (i.e., frequency) with the XY motion of the traverse which moves the sample. The mathematical equation derived for speed of traverse is:

$$v = \frac{l\upsilon}{n}$$

Where, l is the length of the sample or one run, which is equal to:

$$l = \omega p\left[1 + n\left(\frac{1-p}{p}\right)\right]$$

Where, ω is the beam width
p is the overlap
n is the number of laser spots (i.e., shots)
ν is the frequency of the pulse laser (i.e., repetition rate)

5 Conclusion:

Laser Shock Processing set-up was made for shock processing of Cu-based bulk metallic glass using a 308 nm wavelength excimer laser. The set-up consisted of an excimer laser, a mirror, a biconvex lens, a glass container with distilled water and the sample. The sample assembly was housed on a traverse with one free axis and one controlled axis. Trials were done on a titanium alloy sample of Ti-6Al-4V to validate the made experimental set-up with the existing data in literature. Results obtained from microhardness testing showed that there is no change in the hardness values of processed and unprocessed titanium samples. Results give insight into the importance of synchronization of laser pulse and sample movement. Future work will concentrate on building a computer interface between laser pulse and traverse to synchronize the motion of sample with the laser frequency.

6 Acknowledgement:

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7 References:

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