

Ballistic - Dynamic Stress-strain Investigation

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1. Dynamic Stress-Strain Investigation (Ballistic)

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2. Abstract

The aim of this simulated experiment was to investigate the stress-strain behaviour of an aluminium target plate whilst it undergoes an impact from a projectile travelling at different velocities. The velocities selected were between 50ms^{-1} and 250ms^{-1} . The projectile penetrated the target for all five of the selected initial velocities, but only perforated the target at the two higher velocities. The aluminium targets experienced both direct and shear stresses during the impacts, with the compressive and tensile direct stress being much higher than the shear stresses involved. The direct stresses caused the aluminium target material to move from its elastic region into its plastic region when it reaches a certain stress value. This causes the material to deform permanently and fail, thus allowing the projectile to penetrate and in the case of higher velocities, above its ballistic limit, perforate the target.

3. Introduction

The aim of this simulated experiment was to investigate the stress-strain behaviour of an aluminium target whilst it undergoes an impact from a projectile travelling at different velocities.

When a load or force is applied to a material, there are a number of types of stress that it can undergo. This is dependant on the force that is applied. If the force is tensile, i.e. the material is stretched, then it is undergoing a tensile stress. If the force is compressive, i.e. being squashed, then the material experiences compressive stress. Some materials are weak under compressive stress but strong under tensile, and vice versa. In engineering applications, the ability for a material to withstand high compressive stresses is desirable. For example, steel is strong under both tensile and compressive stress, whereas concrete, is only strong against compressive strength [1].

Shear stresses, which are also known as tangential stresses, can also occur when a force is applied to a material. Where a specific area is resisting a force, i.e. the area directly impacted by the projectile, the forces that run parallel to this cause shearing stress. Tensile and compressive stresses are caused by forces acting perpendicular to the area and are known as direct stresses [2].

Different materials have different characteristics and properties. Young's Modulus is a material property, that describes a material's stiffness. This is an important characteristic during an impact as the material's stiffness will contribute to the performance of the targets. When a stationary object experiences an impact by a moving projectile, the projectile transfers energy into the object. This energy is stored elastically or dissipated plastically. The way a material stores this energy is summarized in stress-strain curves (an example can be seen in figure 1 below) [3].

Stress is defined as force per unit area and strain as elongation or contraction per unit length.

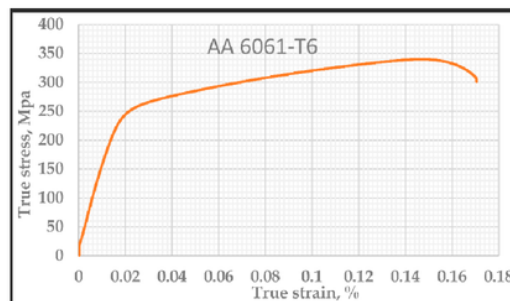


Figure 1 - Example of Stress-Strain Graph for Aluminium [4]

The stress-strain curve for Aluminium shows an initial steep gradient, like many other ductile metals. As mentioned above, this is the Young's Modulus and it's an indication of a material's stiffness. If the aluminium material undergoes stresses below the yield strength, then the aluminium material returns to its original shape when the forces causing the stress reduce. If stresses exceed the yield strength, then the material moves into its plastic region where the strain deformation is permanent. The ultimate tensile strength is the highest point on the graph, and if stresses reach this magnitude, then the material will fail or break.

When a material deforms elastically, the amount of deformation can depend on the size of the material, but the strain for a given stress is always the same. This is because the two are related by Hooke's Law (stress is directly proportional to strain):

$$\sigma = E \cdot \epsilon$$

where σ is stress [MPa]

E modulus of elasticity [MPa] [3]

ϵ strain [unitless or %]

From the Hook's law the modulus of elasticity is defined as the ratio of the stress to the strain;

$$E = \frac{\sigma}{\epsilon} \quad [\text{MPa}] \quad [3]$$

4. Material Data

The target plate is Aluminium Alloy 6061. It is a very commonly used metal in the world of engineering. It can be found in the following industries:

- Truck and marine components
- Furniture
- General structural and high-pressure applications
- Pipelines
- Heavy-duty structures
- Railroad cars
- Tank fittings

The material data used for this experiment can be seen in figure 2 below.

Chemical Composition

The following table shows the chemical composition of Aluminium / Aluminum 6061 alloy.

Element	Content (%)
Aluminium / Aluminum, Al	97.9
Magnesium, Mg	1
Silicon, Si	0.60
Copper, Cu	0.28
Chromium, Cr	0.20

Physical Properties

The physical properties of Aluminium / Aluminum 6061 alloy are outlined in the following table.

Properties	Metric	Imperial
Density	2.7 g/cm ³	0.0975 lb/in ³
Melting point	588°C	1090°F

Mechanical Properties

The mechanical properties of Aluminium / Aluminum 6061 alloy are tabulated below.

Properties	Metric	Imperial
Tensile strength	115 MPa	16680 psi
Yield strength	48 MPa	6962 psi
Shear strength	83 MPa	12038 psi
Fatigue strength	62 MPa	8992 psi
Elastic modulus	70-80 GPa	10153-11603 ksi
Poisson's ratio	0.33	0.33
Elongation	25%	25%
Hardness	30	30

Figure 2 - Material data for Aluminium 6061 [5]

5. Simulation Model

The experiment was to investigate the stress-strain behaviour of an aluminium target plate, whilst it undergoes a number of impacts by a projectile at different velocities. The simulation was created on Abaqus CAE and a predefined Abaqus model (ballistic.cae) was provided. The model of the target and projectile were provided and the projectile was determined to be a rigid body which would not deform.

- Input Material data for the target plate was entered in the property module section on Abaqus.
- An initial velocity was assigned to the projectile by entering the velocity into the 'predefined fields' in the Load module section.

- The simulation was submitted to run and the results of the impact and the stress behaviour of the target plate were analysed (This was done by looking at the direct stresses using the Max Principle field output and the shear stresses using the S23 field output).
- The velocity of the projectile was plotted against time on a graph to show the velocity of the projectile as it impacts the target and the residual velocity of the projectile if it perforates the target.
- The simulation was then repeated at the other selected initial velocities.

6. Results

I selected five different initial velocities. These were 50ms^{-1} , 100ms^{-1} , 150ms^{-1} , 200ms^{-1} & 250ms^{-1} . The results below show snap shots from Abaqus to show the direct and shear stresses at two different points in the simulation. The images on the left-hand side show the results shortly after the initial contact, and shows the initial stress waves propagating through the target material. The images on the right-hand side show a snap shot of the target as the projectile penetrates the aluminium target, and for the lower two velocities (50ms^{-1} , 100ms^{-1}) this was when the projectile came to a stop within the target.

50ms^{-1}

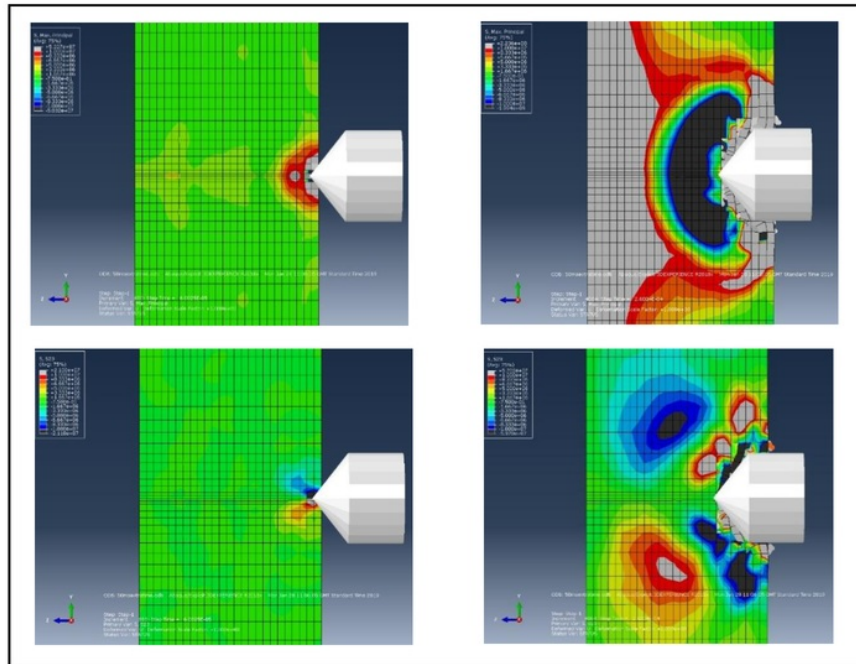
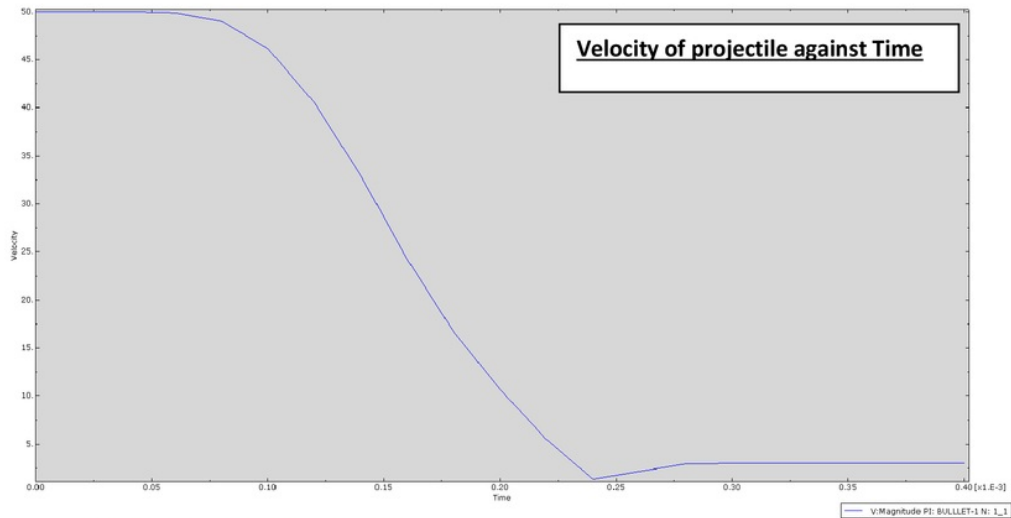


Figure 3

Figure 4 – Velocity of projectile – 50ms^{-1}

At 50ms^{-1} the projectile did penetrate a small distance into the aluminium target but it did not perforate the target. There is no residual velocity as the projectile was contained within the target. At the initial impact the images in figure 3 (above left) show that a small compression wave is formed and shear stresses are beginning to occur in a diagonal direction. As the bullet penetrates further into the material the stresses, both shear and direct, increase as they pass through the target. The compression wave and area of saturated tension are in the magnitude of 1.9GPa and 220MPa respectively and the shear stresses are in the region of 60MPa . When the stress values for elements within the simulation reach figures above the yield strength of the aluminium alloy then the material has moved from the elastic strain region into the plastic strain region, which is why the material begins to deform and energy is absorbed by the deformation of the target.

100ms^{-1}

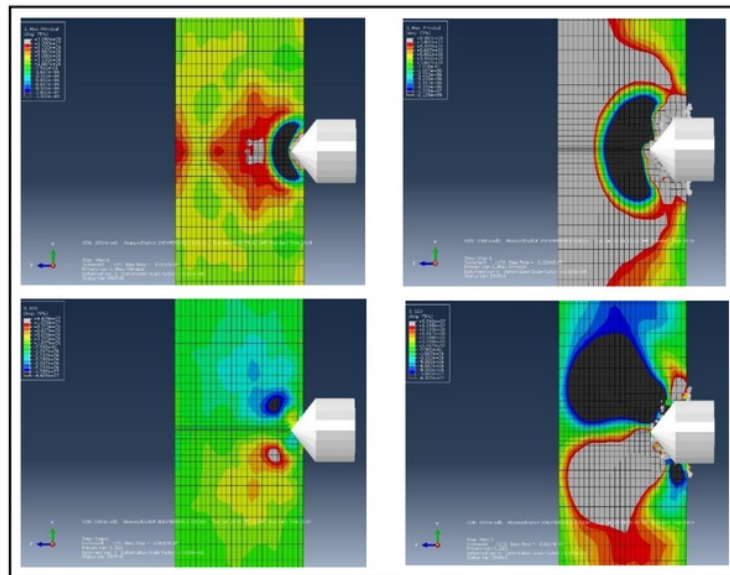


Figure 5

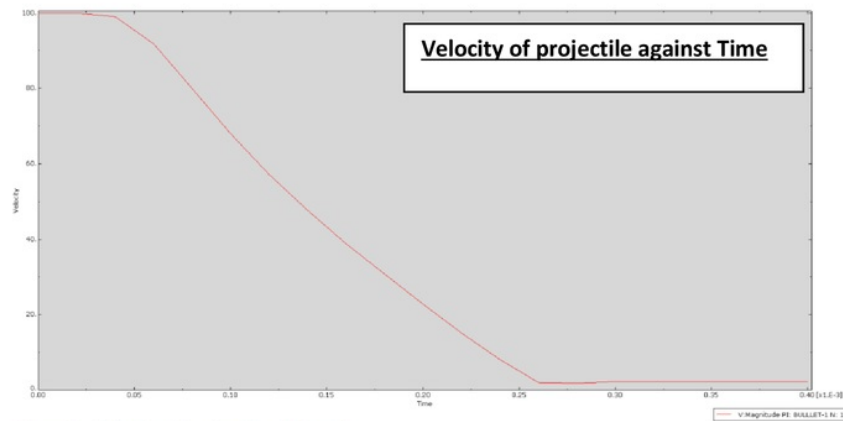


Figure 6 – Velocity of projectile – 100ms^{-1}

At 10ms^{-1} the projectile did not fully penetrate the aluminium target. There is no residual velocity as the projectile was contained within the target. At the initial impact, figure 5 (above left) shows that a small compression wave is formed. There are parts of the material undergoing direct stress under tension in the region of 8-10MPa, but the area experiencing compressive stress is experiencing stresses of approx. 1.3GPa. There are also signs of shear stress to either side of the area in direct contact with the projectile. This is caused by the material directly in front of the projectile being pushed through the target, as this affects the area surrounding by shearing. As the projectile penetrates further into the material the stresses, both shear and direct, increase as they pass through the target. The compression wave and area of saturated tension are in the magnitude of 2GPa and 10MPa respectfully and the shear stresses are in the region of 60MPa.

150m/s

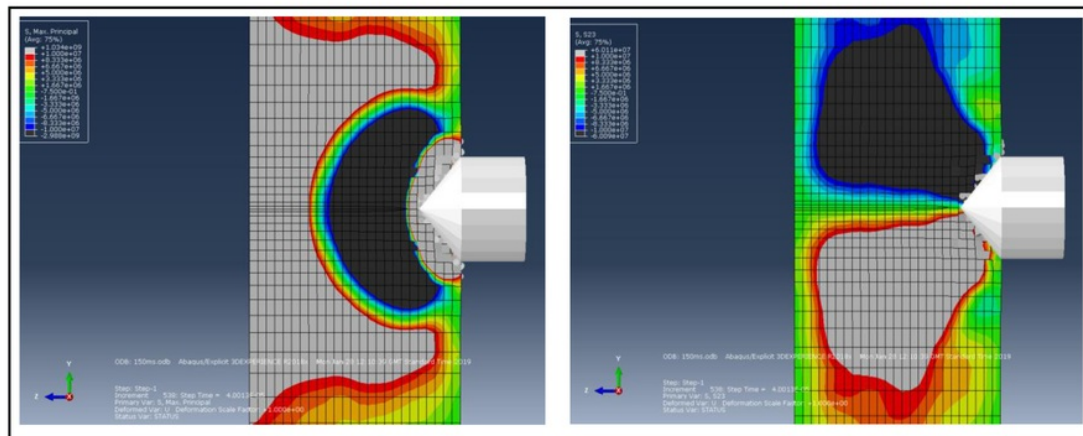


Figure 7

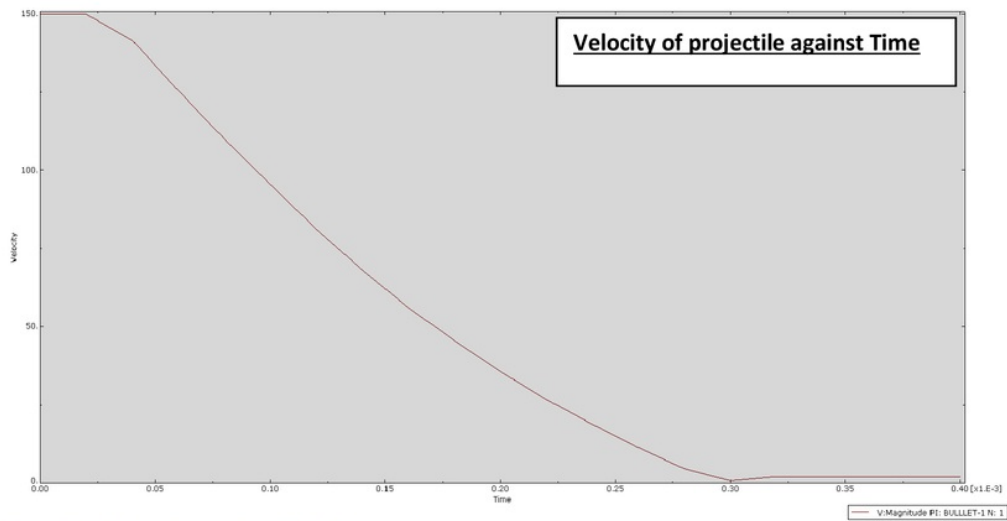


Figure 8 – Velocity of projectile – 150ms^{-1}

At 150ms^{-1} the projectile did not fully travel through and penetrate the aluminium target. There is no residual velocity as the bullet was contained in the target. At the initial impact, the image on the left above (figure 7) shows that a large compression wave is formed. The aluminium target is largely affected by direct tensile stresses but these are much lower than the compressive stresses. The image on the right (figure 7) shows signs of shear stress to either side of the area in direct contact with the projectile. As the projectile penetrates further into the material the stresses, both shear and direct, increase as they pass through the target. The projectile didn't have quite enough energy to fully penetrate the target and came to rest shortly before travelling through the rear of the target. Some bowing of the material was observed in the simulation.

200ms^{-1}

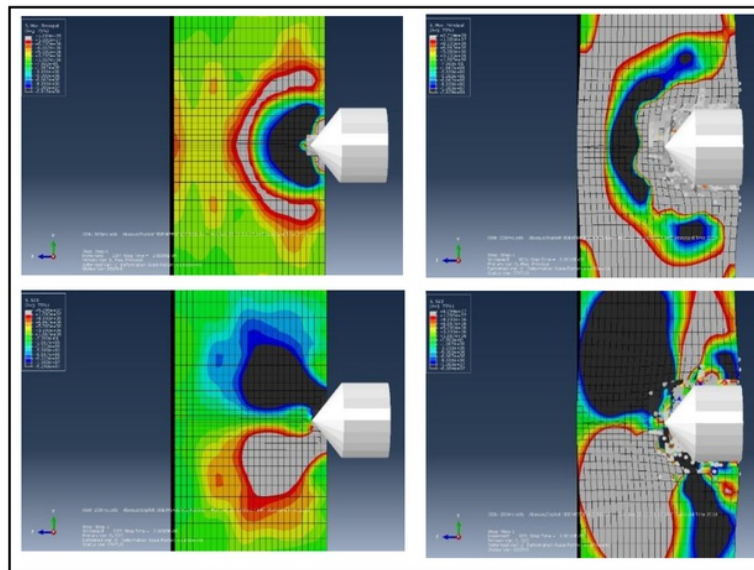


Figure 9

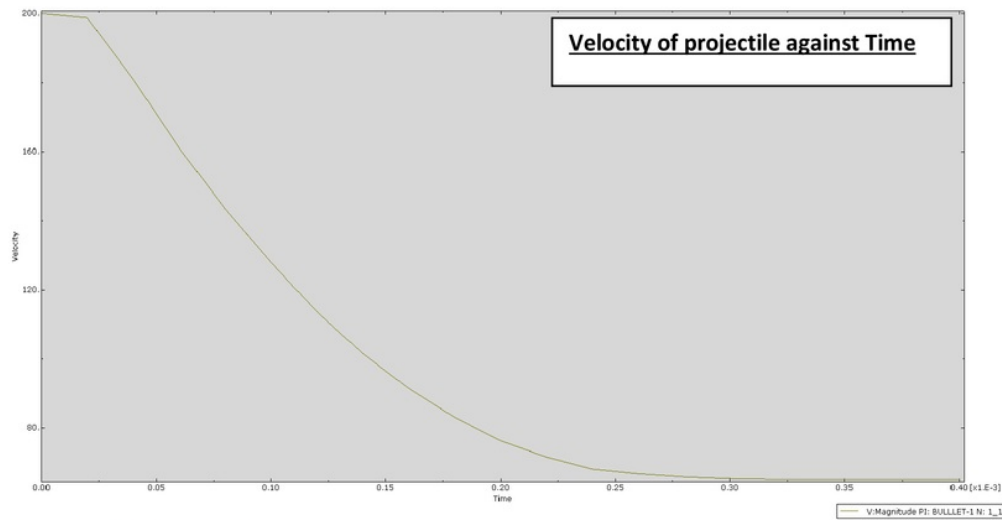


Figure 10 – Velocity of projectile – 200ms^{-1}

At 200ms^{-1} the projectile perforates the Aluminium target and exits the rear of the target with a residual velocity of approx. 65ms^{-1} . On initial contact a tension wave followed by a compression wave travelled through the Aluminium target. These stress waves are in the magnitude of 3GPa . There are shear stresses occurring in the aluminium in the magnitude of 60MPa , as can be seen in the figure above, where shear stresses acting in opposing directions but having similar values (shown by the saturated compression and tension areas). As the projectile fully penetrated the target, the direct stresses are shown to be the cause of failure due to having much higher magnitudes of stress. These stresses are much higher than the tensile strength of this material which explains why it failed.

250ms^{-1}

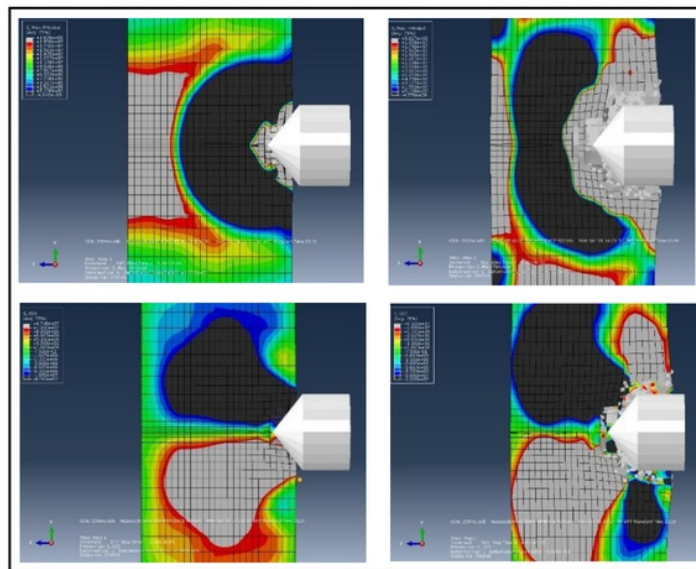


Figure 11

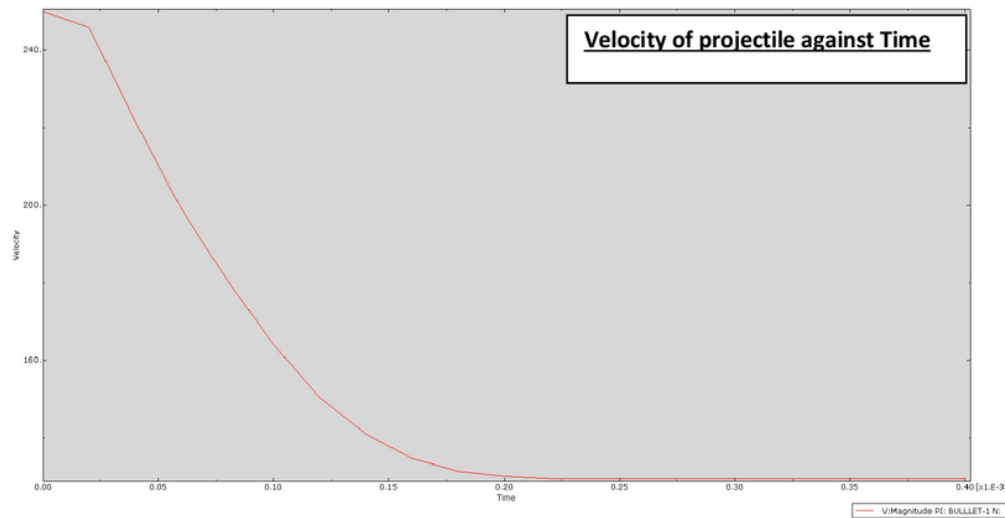


Figure 12 – Velocity of projectile – 250ms^{-1}

At 250ms^{-1} the projectile fully penetrates the Aluminium target and exits the rear of the target with a residual velocity of approx. 130ms^{-1} . On initial contact a tension wave followed by a compression wave travel through the Aluminium. These stress waves are in the magnitude of 5GPa . There are shear stresses in the aluminium in the magnitude of 60MPa , as can be seen in the figure above, where shear stresses acting in opposing directions but having similar values (shown by the saturated compression and tension areas). As the projectile fully penetrated the target, the direct stresses are shown to be the cause of failure due to have much higher magnitudes of stress. These stresses are much higher than the tensile strength of the aluminium target and the material fails. The ductile nature of the target and the large plastic region means that target doesn't shatter or crack, but deforms.

7. Conclusion

The projectile did not fully penetrate the aluminium target at the velocities 50ms^{-1} , 100ms^{-1} or 150ms^{-1} . For both of the two higher velocities the projectile penetrated the target plate. In this instance therefore, the ballistic limit for this Aluminium alloy target plate is determined to be between $150\text{--}200\text{ms}^{-1}$.

The projectile was modelled to be rigid, thus allowing the focus of the investigation to be on the stress and strain of the aluminium target, rather than the deformation of the projectile. In a real life experiment the projectile would have properties that would be affected by the forces involved in the impact at high velocities, and therefore some of the energy of the impact would be spent deforming the projectile. This is not accounted for in this simulation.

In all of the simulated velocities, the values of direct stresses are much higher (in some cases as much as ten times higher) than the shear stresses observed. When a rigid projectile impacts an aluminium plate at high velocities, the compressive and tensile stresses experienced in the target are higher than the tensile strength of the material, which causes the material to fail. This is because sufficient force has been applied to the material under load which causes the material to go beyond its elastic limit. The forces then cause permanent displacement of the material in its plastic region and eventually failure of the material at its breaking point.

There are some limitations of a simulated ballistic model. Where forces reach certain a magnitude, the simulation converts those particles to circles to avoid the simulation from crashing – this can create some distortion. Due to the time for simulations to run, a limited number of elements were used and therefore the mesh could be more defined at the point of impact.

The size of the plate will also have had an impact on the stresses observed during the simulations. Due to the small target plate, stress waves travel through the material and then reflect back into the material due to the boundary constraints. Therefore, by using a much larger target, the stresses observed would be more accurate as they would be caused solely by the impact, and wouldn't include the stress waves travelling back through the target.

8. Reference List

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- [2] Unknown Author – Shear Stress. (Accessed online 05/03/2019) <https://www.mathalino.com/reviewer/mechanics-and-strength-of-materials/shear-stress>
- [3] Unknown Author - Modulus of Elasticity Chapter 15 Page 79. (Accessed online 05/03/2019) <https://tpm.fsv.cvut.cz/student/documents/files/BUM1/Chapter15.pdf>
- [4] Image taken from Article - Experimental Investigation of Forming Forces in Frictional Stir Incremental Forming of Aluminium Alloy AA6061-T6 ; Published: 7 November 2017 (Accessed online 06/03/2019) https://www.researchgate.net/publication/320916077_Experimental_Investigation_of_Forming_Forces_in_Frictional_Stir_Incremental_Forming_of_Aluminum_Alloy_AA6061-T6
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