

OME PHYSICS

Ballistic impact analysis of aluminium 5083.

ABSTRACT

A Finite Element Analysis was undertaken using Simulia Abaqus to analyse the stresses induced by an aluminium plate under ballistic impact of increasing velocities. The aluminium is a grade used for armour plating, and the projectile velocities are matched to artillery ammunition. It was found that the slowest projectile came to rest within the material as expected for an indirect shell. The medium speed projectile perforated, which isn't expected in real life however due to modelling differences, this is not unusual. The fastest velocity perforated the aluminium with ease as was expected to match the armour piercing shot it was representing. The failure mode of the aluminium was mainly spalling and the dominating force at each velocity was tension. Each velocity displayed tensile stresses following the behaviour of the Hertzian cone theory.

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1 Introduction

1.1 Overview

In this report, a simulation is carried out to analyse the performance of aluminium 5083 when subjected to a ballistic impact. A projectile of 30mm diameter is used to replicate a bullet or shell in a real-world situation. The projectile impacts the aluminium plate at varying velocities from 210 to 945m/s. These velocities are used to replicate the muzzle velocity of a range of artillery shells. Although the size of the projectile isn't matched to a real shell, this study is just to investigate the performance of the aluminium at a range of speeds. The aluminium chosen is commonly used in armour plating, due to its high performance in extreme conditions and low density. The analysis uses a rigid body for the projectile, this is to focus the analysis and simulation time on the aluminium plate, although this is detrimental to the accuracy of the results as a real-world situation would result in some deformation in the projectile absorbing some of the energy. The simulation software Abaqus by Simulia will be used to complete the simulation, giving the results of each one ready for analysis, primarily focusing on the direct and shear stresses of the material. [1]

1.2 Velocity Context

The velocities used in this simulation have been chosen to replicate the muzzle velocities of certain artillery shells.

Velocity (m/s)	Shell	Purpose
210	105mm	The 105mm is a short-range indirect artillery shell, meaning that it should not come into contact with anything, they are designed to detonate using a timed/proximity fuze. [2]
451	155mm	The 155mm is a longer-range indirect artillery shell. Detonated in the same way as the 105mm, however it travels at a much higher velocity due to it needing to travel further. [2]
945	120mm	The 120mm APFSDSR (Armour piercing fin stabilised discarding sabot), is a shorter-range direct shot. It is made from solid metal and is designed to pierce through armour. [2]

2 Background knowledge

2.1 Stress

The stress of a material is defined as the force per unit area applied to the material, the point at which the material can no longer take the amount of stress applied is called the ultimate tensile stress.

$$\sigma = \frac{F}{A}$$

This equation shows the stress being equal to the force (N) divided by the cross-sectional area (m²). The stress is given in Nm⁻² or Pascals (Pa). [3]

2.2 Strain

Strain has no units unlike stress as it is given as a ratio. It is calculated as the extension divided by the original length. [3]

$$\text{Strain} = \frac{\Delta L}{L}$$

2.3 Tensile stress

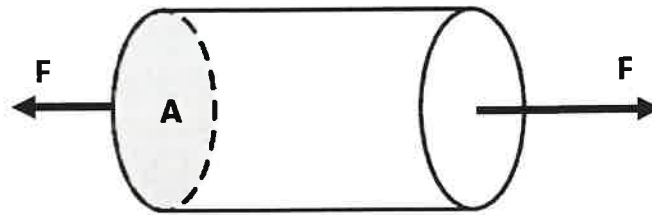


Figure 1 Tensile Stress

As shown in the diagram above, tensile stress occurs when the forces applied are acting in opposite directions away from each other, essentially causing the material to stretch. A material can experience tensile stresses and return back to its original shape, this is plastic deformation which occurs in its elastic limit. Beyond this point, the material will deform and lose its strength. [3]

2.4 Compressive stress

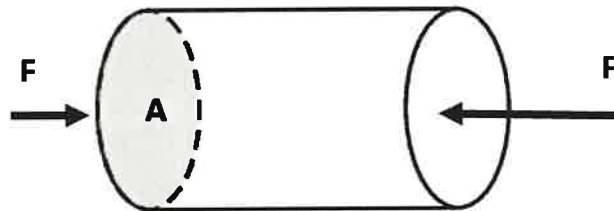


Figure 2 Compressive Stress

Compressive stress occurs when the forces acting on a body, are acting in opposite directions towards each other, essentially crushing the material. This follows the same theory as compressive stress, where the material can come under compressive stresses and return to its original shape within its elastic limit. [3]

2.5 Contact mechanics

Contact mechanics is the study of the deformation between two objects that come into contact at one or more points. In this experiment, the bullet coming into contact with the aluminium plate will use contact mechanics to analyse the stresses shown using the finite element analysis software. One theory within contact mechanics is the Hertzian cone theory, which was developed, leading on from the Hertzian indentation, named after Hertz, who originally calculated the relevant pressure indenter under the indenter. The theory details how when a conical/spherical object comes into contact with another solid object, the resultant stresses induced form a cone of stress around the impact point. [4]

3 Simulation information

3.1 Material model

The material model is ^{one of} the crucial component in the simulation to ensure that the results are as accurate as possible. The projectile is modelled as a rigid body to focus the analysis on the

aluminium plate, although the profile of the projectile is not similar to the ogive of an artillery shell, therefore the results cannot be accurately related to a real-world scenario.

The aluminium plate has been created at 198.75 x 200mm. The aluminium chosen for this simulation is 'Aluminium 5083 – H112'. This particular material is known for exceptional performance in extreme environments, being highly resistant to seawater and chemical attacks. It is stated as having the highest strength of all non-treated aluminium.

These properties are the reason it was chosen for the simulation, it is used in shipbuilding and armour plating for light vehicles due to its exceptional performance. Thus, giving it the most relatable application to the OME industry. [5]

Aluminium 5083 Properties	
Density	2.66 kg/m ³
Young's modulus of elasticity	70.3GPa
Poisson's ratio	0.33
Yield stress	125MPa
Ultimate stress	275MPa
Plastic Strain	12%

Figure 3 Al 5083 Properties

The aluminium properties vary depending what thickness of material is being used, therefore, the values chosen were the ones that fall into the bracket of 6.35 – 38.1mm to fit the plates thickness of 20mm.

Aluminium 5083 Composition	
Aluminium, Al	92.4 – 95.6%
Chromium, Cr	0.05 – 0.25%
Copper, Cu	≤ 0.1%
Iron, Fe	≤ 0.4%
Magnesium, Mg	4 – 4.9%
Manganese, Mn	0.4 – 1%
Silicon, Si	≤ 0.4%
Titanium, Ti	≤ 0.15%
Zinc, Zn	≤ 0.25%
Other	≤ 0.15%

Figure 4 Al 5083 Composition

3.2 Simulation model

Firstly, it should be noted that the projectile used in this simulation is that of a rigid body, meaning it has no mesh that can deform. In the real world, the projectile would deform upon contact with the aluminium plate and would be absorbing some of the energy. Therefore, the values extracted from these simulations for the performance of the plate may not be completely accurate to real life.

The mesh of the aluminium plate has been done using tetrahedrons as it is a simple shape. The impact area and close surroundings use a much finer mesh than the outer area as there will be much more detailed analysis required around the impact. The outer area does not need a fine mesh due to the stresses in this area not being high enough to deform the plate. [6]

4 Results

4.1 Job 1 – 210m/s

4.1.1 Direct stress

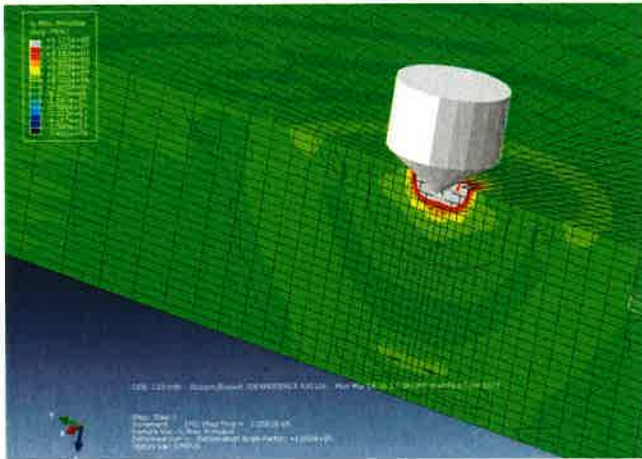


Figure 5 210m/s Maximum Principal

Upon contact between the plate and the bullet, it is shown here that there is a tensile stress of 127MPa directly underneath the bullet. However, there are lower tensile waves being sent through the material, as shown by the yellow ring around the surface of the material. It can also be seen that the stress wave shown by the black line, has already met the edge of the material model, this results in the wave bouncing back towards the bullet, this will in turn, interfere with the stress values shown by the software.

As the bullet travels through the plate, the stresses become much higher, the grey area that dominates the material is a tensile force of 2.4GPa. The force has acted in a fashion that is similar to the Hertzian cone theory however it has not reached a value that would result in cracking. Cracking has appeared at the bottom of the material directly under the bullet, however the bullet does not perforate the material fully and came to rest within the material.

4.1.2 Shear stress

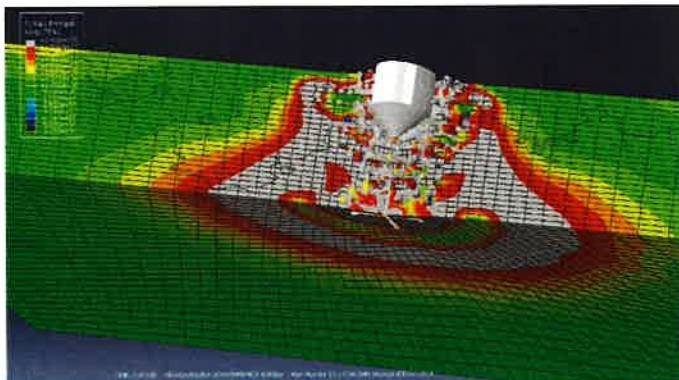


Figure 6 210m/s Maximum Principal

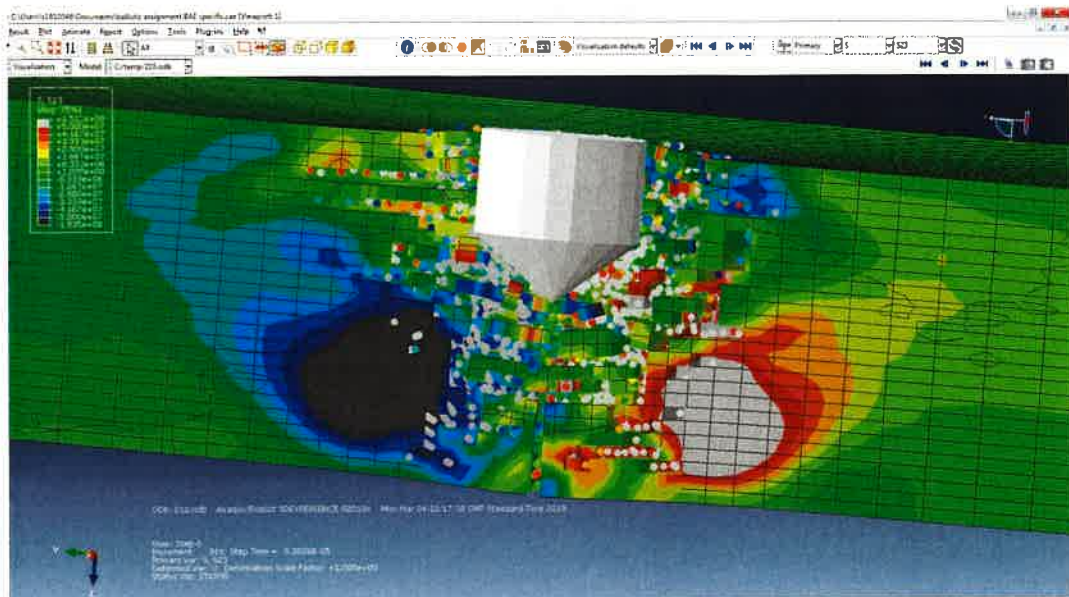


Figure 7 210m/s, stress in the YZ Plane

The shear stresses in the YZ plane are shown above, they have a maximum magnitude of 151MPa. These stresses are shown in grey and blue going in opposite directions, showing that the stress is travelling in a circular direction around the bullet. This is the Hertzian cone theory. The stresses formed are taking a conical shape around the point of impact.

4.2 Job 2 – 451m/s

4.2.1 Direct stress

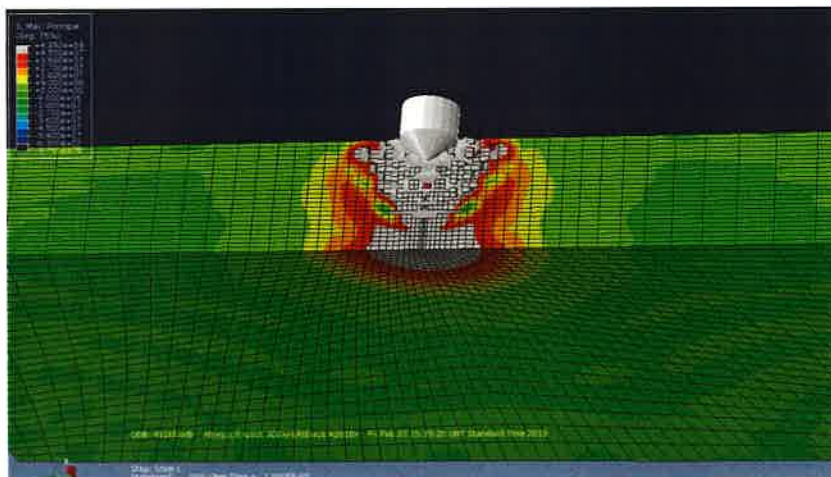


Figure 8 451m/s Maximum Principal

At 451m/s, the tensile stress waves throughout the material are much more frequent, the tensile stress has also reached the bottom of the material before the bullet has fully entered the material. The grey area that takes up the majority of the stress, is at 4.9GPa.

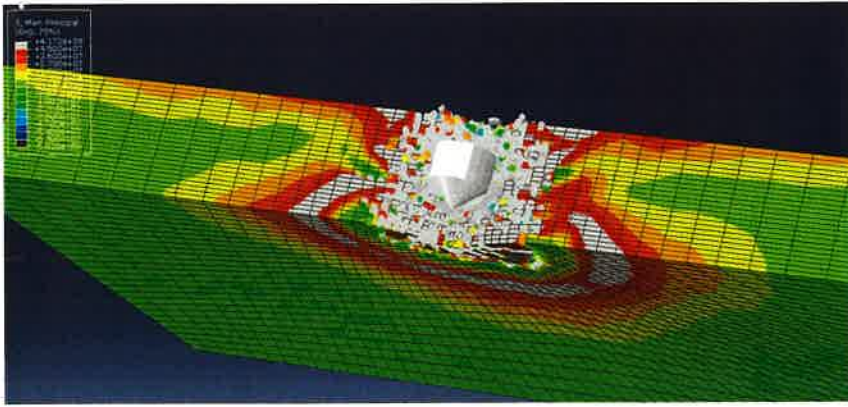


Figure 9 451m/s Maximum Principal

It can be seen that once the bullet has entered the material, the stresses in the grey area have dropped down the 4.2GPa, it is still showing the behaviour of Hertzian cone theory. The aluminium plate has started to show signs of spalling, where the material starts to break off the main body. This is occurring directly underneath the bullet. A crack has formed in the material and some of the elements have broken off. There is also a much larger deformation underneath the bullet, showing that the material is being pushed downwards by a larger force.

4.2.2 Shear stress

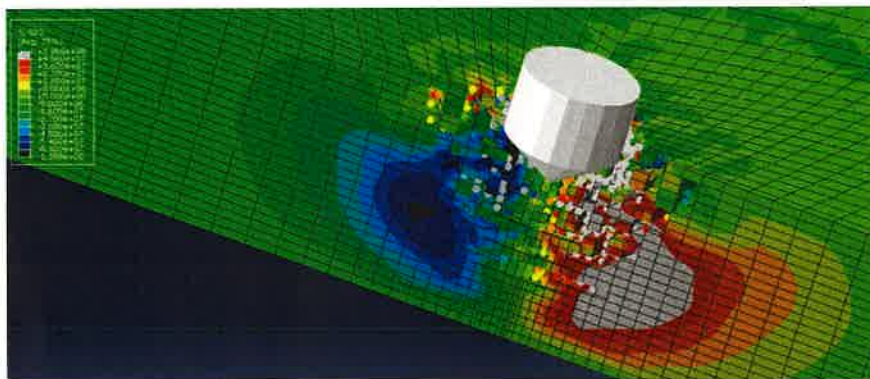


Figure 10 451m/s, stress in the YZ Plane

The shear stresses shown here, are very similar to that of the 210m/s velocity bullet, as it is showing the same 360° behaviour of the Hertzian cone theory. Although the stresses are slightly lower, peaking at 136-150MPa as it travelled through the material.

Difficult to justify
for course limits

4.3 Job 3 – 945m/s

4.3.1 Direct stress

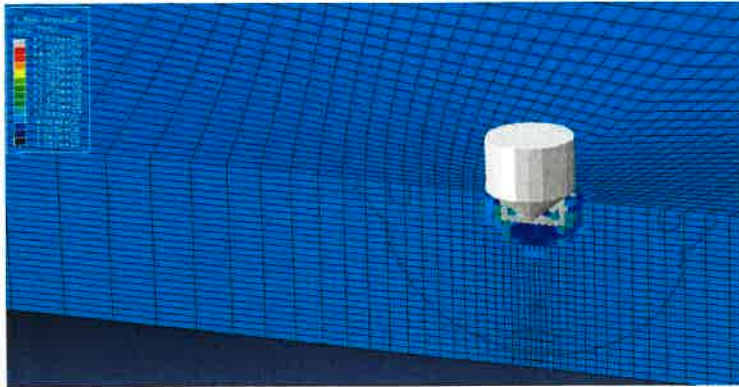


Figure 11 945m/s Maximum Principal

At 945m/s, more information about the forces acting through the material is being shown. You can see the tensile wave travelling through the material and hitting the edge of the sheet before the bullet has entered, similar to the slower velocities. As shown in the 210m/s max principal evidence, there is a similar tensile force directly under the bullet at this speed. However, there is also evidence of a compression wave shown by the dark blue elements, these are acting with 1.5GPa of compression. The force of the tensile region is much higher at 7.8GPa.

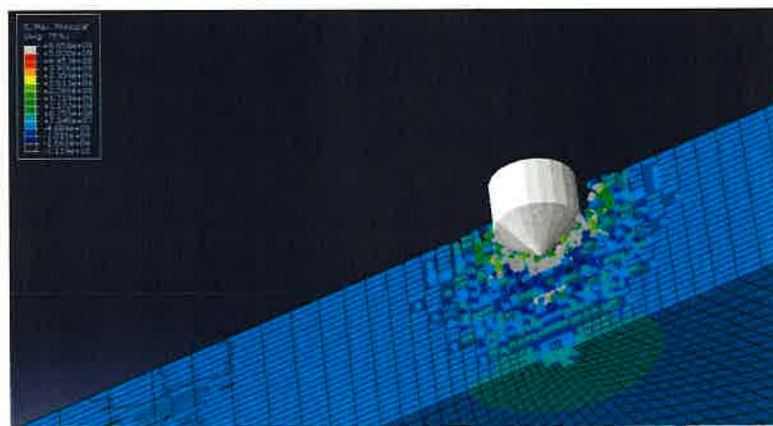


Figure 12 945m/s Maximum Principal

As the bullet travels through the material, the forces are much higher than any previously seen at the slower speeds. In this screenshot, it is dominated by tensile force, ranging from 78MPa – 8.9GPa. Unlike the slower speeds that either showed no spalling or very little, at 945m/s, the elements are starting to break away from the material much sooner and covering a larger area.

4.3.2 Shear stress

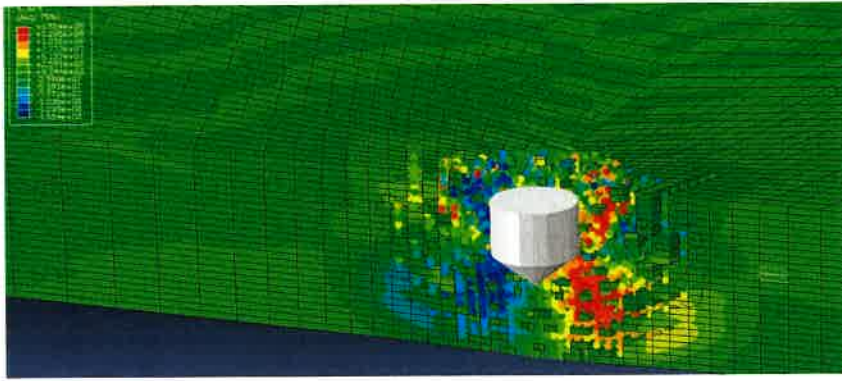


Figure 13 945m/s, stress in the YZ Plane

The shear forces are still showing behaviour representing the Hertzian cone theory, they are also at a similar value as the previous velocities, these forces are peaking at 155MPa, slightly above the previous simulations. The amount of spalling at this velocity can be seen clearer here, it is much more than the slower velocities, the bullet is at such a high speed that it is shattering the material in its way and breaking it off of the main body.

5 Discussion

5.1 Hertzian cone theory

The Hertzian cone is a reoccurring observation throughout each simulation. This was expected as the impact of the bullet is in line with the laws of contact mechanics, as it is a conical shape that impacts first, it forms a cone of force into the material that travels at a rate much faster than the bullet itself. It was surprising to see that the forces in the YZ plane were not largely different between the velocities as they were all near 150MPa. It is noted that although the forces shown in the simulation have taken a conical direction, there has been no physical deformation/cracking at a conical angle. The only deformation occurred was in, and directly next to the bullets path. [4]

5.2 Spalling

The spalling of the material was noticeably more prominent as the velocity increased. As spalling is the breakaway of material from the main body, this wasn't seen at 210m/s and only started to occur at 451m/s. At 945m/s, the spalling was obvious and there were multiple elements underneath the bullet that would be fracturing away from the aluminium plate. [7]

5.3 Dominant force

The dominant force in each simulation has been tension. This has been in the form of tension waves travelling through the material, and tensile force around the bullet itself. Although there is compression happening simultaneously in certain areas, it is of a much smaller scale than the tensile forces.

5.4 Interference

The accuracy of the simulation cannot be claimed to be perfect, predominantly because the size of the plate is reasonably small in respect to a real-life application. This has meant that waves of force have been travelling to the plate boundary and bouncing back. As they bounce back, they interfere with the stress values and may cause inaccuracies, a larger aluminium plate would minimise this interference. ✓

5.5 Model accuracy

The accuracy of the model also brings some margin of error into the simulations. With the bullet modelled as a rigid body, it absorbs none of the kinetic energy, it is all absorbed by the aluminium plate meaning that the stresses seen in these simulations may be higher than real life. This would also have an effect on the residual velocity of the bullet, if it deformed and absorbed some of the energy then it would have slowed down faster than it has in this experiment. *good modelling*

I believe the meshing of the aluminium plate has been appropriate for this context, it has provided enough information around the bullet itself to analyse the stresses, and there has been none to very little activity nearer the edge of the material where the mesh is coarser.

5.6 Artillery context

5.6.1 250m/s

The projectile travelling at 250m/s in real life is a shorter-range indirect shell. This means it will not come into contact with a solid object upon firing and detonation, therefore it was not surprising that it was unable to perforate the aluminium armour plating. There is no need for the projectile to pierce through the sheet metal and this has been shown here.

5.6.2 451m/s

At 451m/s, it is a long-range indirect shell. It also will not come into contact with a solid object in firing or detonation, however to the extended range, it travels much quicker. Although it isn't designed to perforate the material, the simulation has shown that it has, and this is not surprising due to the speed that the projectile is travelling. In real life, it is a shell instead of a solid body so it has not been accurately modelled in this simulation, if it was modelled as a hollow shell with a low-density filling then it may not have pierced all the way through.

5.6.3 945m/s

This projectile is designed to be a short-range direct shot, meaning that it is a solid body that does not detonate, it is purely used to pierce through armour. This is exactly what it has done in the simulation, it has pierced all the way through at such a speed that the spalling of the material didn't happen until the projectile had exited the aluminium.

6 Conclusion

In conclusion, it has been proven that tension is the dominating force under ballistic impact, the magnitude of the tensile stresses increases as the velocity of the projectile increases as expected.

The main failure mechanism of the aluminium plate is spalling, the deformation caused by the projectile has meant that the material has fractured off and sent fragments away from the main body.

The ballistic limit of the aluminium is between 250 and 451m/s, between these velocities, the projectile is able to pierce the aluminium. At 250m/s, the projectile came to rest within the material, however at 451m/s, the projectile continued through the plate, further research could be done to determine the exact ballistic limit of aluminium 5083.

7 Background Reading

[8], [9], [10]

8 References

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