Report on “Impact and Ballistic performance of monolithic Al-5083 Alloy and Al - SiC hollow sphere Composite”

For Deep Springs Technology, Inc.

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## Impact Spall Testing of Al-5083 Alloy

Plate impact testing has been performed on commercially available Al5083-H116 from McMaster Carr. During impact, the rear free surface velocity of the Al5083 sample was measured via a velocity interferometer system for any reflector (VISAR) system. Typical VISAR records of impact experiments performed over a range of velocities are shown in Figure 1. The VISAR traces show clear indication of the pull-back signal (dip following the peak velocity) indicative of spallation in the material. The traces also clearly reveal the Hugoniot elastic limit (HEL) seen as the step in the rise time of the shock front, indicating the elastic to plastic transformation response. Subsequent reverberations seen in the free surface velocity are due to “ringing” of the shock wave between the spall plane and the rear free surface. The calculated HEL value was 0.43 GPa. While the HEL is an indicator of the dynamic yield strength in compression, the spall signal represents the dynamic tensile strength.

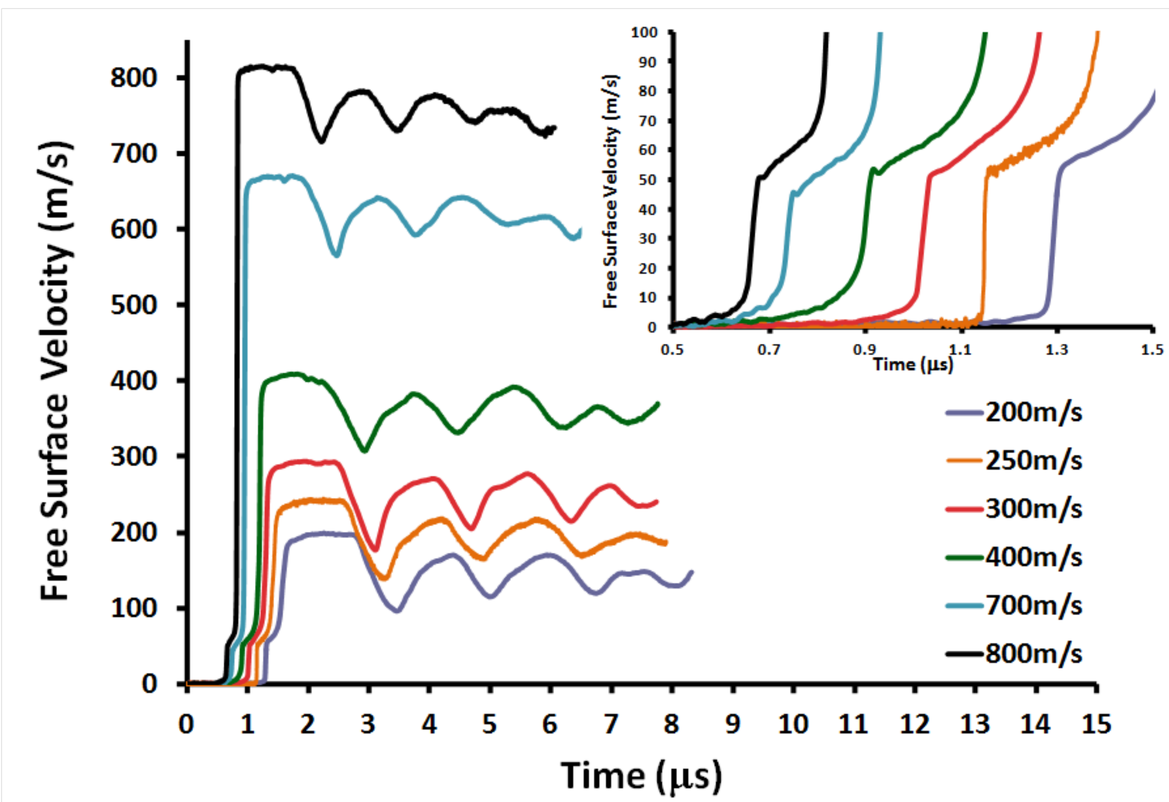


Figure 1. VISAR free surface velocity traces from impact experiments on Al5083 over a range of velocities, showing the spall pull-back signal (dip following the peak velocity). The inset shows clear indication of the step in the shock front indicative of the Hugoniot Elastic Limit (HEL).

The HEL and spall strength values obtained from the VISAR traces plotted as a function of the peak stress, as shown in Figure 2, are observed to be in good agreement with those reported by Boteler and Dandekar[1,2] for wrought Al5083 of various tempers.

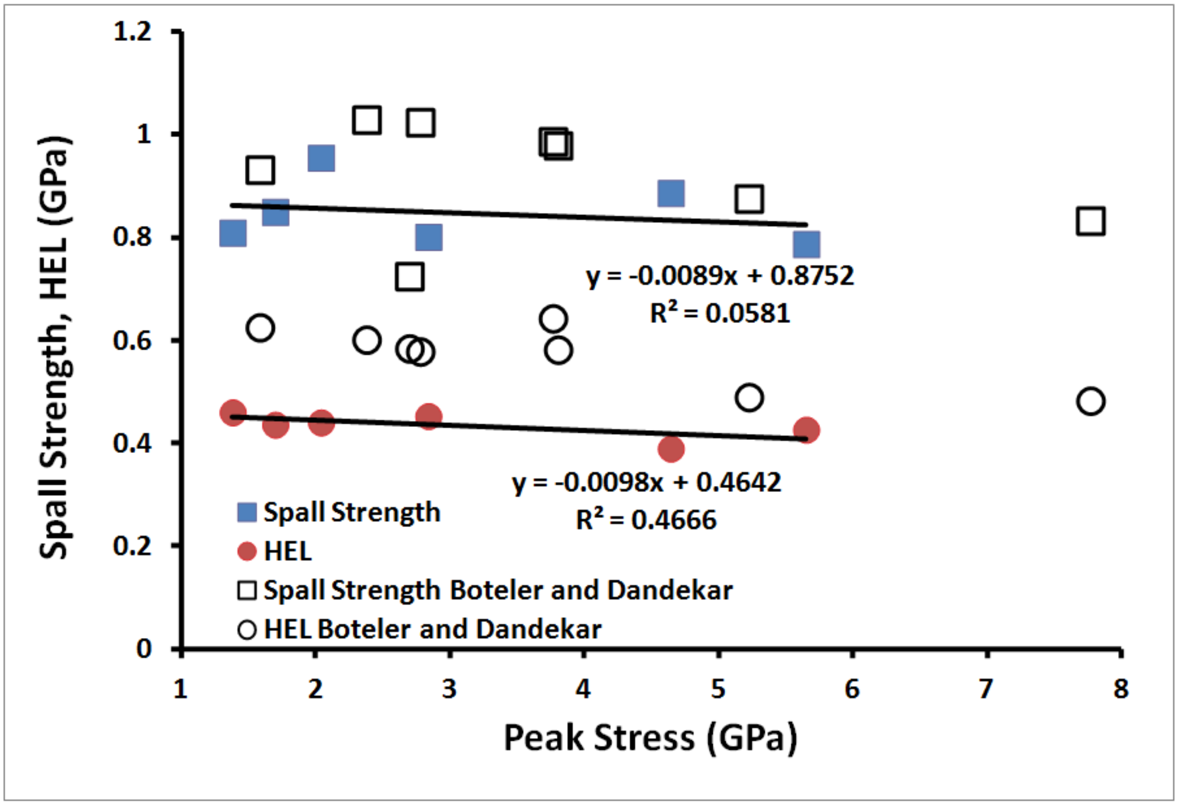


Figure 2 shows a low-mag image of cross-section of impacted sample, illustrating the seperation of the spall along the mid-plane, consistent with the geometry of the impactor (flyer) plate and sample, both of the same material. Figure 3 shows the microstructure of the spalled sample,s illustrating cracks initiating at brittle particles, such as the Mn dispersoid (Figure 3a) while the grains retain their orientation (parallel to the spall plane) after impact (Figure 3b).

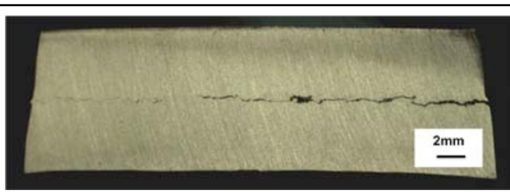


Fig. 2. Cross-sectional image of Al5083 sample impacted at 300m/s, showing spall across lateral dimension

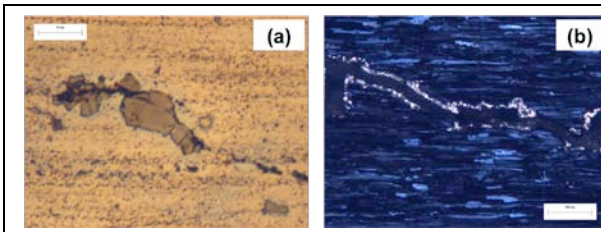


Figure 3. Cracking of brittle particles and retention of oriented grains in Al5083 spalled sample.

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[1] J. M. Boteler and D. P. Dandekar, "Dynamic Response of Two Strain-Hardened Aluminum Alloys," Journal of Applied Physics, 100, 054902, 2006.

[2] J. M. Boteler and D. P. Dandekar, "Dynamic Response of 5083-H131 Aluminum Alloy," Shock Compression of Condensed Matter, CP955, pp. 481-484, 2007.

## Ballistic performance of monolithic Al-5083 Alloy and Al-5083 with SiC hollow spheres

A reverse ballistics experiment was performed on Al-5083 alloy containing SiC hollow spheres provided by Deep Springs. The Al-SiC hollow sphere composite available in the form of a 27-mm thick section was affixed to the front of a 127 mm long, 80 mm diameter aluminum sabot for reverse ballistic testing at 660 m/s. The Al sabot was machined with a 8-mm wide step and 28-mm deep pocket such that the diagonal edges of the composite slab (shown in Figure 4 (a)) rest on the step and maintain an air gap to allow free-travel of projectile in to the Al sabot witness material, in case of penetration through the composite. Figure 4(b) shows the steel bullet shaped target of 7.62mm diameter and 31.78 mm length held in the center of the gun axis by a 6 mm piece of PMMA.

Figure 4. Composite slab mounted on Al sabot (left) and 7.62 mm steel bullet mounted on PMMA plate (right)

Following impact, the sabot and composite material were soft recovered in a catch tank of packed rags, some of which stuck to the surface. The front of the aluminum sabot was removed by turning on a lathe and the sample was extracted. Figure 5 shows images of the recovered debris following the experiment. The front of Aluminum sabot was removed by turning on a lathe and the sample was extracted.

**Figure 5.** Images of recovered debris following reverse ballistic experiment at 660 m/s.

As illustrated in Figure 6, the Al-SiC composite rear surface (far right image) did not show evidence of impacting the bottom of the pocket in the aluminum sabot. The steel bullet was captured in the aluminum sabot after it completely penetrated through the 28-mm thick Al-SiC hollow-sphere composite slab and into the backing Al to a depth of 20-mm. The rear (Al-side) surface of the composite shows some radial cracking and some material removed near the hole, but no evidence of the composite material (spheres or Al matrix) impacting the sabot material.

**Figure 6.** Images of recovered composite and sabot materials following reverse ballistic experiment at 660 m/s, showing clean penetration of the steel bullet through the Al-SiC composite, and the travel of the bullet into the backing sabot material.

Close observation of the recovered impacted sections revealed that there was practically no compression of the slab. The composite retained its original height of 27 mm in the central part that was unsupported by the aluminum sabot. The impact with the plastic target ring holding the bullet pressed the central section into the void space in the sabot while removing the material in the area supported by the sabot. The recovered Al-SiC hollow sphere composite was cross-sectioned to observe the penetration response more closely. A clean penetration of the composite was observed as illustrated in the cross-sections of samples in Figure 7. Further analysis of the cross-sectioned samples, along with computational calculations, are pending to get additional information on the penetration process and associated energy dissipation. Additional ballistics experiments are also planned.

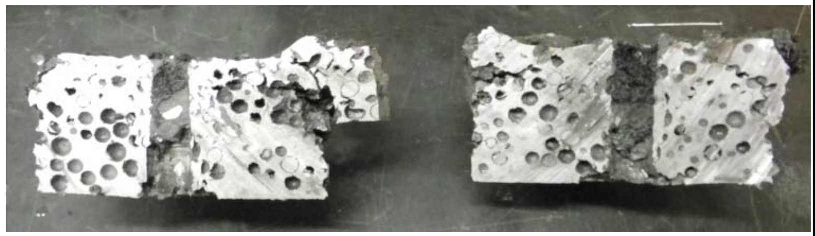

**Figure 7.** Cross-section of Al-SiC composite penetrated by the 7.62 mm steel bullet at 660 m/s.

An additional penetration test was performed on a 15mm thick Al-5083 sample containing SiC hollow spheres. This experiment was performed using a 7.62mm light gas gun with the bullet penetrating the aluminum target at approximately 364m/s. High speed camera was used to observe the material during impact, as shown in Figure 8. The bullet's axis is initially perpendicular to the sample face. *The results reveal an interesting trend notably that upon impact the trajectory of the bullet soon after penetration is altered. It is obvious that the presence of the SiC hollow spheres influences the bullet trajectory and reduces its efficiency for further penetration.*

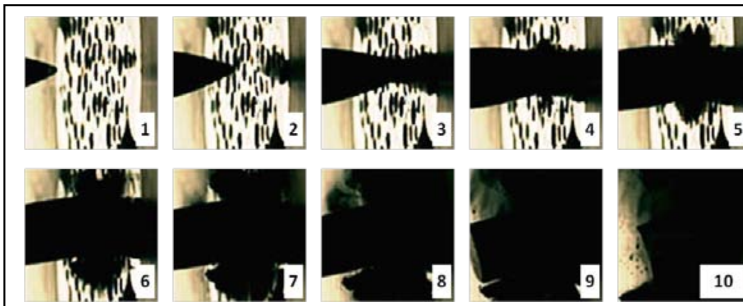


**Figure 8.** High speed images of a 0.30 caliber bullet impacting Al-5083 with SiC hollow spheres at 364m/s. The time lapse between each is 10µs.

After testing, the sample was recovered for examination via SEM. The aluminum target was unable to stop the bullet for the thickness chosen. The target failed by cracking radially outward from the bullet. Cracking occurred preferentially at the aluminum-SiC interface, implying that increasing the interfacial strength is of interest

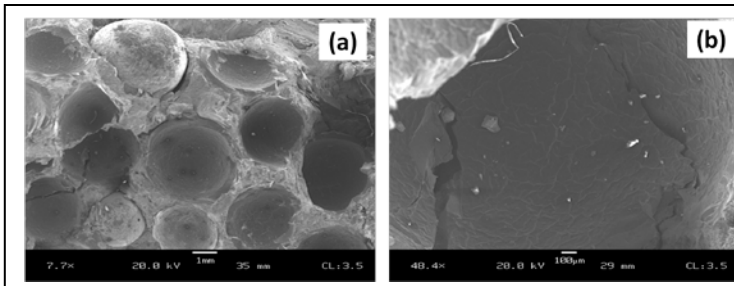


**Figure 9.** SEM images of the fracture surface of the hollow sphere composite sample. The sample fails due to interfacial cracking after penetration by a 0.30 caliber bullet.

for penetrating type impacts of this material. SEM images of the fracture surface of the recovered target are shown in Figure 9. The interfacial nature of the cracking is apparent from the spherical holes visible in the fracture surface where the SiC hollow spheres previously resided. In Figure 9(a), a SiC sphere remains intact on the fracture surface. Figure 9(b) is a higher magnification image of a large interfacial crack inside one of the holes.

## Impact testing of Composite of Al with SiC hollow spheres

Plate impact testing was performed on the composite sample of Al containing SiC hollow spheres provided by Deep Springs. Impact was performed with a 5mm thick Al-5083 plate at 416m/s using the 80mm light gas gun. The impacted composite sample was soft recovered after impact, and it was observed that the material remained intact. The material thickness decreased from 14.9mm to 11.3mm after testing. The sample rear surface had an approximately 3mm thick aluminum layer devoid of SiC spheres. This layer was of similar thickness after testing implying that the reduction in thickness of the composite sample was due to the densification response of the sphere impregnated layer.

The rear free surface velocity was measured via VISAR during impact. It is observed that the rear free surface velocity never reached the expected measured velocity of the projectile even after 25μs from the arrival of the first elastic wave. This result suggests that the composite target containing the SiC hollow spheres is serving as an effective target material for attenuating the shock waves from blast type impact events.

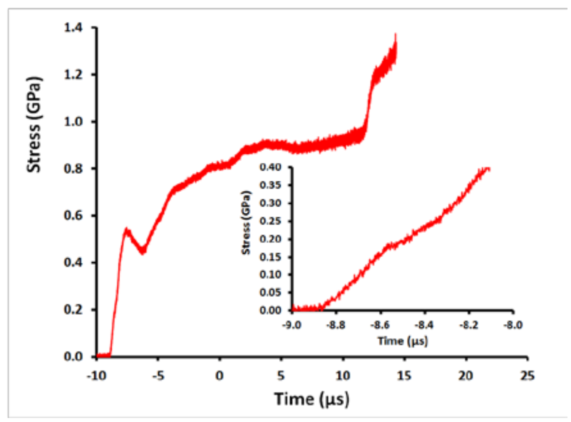


Fig. 10. Stress history of Al-5083 sample with SiC hollow spheres subjected to plate impact at 416m/s.

The velocity data was converted to a stress history diagram, and is plotted in Figure 10. The data shows several distinct features indicating the evolving shock compression and damage/failure mechanisms during impact. The inset in Figure 10 shows a possible HEL, indicating the onset of plastic flow in the matrix. The HEL value was measured to be 0.22GPa, which is of a similar magnitude to that seen previously for Al-5083 H116. After the initial HEL, the stress increases up to 0.55GPa followed by a sharp decrease. The stress then steadily rises up to approximately 0.90GPa, where it reaches a plateau. At approximately 11μs, the stress displays another sharp rise, after which the VISAR record loses resolution. The large increase in stress at long times is due to the air gap behind the flyer plate crushing and sending a secondary shock wave through the material. If a larger air gap were chosen, then this feature may not be present in the VISAR data. The stress states captured by the VISAR trace, such as the first peak or the plateau stress, can provide indication of the "crush-strength" or stress at which the composite reaches full density following the collapse of the SiC hollow spheres, as these reveal indications of the damage response of the material. Computation of the crush strength however, needs correlation with model simulations.

The impact event corresponding to the above experiment was simulated in order to ascertain the microstructural damage and failure mechanisms corresponding to the various the stress features. Simulations were performed using the CTH two dimensional multi-material Eulerian hydrocode. The representative microstructure used for simulation was created from an image of the provided aluminum-SiC sample, with all other materials and geometries kept similar to the actual impact experiment. The simulated material response is shown in Figure 11. It can be seen that the SiC spheres compress severely upon loading,

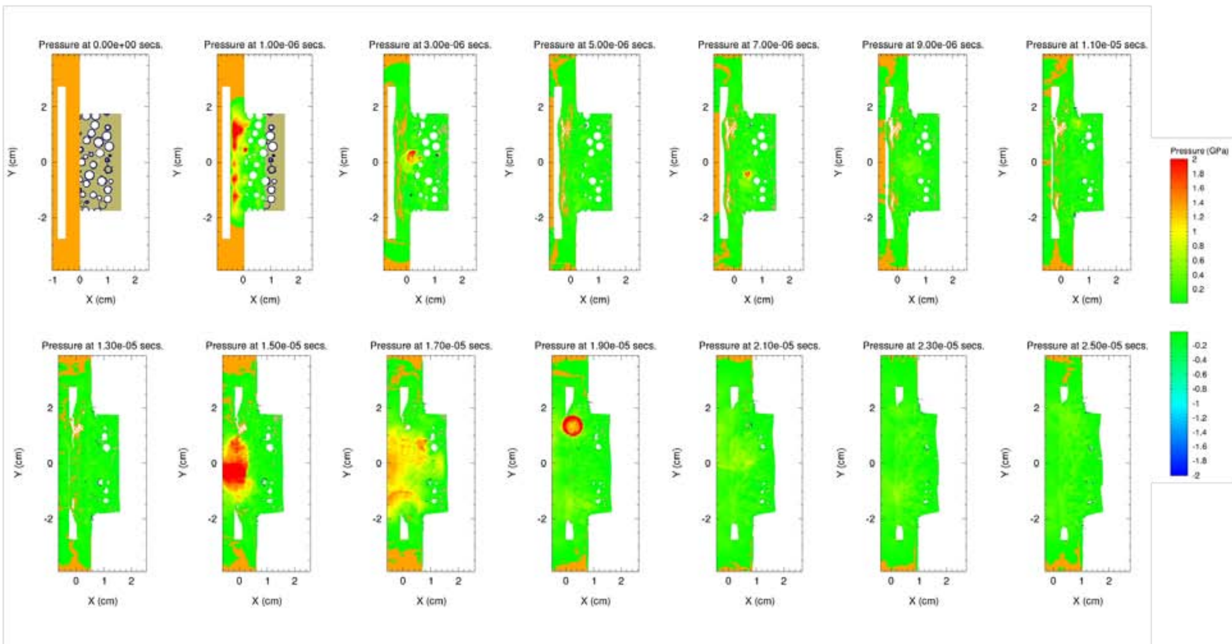

**Figure 11.** Simulated material response of Al-5083 sample with SiC hollow spheres subjected to plate impact at 416m/s. The change in pressure with time throughout the material is also shown.

at different states, until the composite reaches full density. The stress history corresponding to this type of compression response can be used to obtain information about the damage mechanism and overall shock-compression response of the composite. The simulated stress at the back surface of the sample is shown in Figure 12. The same stress features are present in Figure 12 as those that were observed in the VISAR data shown in Figure 10. It should be noted that the time scale in Figure 12 is shifted from that in Figure 10. The simulated HEL and the first sharp decrease in stress occur at approximately 0.1 and 0.4GPa respectively, as opposed to the 0.22 and 0.55GPa observed from VISAR results. Although the specific values from simulation are not

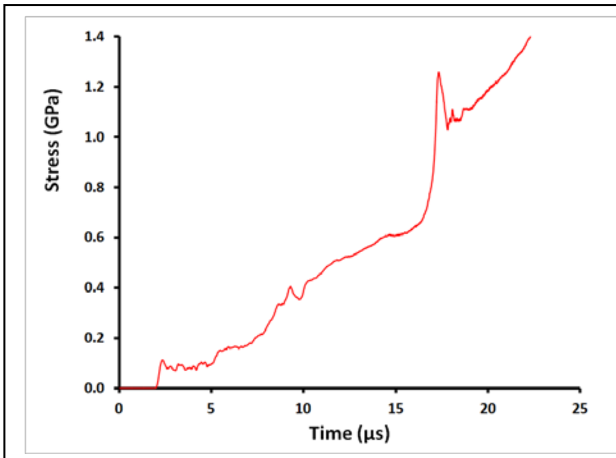


Fig. 12. Simulated stress history for a representative Al-5083 sample with SiC hollow spheres subjected to plate impact at 416m/s.

identical to those seen in experiment since they are a function of the constitutive properties considered, the presence of the features is indicative of the actual material response during impact loading. *This is an important result and can be used to compare different composite systems to determine the "crush-strength" not only as a function of the impact velocity, but also the composite microstructure, including the matrix composition and phase characteristics and the volume fraction of the SiC hollows spheres, their size, wall thickness, etc. The "crush-strength" in turn can be related to the shock and blast attenuation properties of the composite material.*