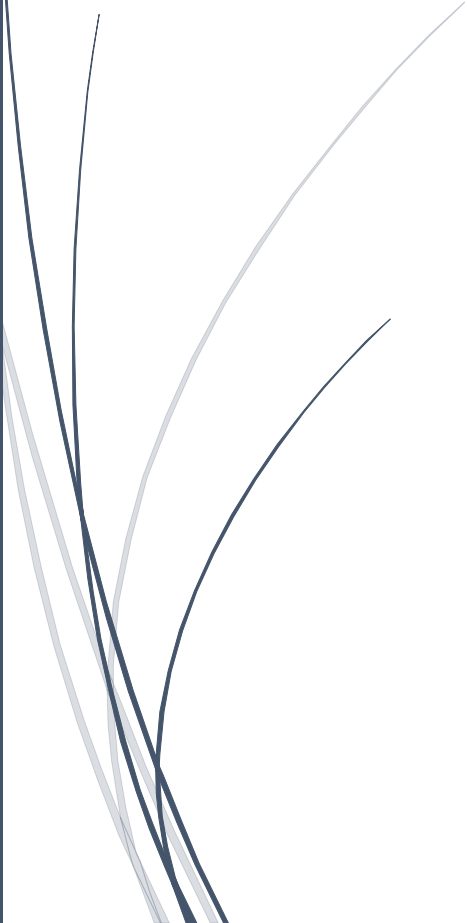


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1/10/2022

Modelling of Shaped Charges

Additive Manufactured Liners

Several thin, curved lines in dark blue and light grey originate from the bottom left and curve upwards and to the right.

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Abstract

This report investigates the suitability of manufacturing shaped charge liners using additive manufacturing techniques. The mechanical properties of an electron beam melted titanium alloy (Ti-6Al-4V) were applied to a shape charge liner in Abaqus and was compared against a copper shape charge liner.

It was found that the Titanium Alloy achieved greater velocities and compressive stresses than the shape charge models with copper liners. Indicating that the mechanical properties of Ti-6Al-4V could be used for shape charge liners and that EBM could be used to manufacture these components.

However, this report does not investigate the effectiveness of Ti-6Al-4V against a target. Therefore, further research would be to simulate a model using an Lagrangian – Eulerian shape charge model with a Ti-6Al-4V liner penetrating a steel target and comparing this against a copper liner.

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Introduction

Shaped Charges

Shaped Charges (SC) are explosive devices which utilise the Munroe effect to concentrate energy to a singular point to penetrate materials [1]. They have been used in various fields from Military use (Land – Air – Sea domains), to Civil Demolitions, and mining uses.

SC (Figure No.1) work by using a hollow point which cause the gaseous products from the explosive material to focus the energy of the detonation products [1]. This creates an intense localized force which can then penetrate materials.

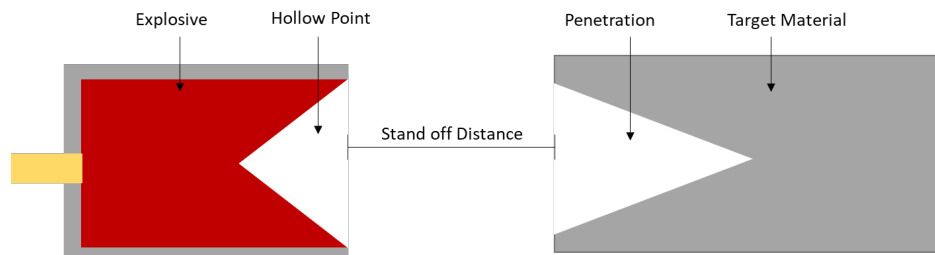


Figure No.1 – Shaped Charge without Liner

The penetration of the SC can be improved by using a thin layer of material (metal, plastic, ceramic) [2] to create a liner which fits intimately with the mould of the explosive material (Figure No.2).

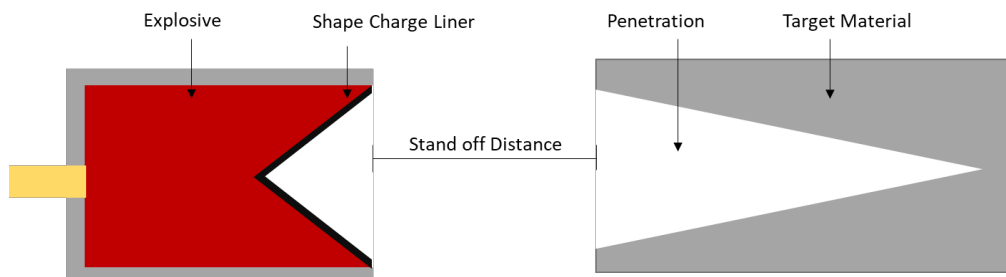


Figure No.2 – Shape Charge with Liner and deeper penetration depth

As the detonation propagates, the liner is accelerated under high detonation pressure creating an inviscid incompressible fluid creating two parts: the jet and the slug (Figure No.3).

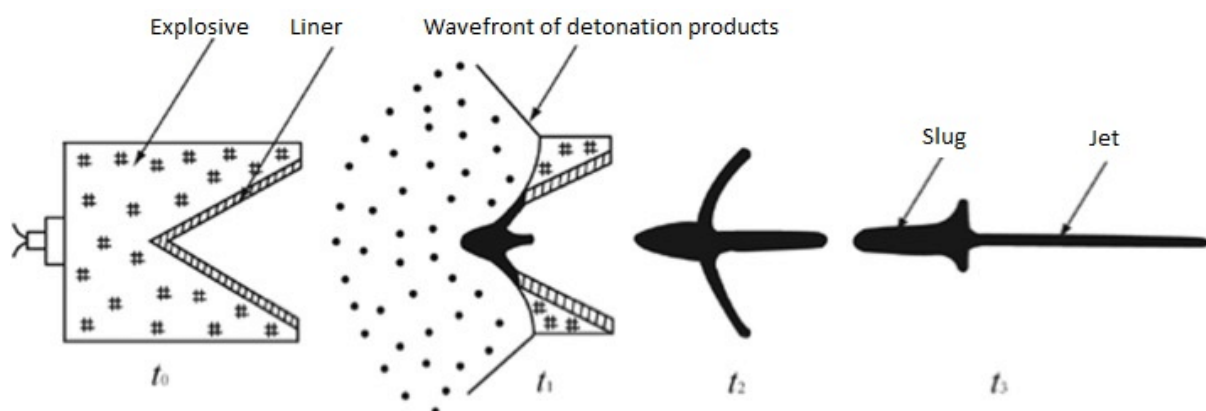


Figure No.3 – Slug and Jet formation from a shape charge [3]

The impact creates peak pressures in target plates of 100-200Gpa, with strain rates of 10^6 and 10^9 . [1] This is because the jet is displacing material from the plate rather than burning, melting the target material. It should be noted when weighing target metal plates, it was found that the weight remained constant even after penetration. Additionally, the depth of penetration at high velocities depended on the density of the liner and material instead of the target material strength (Equation No.1). [2]

$$P = L * \sqrt{\lambda * \frac{\rho_{liner}}{\rho_{target}}}$$

Equation No.1 – Penetration of target material [2]

The penetration of the SC can be affected by a variety of liner design factors both planned and unplanned. Such design features are different geometries (Figure No.4) or different materials or combination of materials (Bi-metallic Uni-metallic) for their properties, and even magnetism. However, the accurate manufacture of liners is faced with many issues such as grain growth, tolerance of wall thickness, apex angle and cylindricalness. [4]

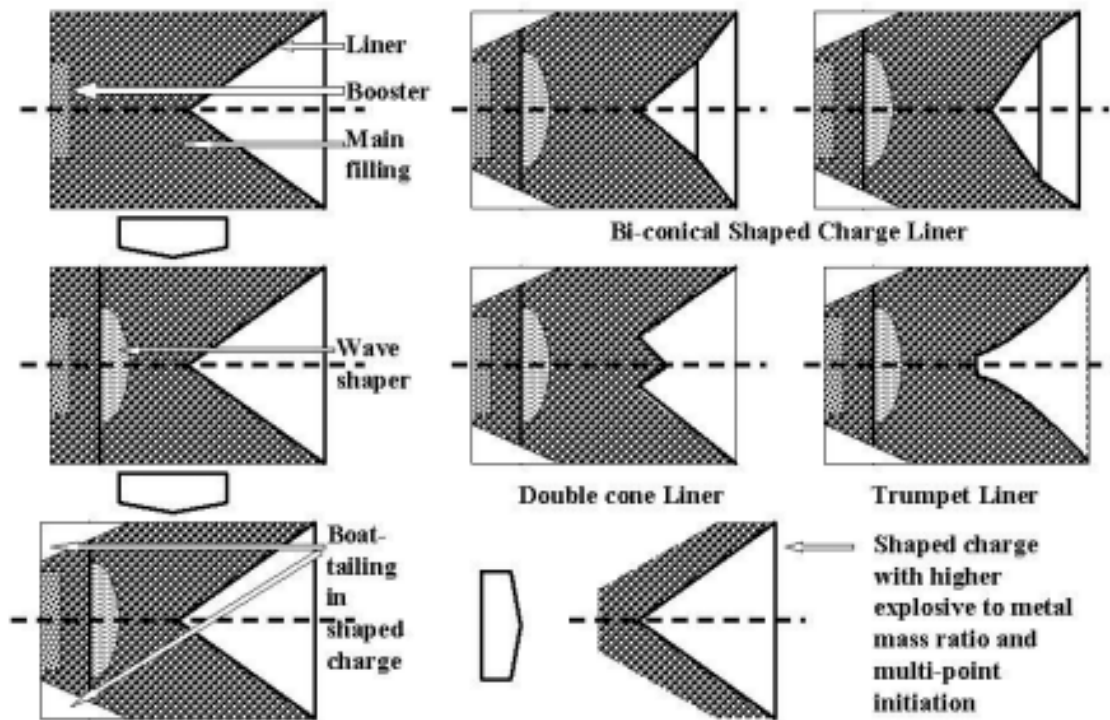


Figure No.4 – Various Shaped Charge Geometries [5]

Additive Manufacturing

Additive manufacturing is the technique of manufacturing polymer components (CAD Designed) layer by layer, by **adding** material by the micrometres. For metallic materials and alloys there are several techniques that have been developed for rapid prototyping and production. These are Laser Beam Melting (LBM), Election Beam Melting (EBM), and Laser Metal Deposition. [6]

These different methods operate on the idea of the manufacturing process depositing a single layer of the component and melt the local area with a heat source.

Advantages of additive manufacturing:

- Manufacturing of complex designs
- Low Production cycle Time
- No tools required
- Reduce manufacturing process
- Light Weight Components (Designed honeycomb to add porosity)

Disadvantages of additive manufacturing:

- Porosities within the material – Lack of Density
- Parts are anisotropic – Different UTS in each axis
- Limited to size of 3D printer

Table No.1 – Advantages and Disadvantages of Additive Manufacturing [6]

For this report EBM has been selected for further review. This is because EBM the capabilities to 3D print metal alloys such as titanium (Specifically Ti-6Al-4V). This grade has been used in medical prosthetics and other components, therefore allowing access to reasonable tested mechanical properties to be used for this study.

Topic of Interest:

With the rise and development of EBM, this has made titanium alloys more readily available and cost-effective compared against machining [6]. EBM could then be used to manufacture Titanium Alloy liners, for shaped charges. This should then allow greater potential penetration at greater stand off-distances when compared to copper. [2]

Therefore, to determine the suitability of an EBM manufactured liner for a shape charge, an Abaqus model will be used to determine: if a Titanium (Ti-6Al-4V) alloy with mechanical properties from an EBM process will perform better or similar to that of a copper liner to determine if the mechanical properties of an EBM Titanium liners can be used in shaped charges.

Method

For the modelling three models were used with one aspect changed in each model. These are:

- A Copper Liner with TNT Fill
- Copper Liner with Composition B Fill
- Titanium Liner with Composition B Fill

For the research a different energetic fill was desired to be able to gather independent Equation of State (EOS) and Jones-Wilkins-Lee (JWL) figures for Abaqus. However, to ensure only one variable was being affected at a time, a Copper Liner with a TNT fill, and a Copper Liner Comp B fill was modelled. This was to establish a baseline which could then be compared against previous results to determine how changing the energetic material would affect the later models.

This was then to help understand where each value originated to ensure repeatability of the experiment / modelling.

Model Solver – Comparison of Lagrangian and Eulerian

Lagrangian

Method: Lagrangian defines each material particle within a mesh type. As the material moves and becomes distorted the mesh moves with the material particles. The materials within each node, do not pass and remain within their mesh point, and therefore are not transported.

Advantages:

Only the material present requires meshing as there is no free space for material to be transported around the area. Can achieve results comparatively faster; However, may not be an accurate representation.

Disadvantages: Highly distorted mesh points either need to be eroded or rezoning. However, this is not a physical representation as mass and energy is lost. This results in less accuracy of a true model.

Eulerian

Method: Eulerian defines a fix grid (mesh) throughout and around the materials. During analysis the materials flow freely through the mesh, allowing accurate analysis of fluid flow and deformation. At each node if materials mix then mass ratios are used, as border of materials are not used.

Advantages:

This method will provide more accurate results with distortion as energy and mass is not erode or rezoned. Accurate analysis of fluid flow and deformation

Disadvantages: Less efficient as the area around the material require meshing, leading to longer computational times. Computational time will also increase with materials mixing within a grid zone.

Table No.2 – Advantages and Disadvantages of different modelling approaches [7] [8]

For the models Lagrangian solving was used. This was because the IT was shared and could not be left to solve for long periods. However, this did lead to trial-and-error testing as major distortion crashed the program. However, from the results a high level of precision was not required as this report investigates if the idea of additive manufactures liners is feasible, not how effective.

Mesh Size

A coarse mesh was applied to the Liner of 0.004. This was done to reduce computational time, while also achieving accurate results.

If a too fine a mesh was applied to the liner, the explosive loading would result in longer times and potentially lead to run-time errors were distortion were too high. However, by reducing the chances of too high distortion this would reduce the loss of data from rezoning and erosion. Although, this would then reduce the quality of the model and reduce how true a representation would be.

Mechanical Properties of Copper and Titanium Liners

Below are the mechanical properties for the copper liner and Titanium liner used within the model.

	Density (Kg/m ³)	Youngs Modulus (GPa)	Poisson's Ratio	Tensile Stress (MPa)	Ultimate Tensile Stress (MPa)	Plastic Strain
Copper	8960	110	0.364	34000000 (Pa)	210	0.6
Titanium Ti-6Al-4V	4430	115	0.35	1150	1120	0.25

Table. No 1- Material Properties for Copper and Titanium Ti-6Al-4V [9] [10] [11]

Explosive Properties of TNT and Composition B

Below are the Explosive Properties of TNT and Composition B used within the models.

	Density (Kg/m ³)	Detonation Wave Speed M/s	A (GPa)	B MPa	Omega	R1	R2	Det Energy Density (J / ρ)	Pre detonation Bulk Mod	Dynamic Viscosity
TNT	1630	6930	373800 (Pa)	3747 (Pa)	0.35	4.15	0.9	3680000	0	10
Comp B	1717	7980	524.2	7.768	0.34	4.15	1.1	5020000	0	10

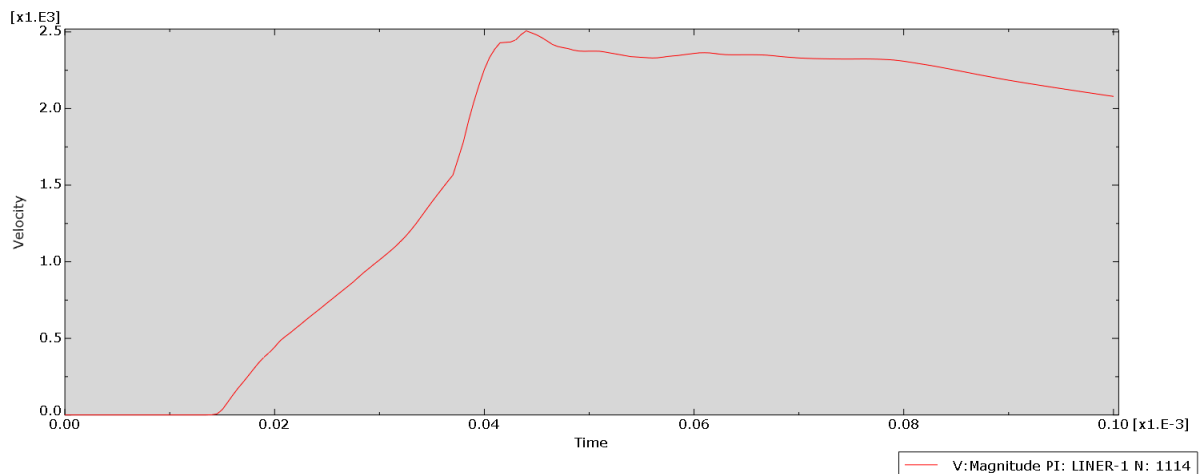
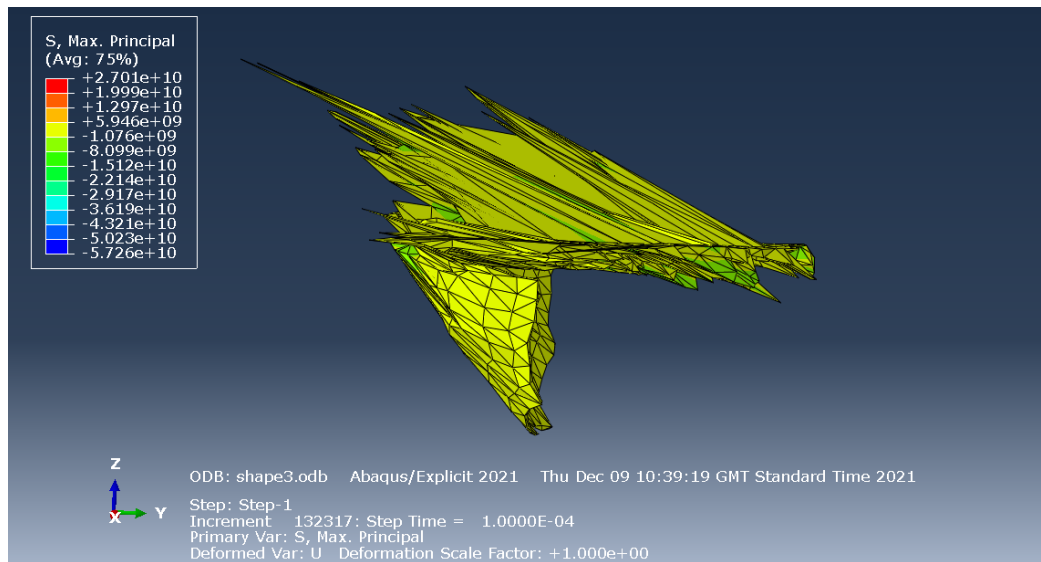
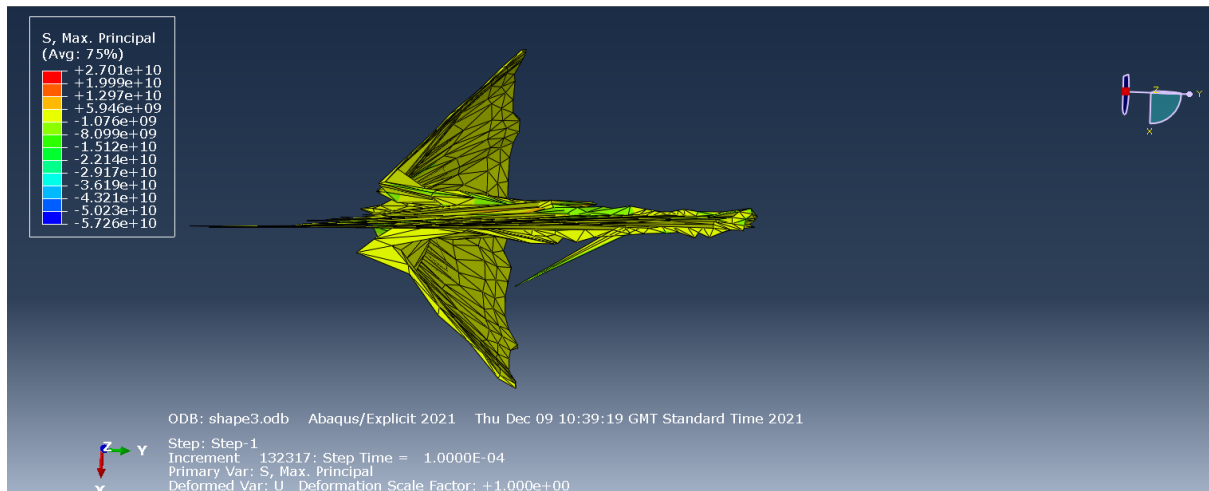
Table No.2 – Equation of State properties for TNT and Composition B [12]

Dependant Variable

The result and pictures collected from the Analysis were:

- Jet Liner Velocity – This was done by taking the furthest point of the Jet and plotting against the magnitude Velocity.
- Jet Liner Stresses – Using Max Principles this was used to determine the explosive loading on the liner.
- Jet Liner Distance - This was done by measuring the furthest point of the jet, to measure the greatest displacement achieved.
- Jet Liner Formation – These were done to compare the formation of the liner to determine if it creates the jet and slug formation.

Results



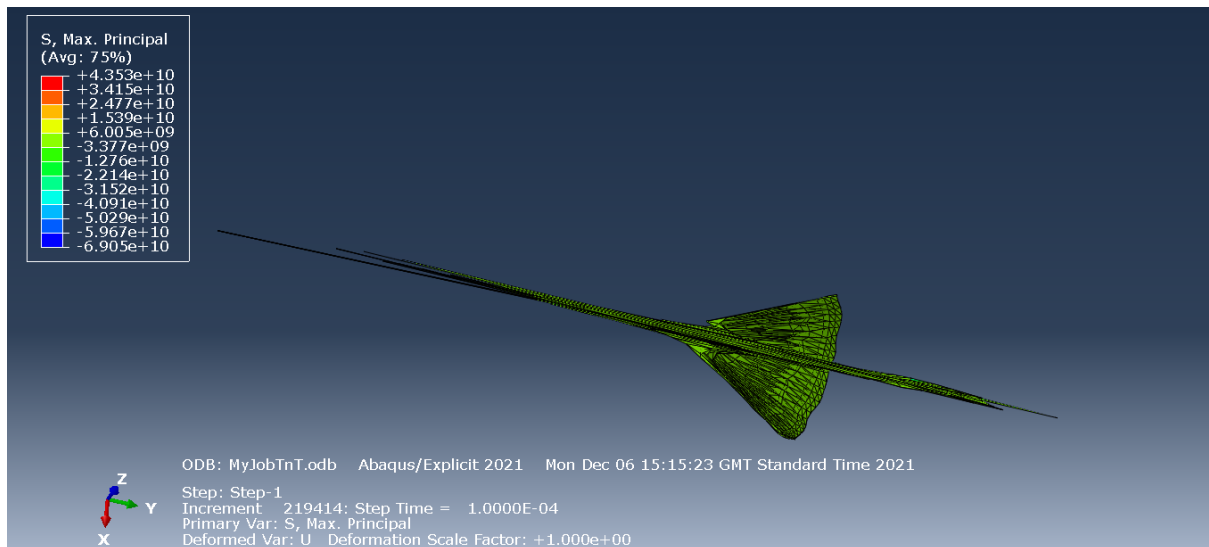


Figure No.8 Copper Liner with Composition B Fill

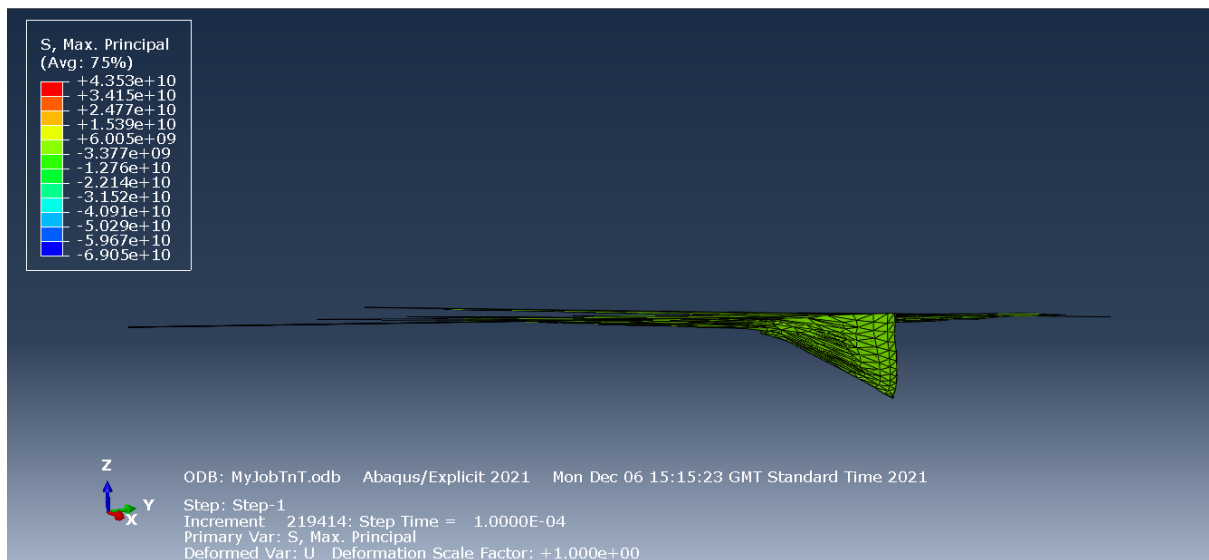


Figure No.9 Copper Liner with Composition B Fill

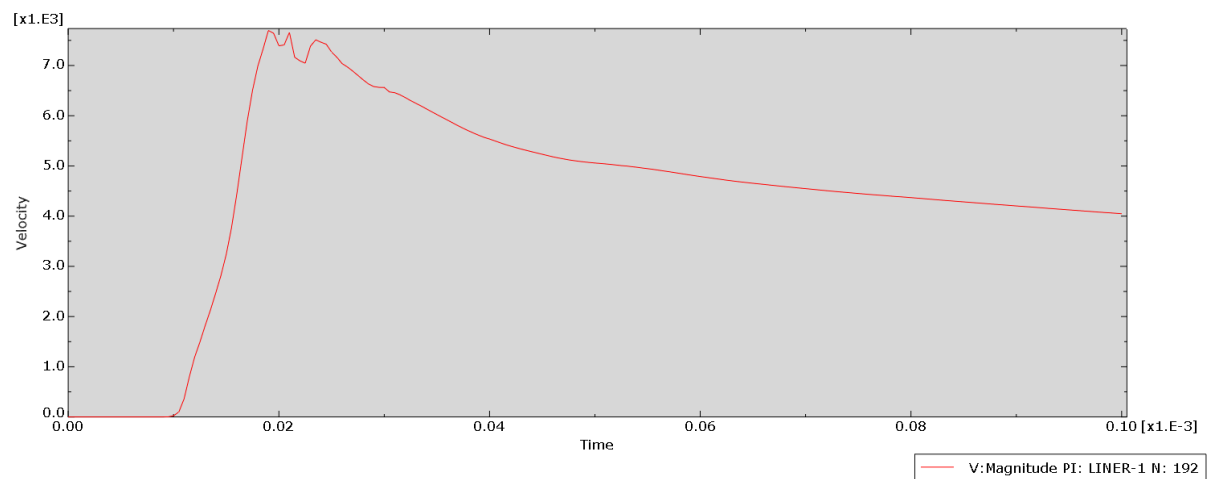


Figure No.10 – Copper Liner Velocity with Composition B Fill

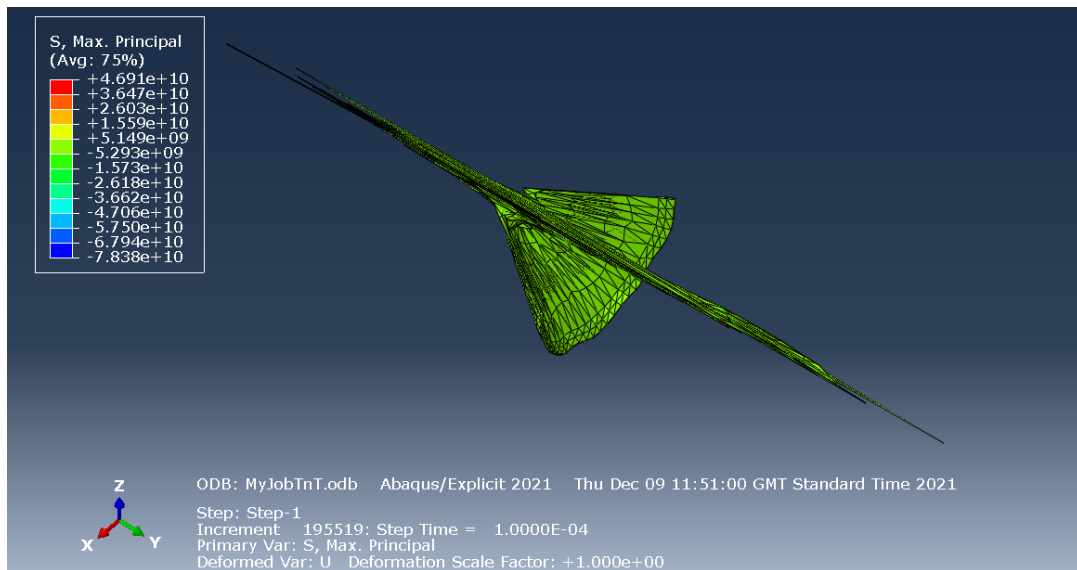


Figure No.11 – Titanium Liner with Composition B Fill

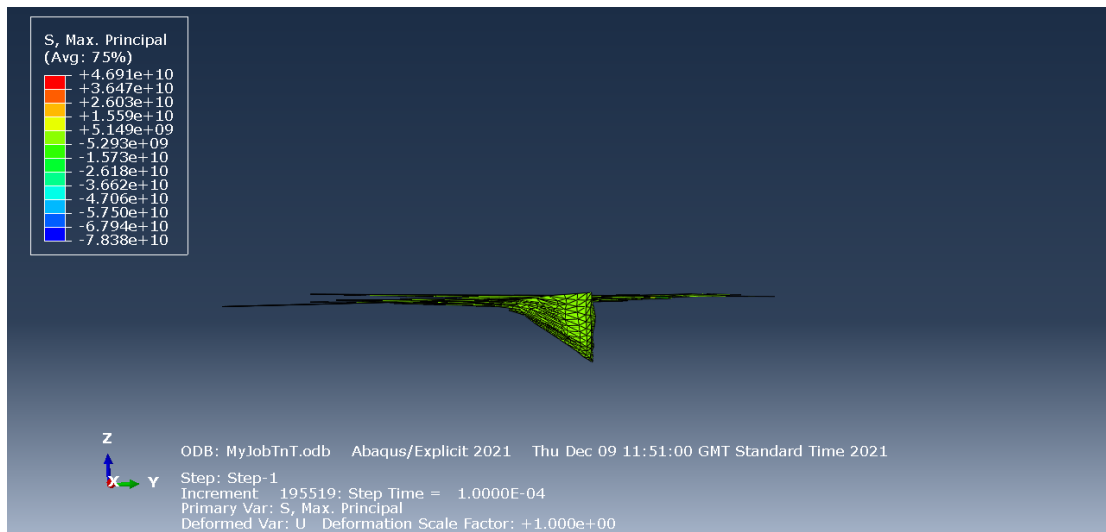


Figure No.12 – Titanium Liner with Composition B Fill

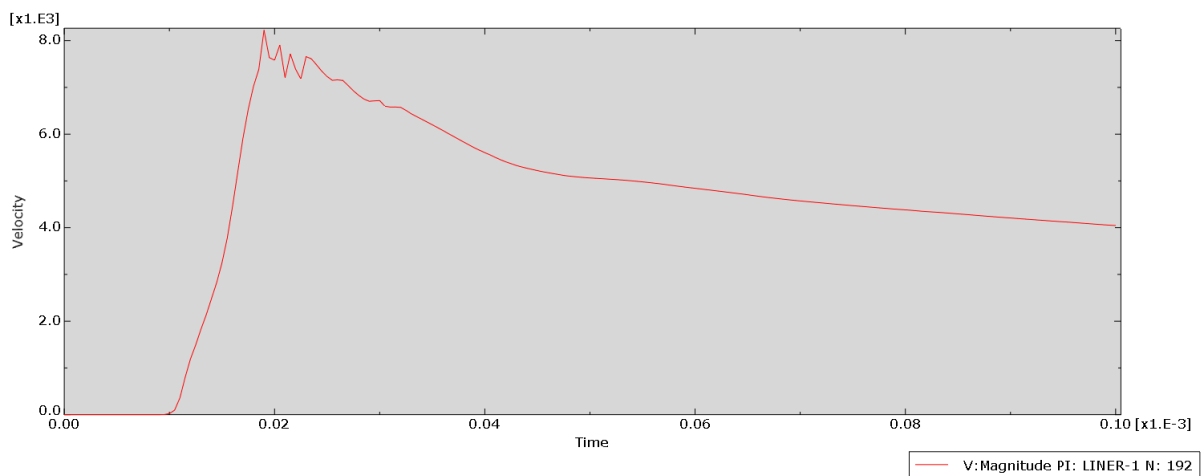


Figure No.13 – Titanium Liner Velocity with Composition B Fill

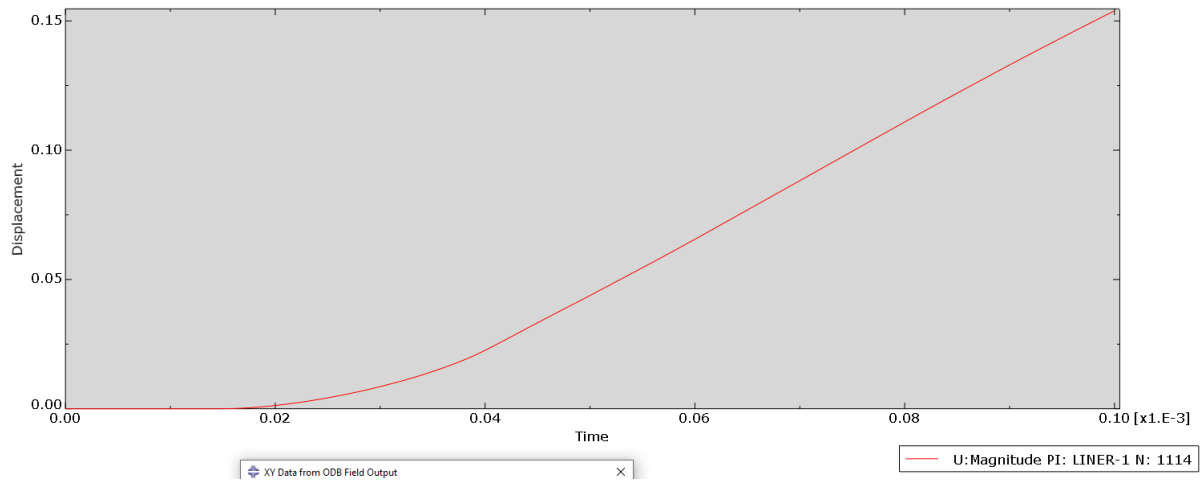


Figure No.14 – Largest Displacement Measured for Model 1 (Copper with TNT Fill)

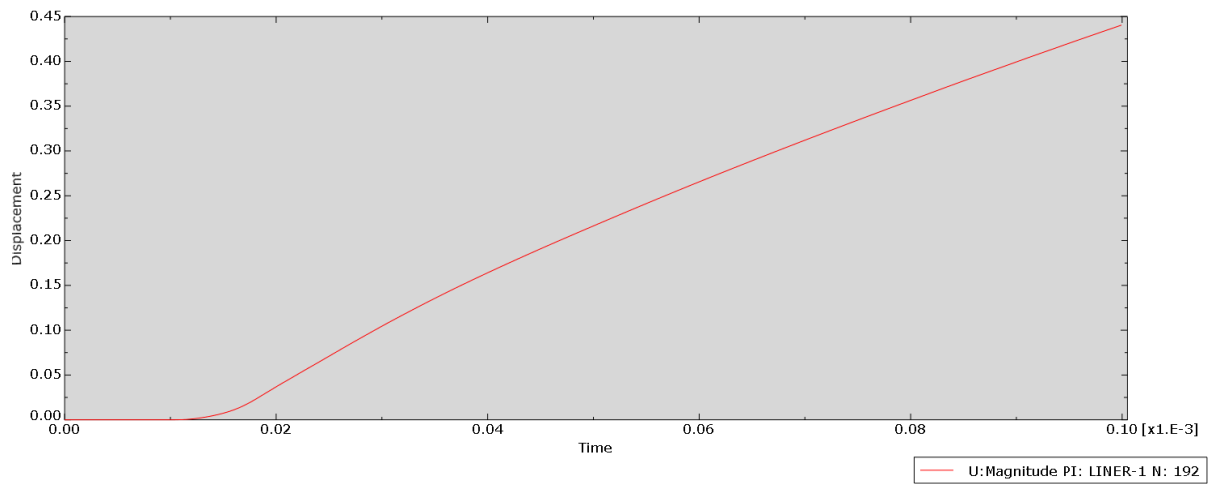


Figure No.15 – Largest Displacement Measured for Model 2 (Copper with Comp B Fill)

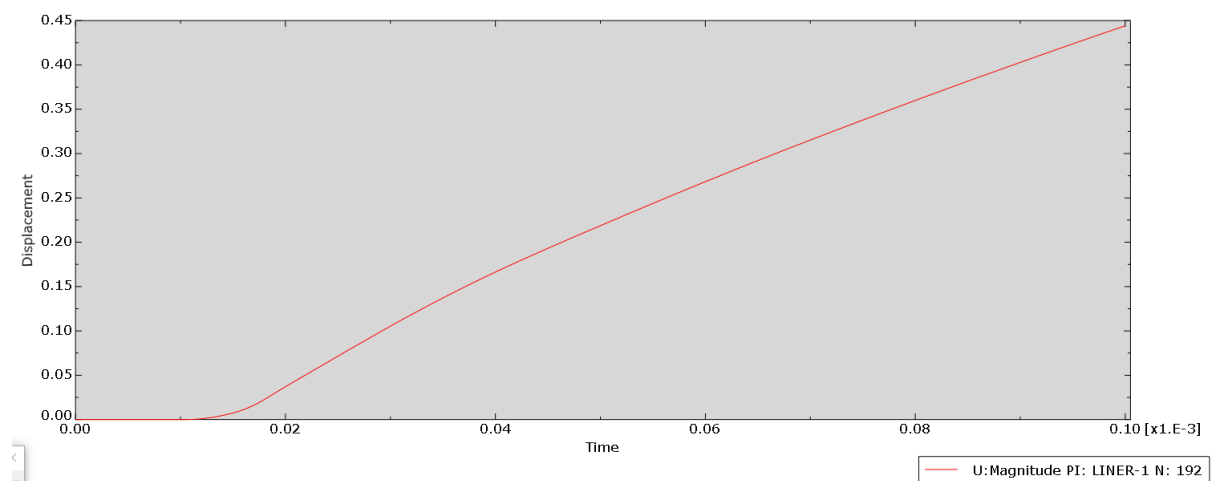


Figure No.16 – Largest Displacement Measured for Model 3 (Titanium with Comp B Fill)

Discussion

Copper Liner with TNT Fill – Model 1 Analysis

Copper with a TNT fill achieved a jet velocity of 2.5km/s with a slow acceleration (When compared to Model 2 and 3) over roughly 0.02ms. Additionally, the liner itself showed signs of compressive stress and tensile stress within the range of +5.946 GPa and - 8.099 GPa. The liner itself did not form into the desirable Slug and Jet formation. The largest displacement measured was 0.15m.

Copper Liner with Composition B Fill – Model 2 Analysis

Copper with a Composition B fill achieved greater velocities 7.5Km/s, and greater acceleration reaching its peak within 0.01ms. Roughly half the time when compared to TNT. The liner only showed compressive stress within the region of -3.377 GPa and - 12.76 GPa, with no indication of Tensile Stress within the model. The copper model had greatly improved, showing signs of a Slug and Jet formation. The largest displacement measured was 0.45m, roughly three times greater than the previous model.

Titanium Liner with Composition B Fill – Model 3 Analysis

Titanium with a Composition B fill achieved the greatest velocity out of the models, reaching slightly above 8Km/s, with a similar acceleration profile to copper with comp B fill. The liner only showed compressive stress within the region of -5.293 GPa and - 15.73GPa, which are greater compressive forces when compared to Copper with Comp B fill. Similarly, to the previous model, Titanium with Comp B produced a Slug and Jet formation. However, the largest displacement measured was also 0.45m. This is most likely due to the time step, and both model 2 and model 3 having similar velocities.

	Jet Velocity Km/s	Jet Displacement m	Stress Region
Model 1 – Copper Liner, TNT Fill	2.5	0.15	+5.946 GPa -8.099 GPa
Model 2 – Copper Liner, Comp B Fill	7.5	0.45	- 3.377GPa - 12.76 GPa
Model 3 – Titanium Liner, Comp B Fill	8	0.45	-5.293 GPa -15.73 GPa

Table No.3 – Summary of Results

Liner Velocities and Formation

From analysing the models with composition B fills, both had improved shape charge models (forming a better Slug and Jet) and had greater liner velocities when compared to the model with TNT fill. This could be because of better units gathered for Composition B. This would then result in a more accurate model when compared to TNT. For example, both Alpha and Bravo for composition B are 10^3 - 10^6 larger than their TNT counterparts. This could highlight that TNT is not being accurately represented in the first model provided as Composition B is part TNT.

Additionally, as Composition B is more powerful than TNT, this could result in composition B having the explosive loading power required to activate the shape charge. Composition B has

a greater detonation wave speed and detonation energy density than TNT. Therefore, within the model it would be expected that Composition B would improve the Liner Velocity.

However, by increasing power this did not just improve the jet velocity. Instead, by increasing the explosive power this created a better Slug and Jet formation and removed any Tensile Stress. This removed any distortion across the cross-cut section and created a cleaner longer jet. One theory is this is because the TNT fill was not powerful enough to fully apply enough explosive load to turn the liner into an inviscid incompressible fluid. Leaving some parts in Tensile stress and leading to heavy distortion, or areas in large compressive stress and others in large tensile stress.

It should be noted that the Titanium liner experienced more compressive stress than copper, even though both models had a composition B charge and therefore be subject to the same amount of energy. This could be because, when a liner is an incompressible fluid the strength of the material does not affect penetration however density does [2].

$$P = L * \sqrt{\lambda * \frac{\rho_{liner}}{\rho_{target}}}$$

Equation No.1 – Penetration of target material [2]

Therefore, because Titanium has a lower density than copper this could be a result of higher compressive loading. However, this is unlikely since Titanium has a higher ultimate strength and would therefore be more resistant to the explosive force before failing.

Suitability of EBM Titanium Liners

From the results the Titanium Liner with Composition B Fill had the greatest liner velocity and compressive stress. This indicates that Titanium manufactured by EBM could potentially be used in shaped charges consisting of a composition B fill as its performance is like that of model 2.

However, this model does not show how effective a Titanium liner would be. This is because it does not factor in deficiencies within the material, neither does the software consider how the material is anisotropic. [13] Therefore, the values provided to the software considered the UTS and TS is the same for the X, and Y axis. This would then affect the overall results.

Although, the time required to then find a method to input and find this data into Abaqus could result in longer computational times and research time. While there would be different values for alternative axis, the model itself does not fully represent the physical action. Therefore, to improve the model by taking an average of the three properties in each direction this could then improve the model.

However, it would be argued this does not change the model drastically and therefore is expected to not have a great effect. Therefore, the time spent on this model using Lagrangian method and the results that this model indicates that Titanium manufactured by EBM could potentially be used in shaped charges consisting of a composition B fill.

Future Research

If there were more time and resources, then a Lagrangian – Eulerian model would be used to model a titanium shape charge with Comp B fill to penetrate a steel target (Similar method to *“Modelling and Simulation of Shape Charges”* [7]).

The Eulerian model would allow better results for the deformation and fluid flow of the slug and jet. While the Lagrangian model would allow accurate and quick calculations of the interaction between the jet penetrating the steel target. This is because, materials cannot flow through a Lagrangian mesh and would therefore show how the materials would interact upon penetration while reducing calculation time.

This method would then possibly highlight how effective a Titanium liner would be and could be compared to a Copper Liner with Comp B fill. Additionally, it would save time and money by avoiding a live experiment, and highlighting if Titanium would be an effective penetrator. This is because concern should be given due to its lower density which could result in less penetration, according to Equation No.1.

Conclusion

- By replacing the explosive fill of the shape charge to composition B with values (EOS & JWL) that better represented the physical properties of the explosive, this improved the overall model performance. It resulted in greater jet velocities and better formation of a slug and jet. This is most likely due to the explosive loading of the explosive. With the values for Comp B being almost a thousand times greater for alpha and bravo.
- The alloy Ti-6Al-4V as a shape charge liner showed good jet velocities (8Km/s) and good Slug and Jet formation with a composition B fill. This indicates that the mechanical properties of an EDM Titanium liner could be used within a shape charge. Providing it can be manufactured to the desired tolerances for testing in a shaped charge. However, this model does not detail how effective Ti-6Al-4V would be against a target material.
- Finally further research would be to do a comparative analysis of a Ti-6Al-4v liner, and a copper liner penetrating a target. Using Lagrangian – Eulerian modelling to determine the effectiveness of a Ti-6Al-4V liner as a penetrator.

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