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Additive Manufacturing of Liners for Shaped Charges

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Abstract

A Shaped Charge (SC) is an explosive device used to focus a detonation in a desired direction, and has applications in demolition and oil extraction. The focusing relies on a void in the explosive mass, shaped by a metal liner that becomes a projectile during detonation. Additive Manufacturing (AM) allows greater design freedom and geometric complexity for the liner portion of the SC. Specifically, hierarchical structuring and functional grading can potentially provide greater velocity, directionality, and efficiency. In this work, Selective Laser Melting (SLM) is used to explore different geometries for an SC liner made out of SS 304L. These are detonated using the explosive Composition C-4 to evaluate performance metrics, depth and standoff, and are observed using high-speed imaging. The work shows the potential for advanced shaped charges produced using SLM.

1. Introduction

Shaped Charges (SC) have been used in various applications throughout the years including demolitions and oil well completion. The primary purpose of an SC is to penetrate barriers with a confined force. In the oil industry, the SC is used to penetrate the casing of the well and geological formations to increase oil flow. Charles Munroe brought hollow SC's into the mainstream through his work in the late 1800's where in one instance he was able to deform a steel plate in the shape of initials inscribed into a charge (explosive engraving). Munroe also found forming a conical cavity in a cylinder of explosive resulted in increased penetration into a steel target. This phenomenon became known as the Munroe effect. SC's with metal liners were later found to have increased performance over hollow liners. [1]

Birkhoff et al. demonstrated and discussed the theory behind SC's with conical liners used for penetrating and wedge liners for cutting materials. The explosive wave generated by detonation of the charge reaches the apex of the liner. This produces high pressures and leads to a collapse of the liner. The walls of the liner begin to collapse in the direction normal to their surfaces. The inner material of the liner then forms a jet and the exterior forms a metal slug traveling at high and low velocities, respectively. [2]

The shaped charge process is further discussed by Walters where it is stated that the spherical pressure waves generated by the explosion travel around 8 km/s and pressures near 200 GPa are reached during the process. Due to the extremely high pressures, the yield strength and ultimate strength of the liner material are negligible. The jet produced from the liner collapse then generates pressures around 100-200 GPa when it strikes a steel target. This produces a cavity in the target through displacement of the impacted material. The target material displacement is caused by the extremely high pressures. The cavity in the target is not primarily caused by a thermal process. [3]

Figure 1 is demonstration of the jet formation and target penetration for a Conical Shaped Charge (CSC) through simulation. In the simulation, the condition of the materials including C4 explosive, the metal CSC liner, and the steel target are determined as a function of time after detonation. The jet and slug formed from the liner as a result of the liner collapse are highlighted in Fig 1 (b). Figure 1 (c) shows the penetration of the jet into the steel target.

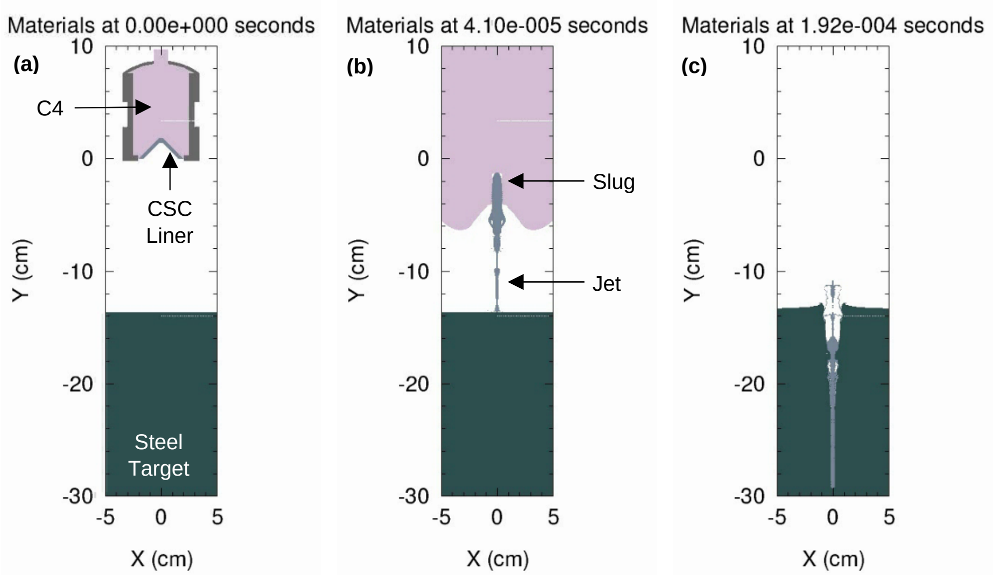

FIG 1: Simulation of CSC liner testing.

The performance of a shaped charge is increased through optimized liner design and distance away from the target. Vigil reported on the optimized design of liners for CSC's. The optimized design for CSC liners is a function of the diameter of the cone and is included as Fig. 2. Liners are traditionally manufactured using this design by forming uniform thickness sheets of copper or steel. Copper liners have the best performance when compared to other materials.

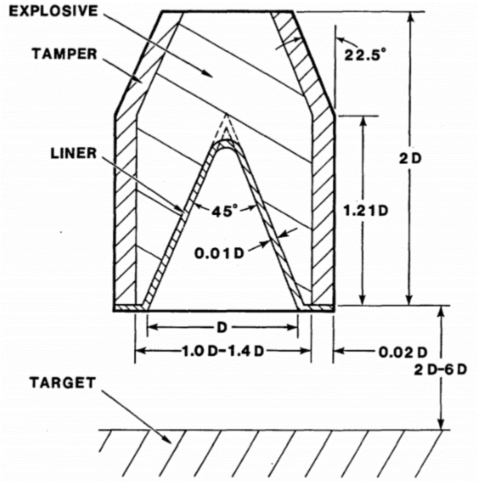

FIG 2: Optimized design of CSC liner [4].

It has been reported that liners manufactured with non-uniform thickness have the potential for increased performance. Efficient manufacturing for these liners is a challenge. Venghhiattis addressed this challenge in the 1960's by developing a process to press powder metal into liners with non-uniform wall thicknesses [5]. Additive Manufacturing [AM] is an ideal process that can be used to efficiently produce CSC liners with non-uniform wall thicknesses, or liners with more complex designs to increase performance beyond the traditionally formed copper liners. The goal of this paper is demonstrate the ability to additively manufacture CSC liners out of 304L stainless steel using the Selective Laser Melting (SLM) process. The hypothesis that anisotropy in the liners will affect performance is also tested.

2. Experimental Approach

The design of the CSC liners in this work was based on the optimized geometry [4] with modifications within the walls possible to manufacture with AM. The liners were manufactured using 304L stainless with a Renishaw AM250 SLM system. The SLM process parameters used during the manufacturing of the CSC liners were optimized for density. The modification to the CSC liner design included the addition of an internal honeycomb structure to alter the liner properties. Figure 3 (a) contains the CSC liner design showing the internal honeycomb structure through different slice views. An image of the completed build is included as Fig. 3 (b).

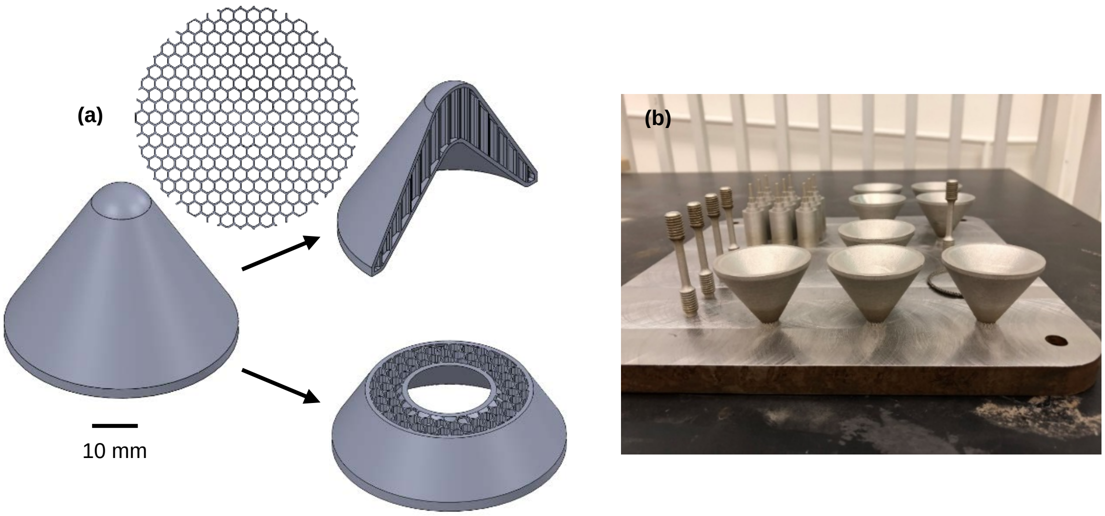

FIG 3: (a) CSC liner design for SLM manufacturing and (b) completed build.

The honeycomb structure was included in the interior of the CSC shell to alter the stiffness of the liner. It was hypothesized that changing the wall thickness of the honeycomb structure would lead to different stiffness for the CSC liners and affect the performance. Varying the wall thickness of the honeycomb also resulted in changes in liner mass. This occurred because the hollow areas of the honeycomb structure are not processed by the laser and retain the density of the trapped un-sintered 304L stainless steel powder. The laser melted areas of the honeycomb reach near full density of bulk 304L. The CSC liners were processed with keeping the center-to-center distance, d_0, of the honeycomb structures a constant 2.5 mm. The width of the hollow section of the honeycomb structures, d_1, was then varied. Figure 4 is the dependence of the CSC liner mass on the ratio of d_1 to d_0. The mass decreases with increasing d_1 from the extreme case of a completely solid liner (d_1 = 0 mm) to the case of a liner that is a hollow shell (d_1 = 2.5 mm).

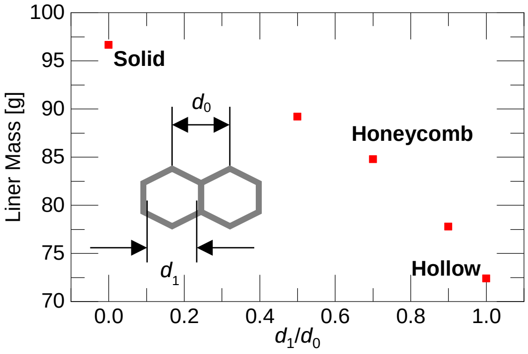

FIG 4: Dependence of CSC liner mass on honeycomb parameters.

The CSC liners were tested using the following procedure to observe the effects of the mass and stiffness on performance. The CSC was firm-pressed into the flat end of a PVC pipe cap, resulting in a tight seal. A PVC pipe was then fitted into the rounded bottom containing the CSC and sealed with rubber cement. Next 300 grams of C4 was massed and then tightly packed into the PVC pipe, covering up the CSC and filling up the tube. A rounded end of PVC pipe was rubber cemented around the open end of the PVC tube. A detonator was inserted into a 10 gram stinger and the stinger was inserted into the hole at the top of the PVC pipe cap. A stack of 6.35 mm thick steel plates were secured to an I-beam with F-clamps to ensure they remained together during detonation. The CSC assembly was then placed at a standoff distance of 0.257 meters from the top steel plate. High speed videos were recorded during testing to determine the velocity of the jet formed for each CSC. Figure 5 (a) is a schematic of the CSC test setup Fig. 5 (b) is an image of the experimental setup. The impact site produced by a CSC in one of the 6.35 mm thick steel plates during preliminary testing can be seen in Fig. 5 (c).

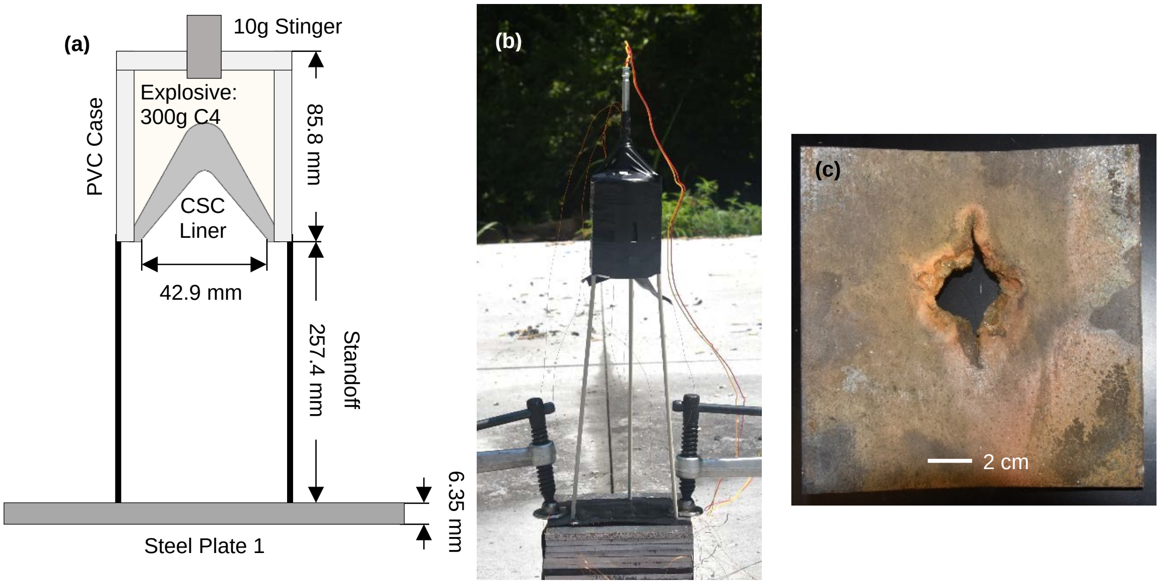

FIG 5: (a) Schematic and (b) image of the CSC test setup and (c) image of first plate impacted during trial run.

3. Results and Discussion

Performance of the CSC liners was characterized by the quantification of the jet velocity in air, the number of plates penetrated, and the number of plates deformed. Figure 6 contains selected frames from the high speed videos captured during testing with a Phantom V2012 camera. The data was collected using a frame rate of 110,000 Hz. The images in Fig. 6 were taken from the recordings of the tests with the hollow and solid liners at 27, 54, and 81 μs after detonation. In the recordings the metal jet generated due to the explosion is assumed to be at the bottom of the plume. With this assumption, it can be concluded that the jet for the hollow liner reached the target within 81 μs while the jet for the solid liner was still in air. This result was quantified through the calculation of the jet velocity in air for each of the five liners tested. The jet velocity was determined by dividing the known standoff distance from the CSC to the first target plate by the amount of time it took the bottom of the plume to reach the surface of the plate.

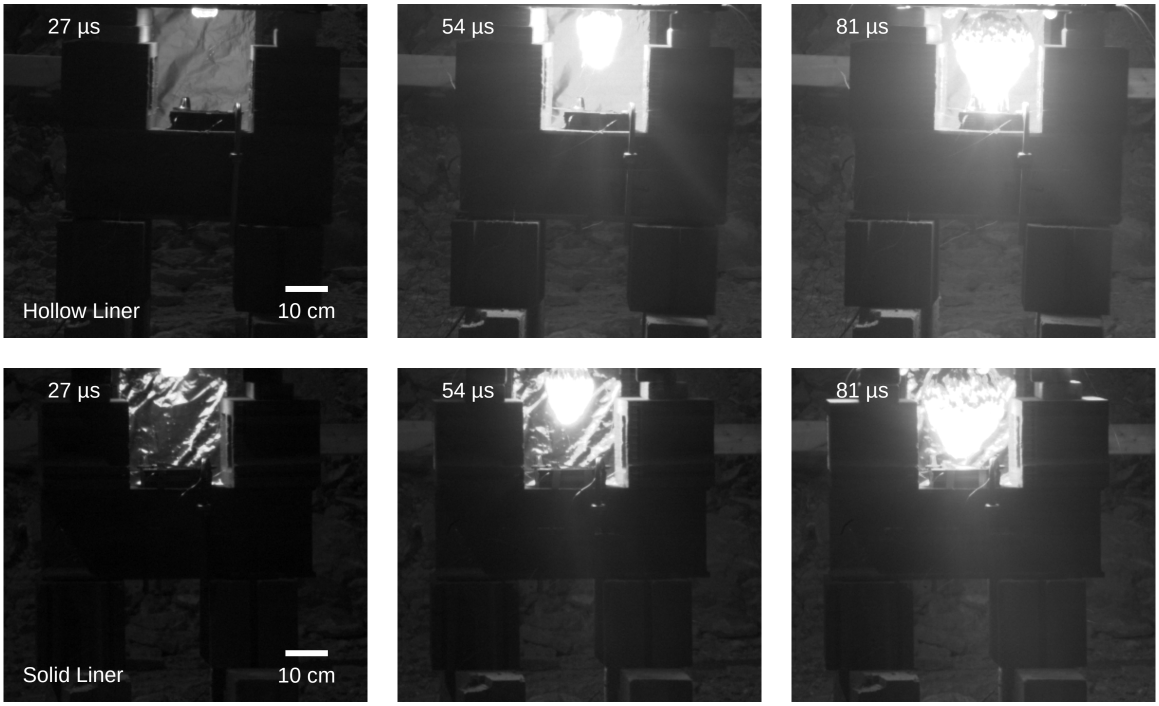

FIG 6: High speed images captured during testing of hollow and solid CSC liners.

The calculation results for jet velocity in air for each liner are plotted against the mass in Fig. 7. The jet velocities were determined to be on the order of kilometers per second. Figure 7 demonstrates that an increase in the CSC liner mass results in a decrease in jet velocity. The maximum jet velocity corresponds to the hollow CSC liner and the minimum jet velocity was generated using the solid liner. Assuming kinetic energy is a constant since the same amount of C4 was used in each test, a simple model for the jet velocity can be developed. In this model, the jet velocity in air is proportionate to the inverse square root of the liner mass. The jet velocities were fit to the model and the result is included in Fig. 7. The fitting results show the model deviates from the experimentally determined jet velocities. This suggests the velocity of the jet depended on more than the liner mass. A possible explanation to the deviation of experimental jet velocities from the model is the anisotropy in the liner stiffness resulting from the honeycomb structures.

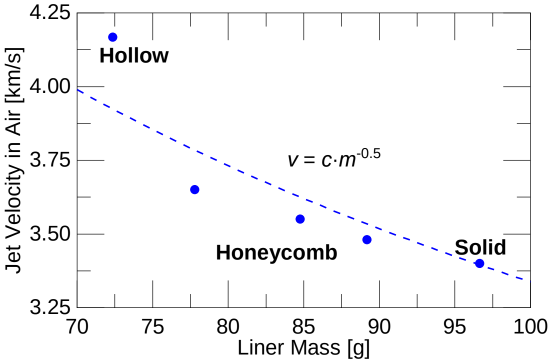

FIG 7: Jet velocity in air as a function of CSC liner mass.

The images in Fig. 8 are of the first two plates impacted during testing of the hollow, solid, and a representative honeycomb liner. The images for Plate 1 show each test resulted in a rough impact crater. The rough deformation of the impact zone for the first plate was most likely due to the metal slug formed at the rear of the jet and possibly some fragmentation of the CSC liner. The first plate catches the slug and fragmented pieces of the liner. This results in a much cleaner impact craters for the subsequent plates since the leading part of jet is the only penetrating element.

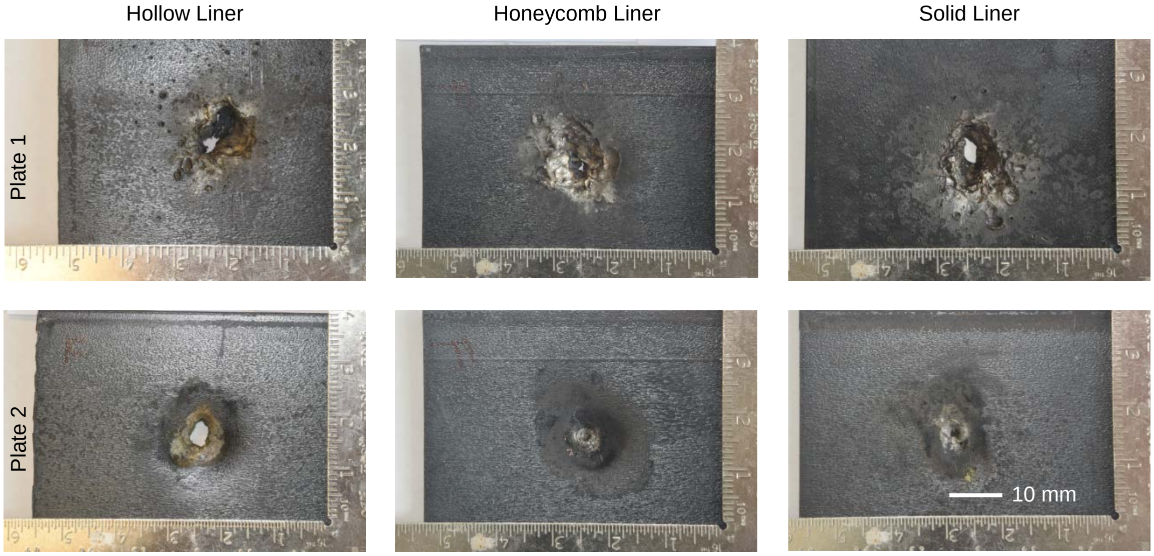

FIG 8: Images of impact craters for first two plates produced with hollow, honeycomb, and solid CSC liners.

Figure 8 also shows each liner penetrated the first plate while only the hollow liner was able to penetrate the second plate. All three liner types were able to deform the second plate. Figure 9 contains a simple quantification for number of plates penetrated and deformed for the five CSC liners plotted against their respective jet velocities. The lower jet velocities generated for the honeycomb structure and solid liners resulted in the penetration of the first plate. While these liners only penetrated the first plate, the deformation of the underlying plates differed. Jet velocities below 3.5 km/s deformed the first two plates. The velocities between 3.5 and 3.75 km/s deformed 3 plates. The highest jet velocity corresponding to the hollow liner penetrated 4 plates and deformed 5. An image of the 4 penetrated plates from the hollow liner test is included as Fig. 9 (c).

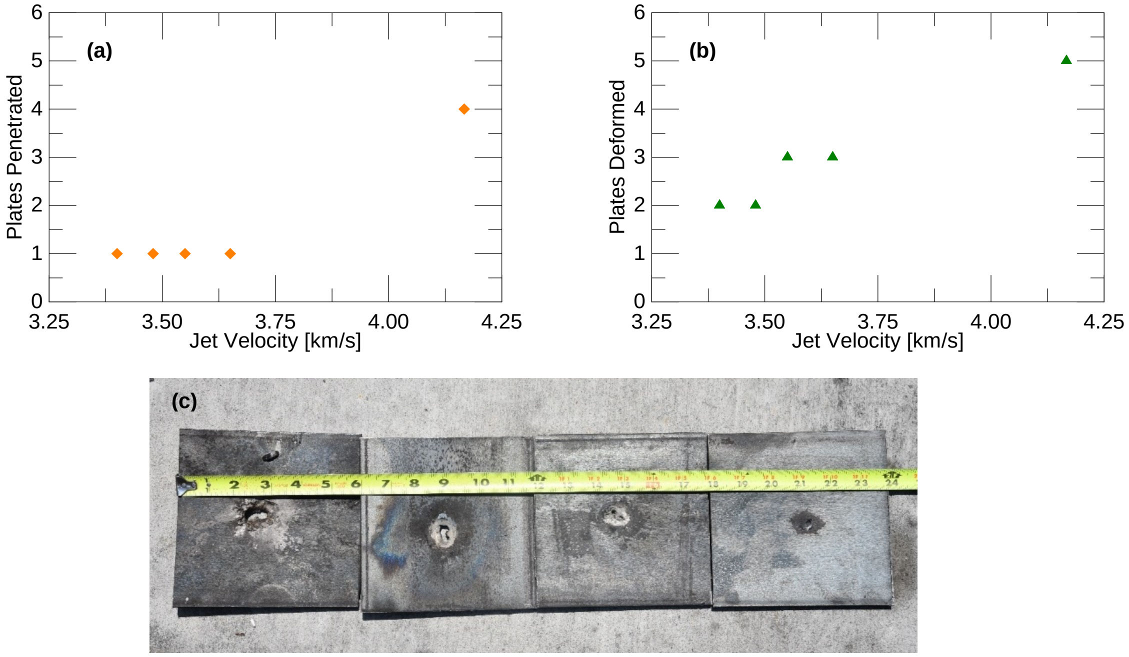

FIG 9: Number of plates (a) penetrated and (b) deformed as a function of jet velocity and (c) images of 4 plates penetrated by hollow CSC liner.

The results in Figs. 7-9 demonstrate the hollow liner performed the best out of the CSC’s tested in this paper. This result is a combination of several factors including liner mass, anisotropy of liner stiffness, and pressure wave propagation impedance mismatch. The liners with a larger mass underperformed. The larger mass lead to smaller jet velocities and resulted fewer plates penetrated. The anisotropy introduced into the liner stiffness also negatively affected the performance. The honeycomb structures most likely provided an increased resistance to collapsing during testing, which led to the lower jet velocities and penetration of a single plate. The primary factor explaining the differences in liner performance is the impedance mismatch during propagation of the pressure wave generated by the explosion through the CSC liner. In the CSC liners with the honeycomb structure, the impedance mismatch for the pressure wave at the interfaces of the near fully dense solidified borders and un-sintered voids resulted in energy loss. These losses were minimized for the hollow liner which only had two fully dense-powder metal interfaces contributing to the impendence mismatch. The solid liner should have even less impedance mismatch, but the mass and stiffness were the dominating factors leading to the decreased performance when compared to the results for the hollow liner.

4. Summary and Conclusions

In this paper Conical Shaped Charge liners were additively manufactured using SLM. The liner design included an internal honeycomb structure to create anisotropy in the stiffness of the CSC liners. The wall thickness of the honeycomb structure was varied to produce five unique liners with different masses. The varied mass of the CSC liners resulted in 0.8 km/s range in jet velocities. A jet velocity of 4.2 km/s generated during testing of the hollow liner resulted in the penetration of four 6.35 mm thick steel plates. The hollow liner preformed best out of the CSC’s tested in this paper. The honeycomb and solid liners preformed worse due to combinations of larger masses, the negative effects of the stiffness anisotropy, and higher impedance mismatch leading to energy loss during propagation of the pressure wave.

The preliminary results in this paper demonstrate the potential of using AM to manufacture CSC liners. The CSC liners were built using SLM with an off nominal material and were able to penetrate and deform steel plate targets. Future work will focus on hierarchically reducing the bending stiffness of CSC liners while increasing radial stiffness. This design will potentially lead to less resistance during the formation of the jet, which should increase the CSC performance. AM also allows the ability to tailor the material response locally by lowering yield stiffness with reduced laser energy density through process parameters adjustments. The reduced restrictions for design along with the advanced manufacturing capability in AM allow the opportunity to tailor liners for peak performance using methods difficult to implement with traditional manufacturing.

5. References

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