

Dynamic Stress-Strain investigation

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Abstract

The purpose of this report is to analyse ballistic impact on an aluminium plate. Using a computer simulation software a projectile was fired at an aluminium plate. From these simulations different types of stress were analysed and comparisons and discussions made on the results. The grade of aluminium used was 7050, this was chosen as it is an aircraft grade which has been designed to withstand high stresses.

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Introduction

This report explores the ballistic impact of a projectile hitting an aluminium plate. Using FEA software a projectile will be fired at the plate at various velocities and results gathered. From these simulations data including images of the impact and graphs will be used to discuss the various velocities.

A number of different scenarios are possible when the projectile hits the plate, these are:

Ricochet – where the projectile dents the plate and comes out

Penetration – The projectile enters the plate

Embedment – This occurs when the projectile enters the plate but does not exit

Perforation – Where the projectile passes completely through the plate [1]

As well as discussing the ballistic impact this report will also look at ballistic limit, projectile velocity and scabbing.

Material

The material that was selected for this ballistic simulation was Aluminium 7050. This is an aerospace grade of aluminium that is commonly used for aircraft parts such as: wing skins, structural parts, fuselage frames among other parts. Aircraft manufactures use this alloy due to its toughness, high strength and stress corrosion cracking resistance. These properties make it perfect for aircraft manufacture as the alloy is very strong yet light enough to be used in aircraft. The specific properties of aluminium are detailed in Figure 1 . [2]

Density	2.83 g/cc
Young's Modulus	71.7 Gpa
Poisson's ratio	0.33
Yield stress / Plastic strain	455 Mpa / 0
Yield stress / Plastic strain	510 Mpa / 0.11

Figure 1 Properties of material

Modelling

Abaqus CAE 2018 was used to run the ballistic impact simulations. From research the material properties detailed in table 1 were entered into the material properties of the screen.

A number of fields in the CAE file were predefined these were:

- An assembly with the plate and projectile.
- The solver step was set to explicit.
- Within the load module the edges of the plate were fixed.
- An initial velocity of 300 ms^{-1} was set ready to be changed.
- Surface-to-Surface contact interaction in the interaction module.
- The plate had been meshed with hexahedral elements.
- The projectile was set to no deformable as set in the assignment brief.

Component sizes

The plate was 198.25 mm x 200 mm x 20 mm.

The projectile had a $\varnothing$ of 9.8 mm a length of 9.95 mm and a mass of 30 g.

Once set up the job module was selected, from the job manager jobs were created and run. Four different striking velocities were selected meaning four different jobs needed to be created. Before a different job was run the velocity needed to be changed. This was done by editing the predefined field within the load module.

The four striking velocities used were 50 ms^{-1} , 200 ms^{-1} , 350 ms^{-1} and 400 ms^{-1} . These were chosen because of the variety of results they gave. After the velocity had been changed the job was run from the job module and the results viewed from the visualisation module.

Within the visualisation module the visual graphic could be changed to show different stresses. The default view is von mises stress. Von mises shows where a component has started to yield and shows the maximum stresses on the component. To show the tensile and compressive stresses acting on the plate maximum principles was selected. Shear stress was shown using the S13 view. The S value shows shear stress in different planes, for this simulation a cut was made in the Y plane showing the shear stress in the X, Z plane.

Each velocity was analysed and images taken at the most appropriate time to show data for discussion.

Theory

Direct stress

Direct stress can be applied in two ways, tensile stress or compressive stress and the load is applied normal to the plane.

Tensile stress also known as ultimate tensile stress (UTS) is a measure of the maximum stress a material can withstand before it begins to elongate, stretch or pull. Tensile stress is usually defined as force per unit area and given the symbol σ , the SI unit is Nm^{-2} or Pa. Most materials have elastic and plastic regions before failure. In the elastic region a force is applied and the material deforms in a linear fashion and will return to its original shape when the force is released. The point at which the material changes from the elastic to plastic region is known as its yield strength. Once in the plastic region the material won't return to its original shape and will begin to fail. Figure 2 shows a typical stress strain graph.

Compressive stress is very similar to tensile stress however it is the maximum stress a material can withstand before it begins to crush or decrease in length. As with tensile stress it is calculated in the same way and defined as force per unit area. Equation 1 shows the calculation for direct stress. [3]

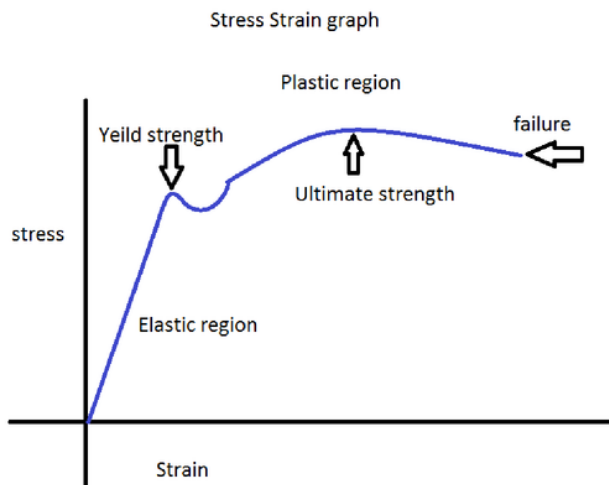


Figure 2 Stress strain graph

Young's modulus

The young's modulus of a material is a numerical constant that describes a materials ability to withstand changes in length due to tension or compression. Young's modulus is an important property of a material that only changes with temperature, it measures a materials resistance to elastic deformation. Under small amounts of strain most materials obey Hooke's law. [4]

Poisson's ratio

Poisson's ratio is the ratio of transverse contraction normal to the applied load. Tensile deformation is positive and compressive deformation negative, so the calculation for Poisson's ratio contains a minus sign so that materials have a positive ratio. Equation 5 shows how the ratio is calculated with the strain in the direction of the load divided by the axial strain. As this is a ratio it has no units. [5]

Hertzian theory

A Hertzian cone can be seen as body waves through an object as a projectile interacts with it, or as a physical cone where material has been ejected. A physical cone is often seen in brittle materials like a car windscreen being hit by a stone. Propagation waves are seen in harder materials that don't have physical cones.

Hooke's law

Hooke's law states that 'the stress imposed on a solid is directly proportional to the strain produced, within the elastic limit.' [6] This only applies for small deformations of an object and originates from springs. For example if a spring is stretched 5 mm by a force of 1 newton it will be stretched 10 mm by a force of 2 newtons. The equation for Hooke's law is shown in Equation 4 with K being the spring constant, T the force applied and X the extension of the spring. [7]

Direct strain

Strain is the deformation of a material due to an applied load or stress. As with stress strain can be compressive (negative) or tensile (positive). Strain is calculated using Equation 2 which is extension over length. As this is a ratio strain has no units.

Shear

Shear stresses act at parallel planes to the applied load unlike direct stress like tension or compression which act perpendicular to the load. The material deforms by slipping along the plane on which the force is applied. Figure 3 shows the difference between direct stress and shear stress.

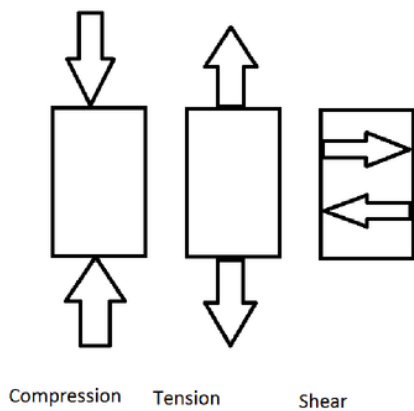


Figure 3 Shows how different stresses act in different planes

Ballistic limit

The ballistic limit of a material is the minimum velocity at which a projectile will consistently, completely penetrate the material. [8]

Equations

Equation 1

Stress [9]

$$\text{Stress} = \frac{\text{load}}{\text{area}}$$

Equation 2

Strain [9]

$$\text{Strain} = \frac{\text{Extension}}{\text{Original length}}$$

Equation 3

Young's modulus [9]

$$\text{Youngs modulus} = \frac{\text{Stress}}{\text{Strain}}$$

Equation 4

Hooke's law [9]

$$T = KX$$

Where T = force

K = the spring constant

X = extension of the spring

Equation 5

Poisson's ratio [10]

$$\text{Poisson's ratio} = - \frac{\epsilon_t}{\epsilon_1}$$

Where ϵ_t = transverse strain

ϵ_1 = longitudinal strain

Results

Background

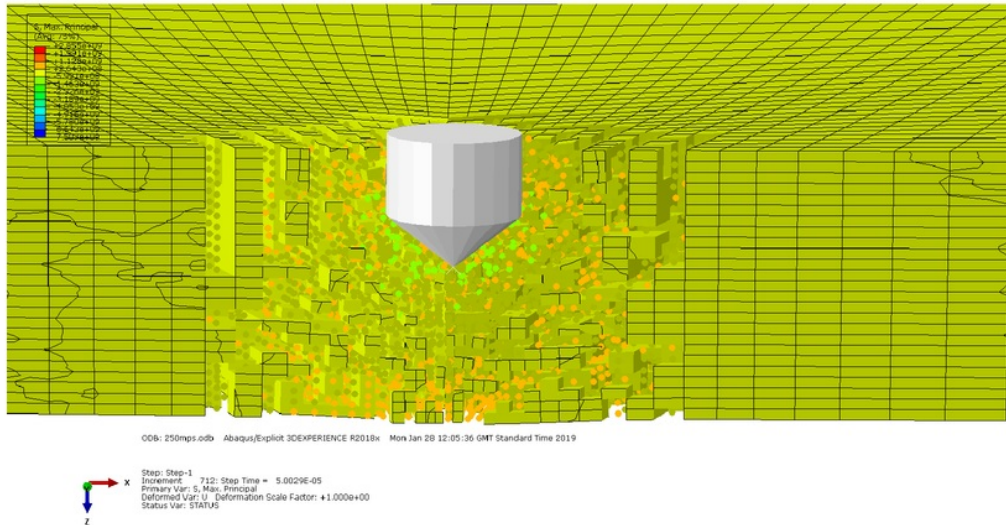


Figure 4 shows direct stresses acting on the plate

The above image (Figure 4) shows direct stresses on the plate. The green elements show compression under the projectile and the orange show tension where the plate is starting to bed.

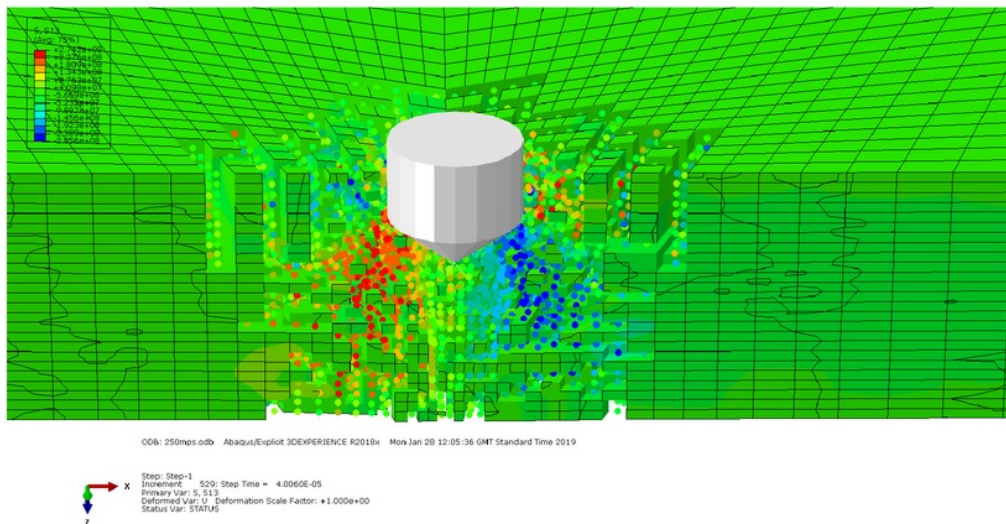
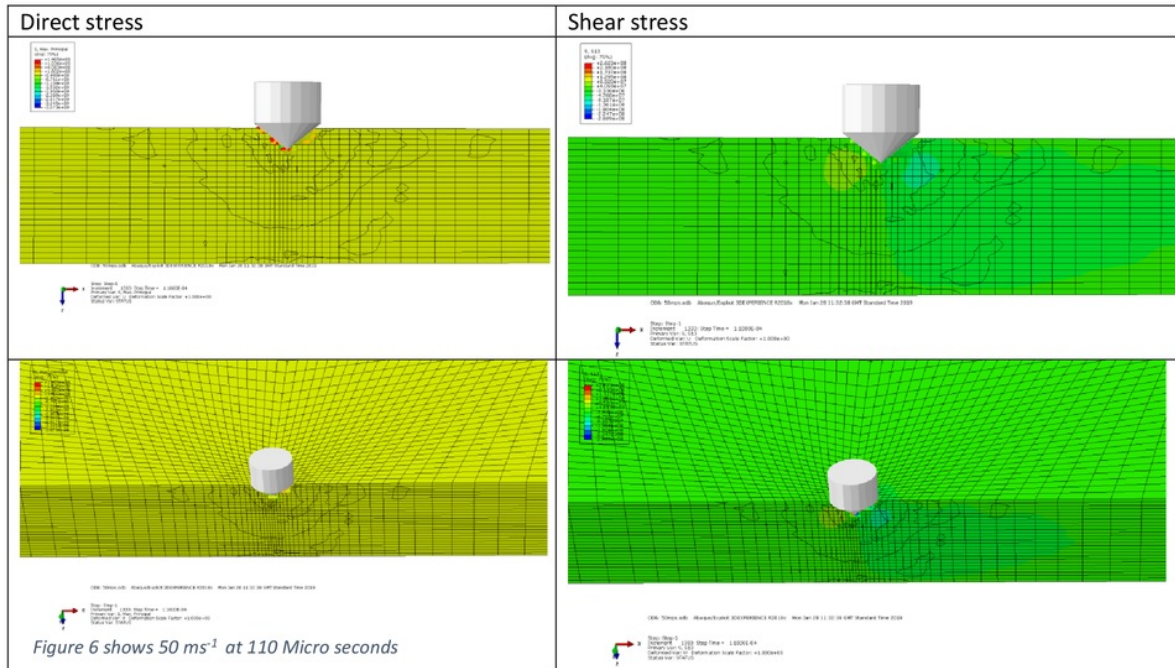


Figure 5 shows shear stresses acting on the plate

This image (Figure 5) shows the shear stresses acting on the plate. The red and blue are the shear stresses, although acting in the same direction the blue is negative and the red is positive. This is the way Abaqus shows shear stress. This image also shows body waves propagating through the plate.

50 ms^{-1}



50 ms^{-1} was the slowest velocity simulated. As can be seen from Figure 6 the direct and shear stresses that are being applied to the plate are low and concentrate around the tip of the projectile. Very little direct stress is seen but more shear is observed with the orange and turquoise colours. This simulation clearly shows tension waves traveling through the material. At this timestamp the waves have just hit the bottom on the plate. The waves are propagating from the projectile through the body, when they reach the free face of the plate they will reflect back towards the projectile as compression waves because of the fixed boundaries. Once they have hit the free face and reflect back they will start to interact and interfere with the projectile. At 50 ms^{-1} the projectile penetrates the plate and embeds in the plate.

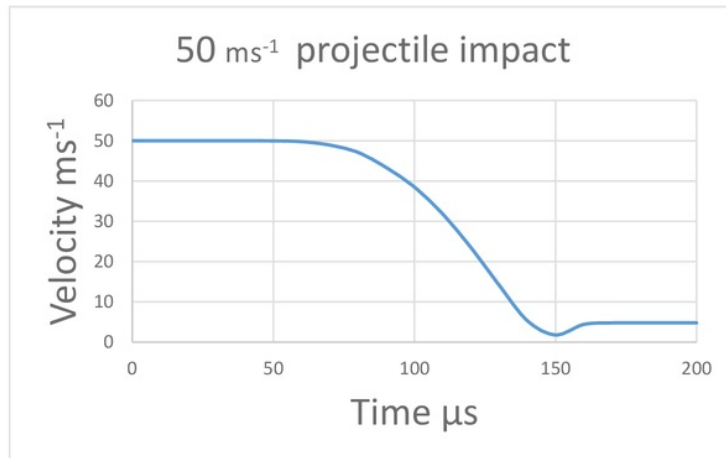


Figure 7 shows the velocity graph at 50 ms^{-1}

This graph shows the velocity of the projectile as it embeds itself within the plate. As can be seen there is a dip where the projectile come to rest, this is where the projectile has relaxed within the plate. The velocity doesn't reach zero because I believe the projectile is still moving slowly within the plate. If the simulation was run for longer it would show the velocity reaching zero.

250 ms^{-1}

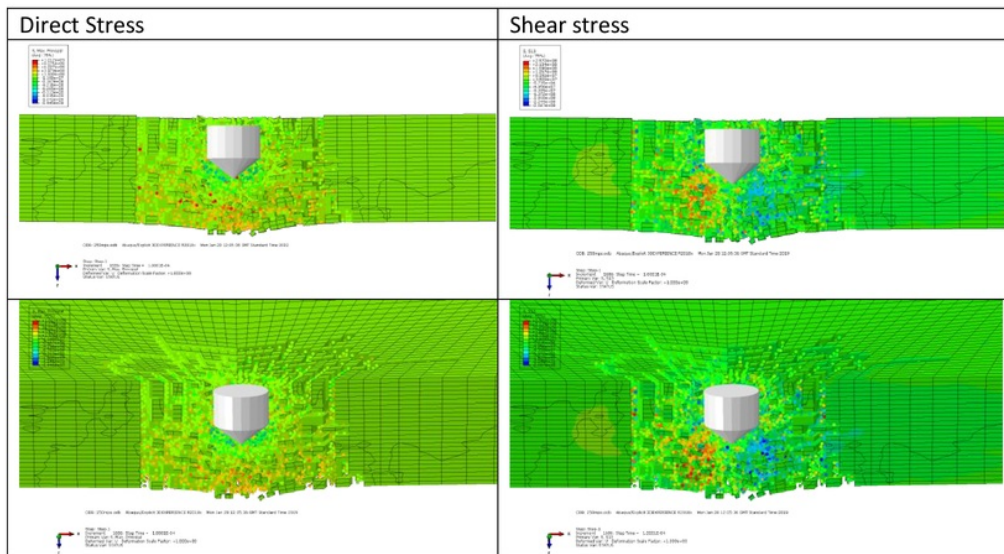


Figure 8 shows 250 ms^{-1} at 100 micro seconds

In this simulation shear stresses can be seen by the orange and blue colours as the projectile penetrates the plate. Areas of shear stress can be seen outside the main colours in dimmer patches of shear stress. The green elements in between the orange and blue are in equilibrium as the stresses act either side of the projectile. Tensile and compressive stresses are seen under the projectile as compressive stress and the bottom of the plate is in tension. The bottom of the plate can be seen bending under the tensile stress. Stress waves can be seen propagating on top of the plate in a circular form as the energy of the projectile is dissipated through the plate. These waves could be in the shape of a Hertzian cone. In this simulation the projectile is embedded in the plate however scabbing can be seen on the bottom of the plate as material is ejected but the projectile doesn't perforate.

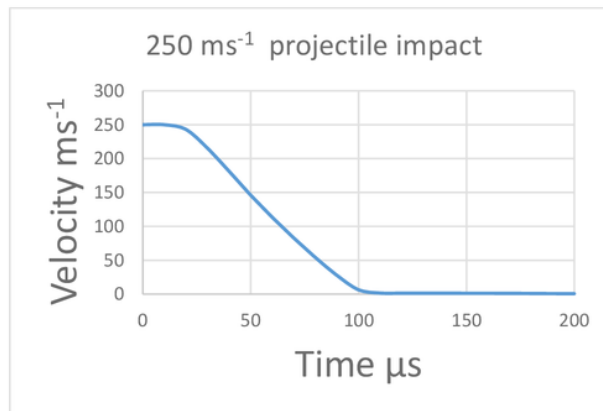


Figure 9 shows the velocity graph at 250 ms⁻¹

This graph shows how the projectile slows as it enters the plate and nearly reaches zero. This graph shows the projectile coming to rest after 100 μs however at 50 ms⁻¹ the projectile came to rest after 150 μs. At 50 ms⁻¹ the projectile takes longer to enter the plate and therefore spends less time in the plate whereas at a higher velocity it enters the plate sooner.

350 ms⁻¹

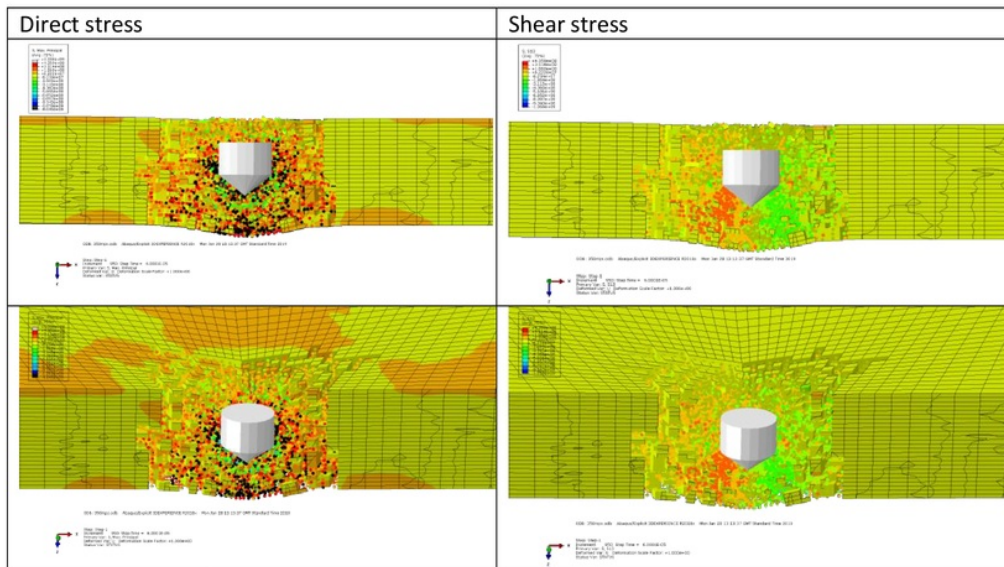


Figure 10 shows 350 ms⁻¹ at 60 micro second

At 350 ms⁻¹ the projectile was embedded in the plate. As with 250 ms⁻¹ shear stress was observed either side of the base of the projectile. At this timestamp direct stresses can be seen in tension at the top and bottom of the plate by the orange colours. These stresses will be caused by the plate bending due to the higher velocity. Body waves can be seen within the plate, these waves will be reflected waves from the fixed boundaries and could explain why no clear tension or compression can be seen around the projectile.

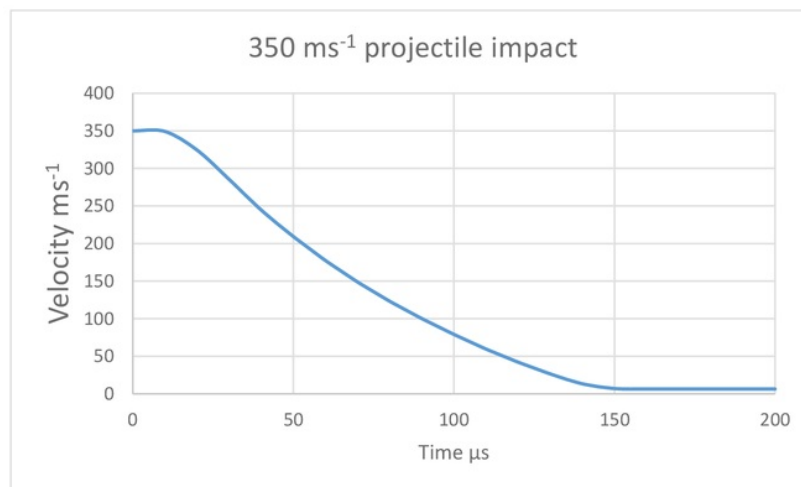


Figure 11 shows the velocity graph at 350 ms⁻¹

Figure 11 shows that at 350 ms^{-1} the projectile embeds within the plate. Again the velocity didn't reach zero due to the residual energy in the projectile. Unlike at 50 ms^{-1} the graph doesn't have a dip in it where the projectile relaxes within the plate, this is due to the higher velocity.

400 ms^{-1}

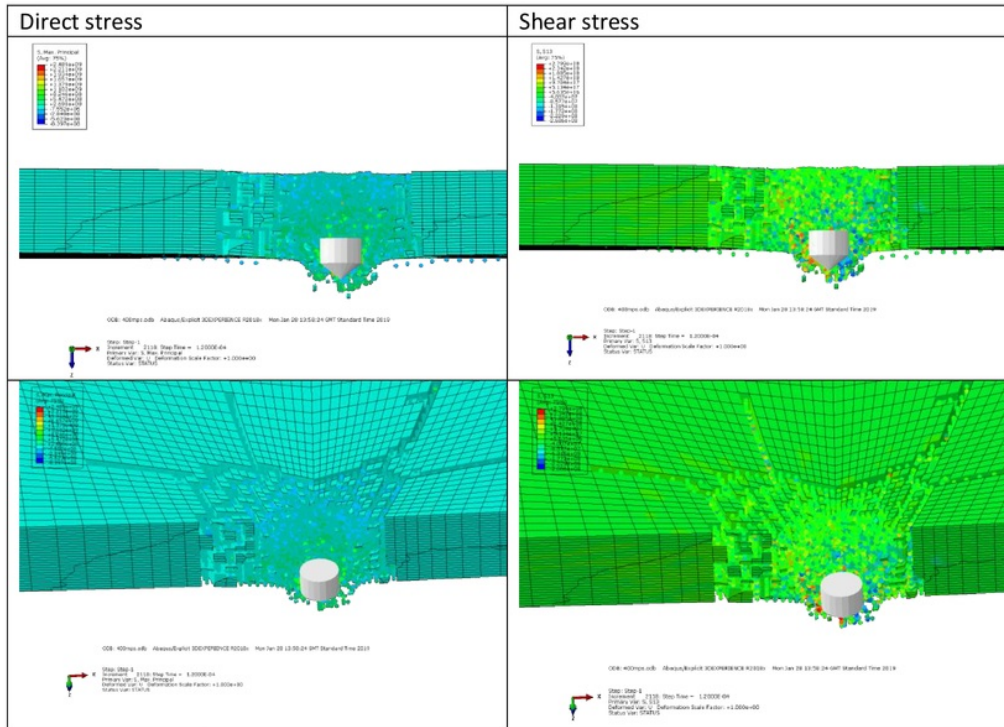


Figure 12 shows 400 ms^{-1} at 120 micro seconds

400 ms^{-1} was the fastest simulation that was run, as can be seen from Figure 12 the projectile perforates the plate. Large fracturing can be seen on the top face of the plate as the projectile exits. The shear stresses can be seen in material being ejected from the plate along with the projectile. Where the projectile entered the top of the plate compression is observed with tension where the projectile perforated the plate. As the projectile leaves the plate scabbing was observed with material leaving with the projectile. Because the projectile perforated the plate little bending of the plate was observed as the projectile spent less time in the plate.

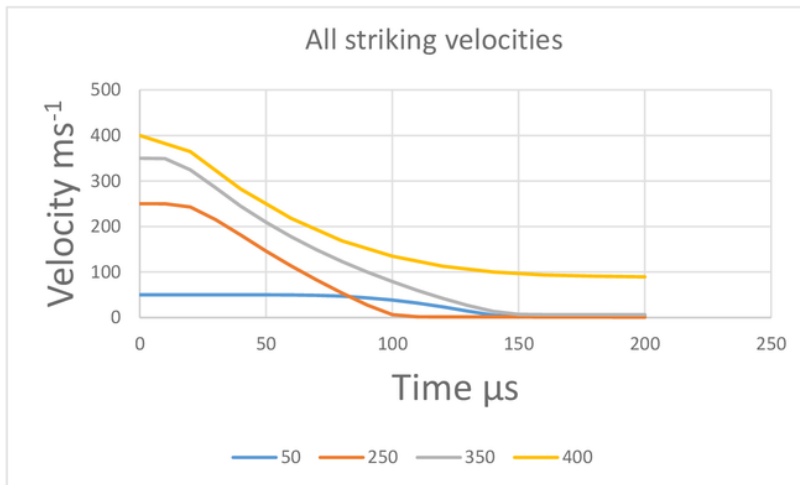


Figure 13 shows all striking velocities

Discussion

Perforation occurred at 400 ms^{-1} however when the projectile exited the plate it did so with no plug of material being ejected. Due to the high stress and strain rates of the aluminium used the hole is formed by ductile hole enlargement rather than shear stress forcing a plug out. The conical shape of the projectile will also help remove material rather than a blunt object pushing a plug out. [11] In this simulation the projectile was set up as non-deformable therefore no stresses were absorbed by it. This could also contribute to there being no plug ejected.

As can be seen in all simulations the maximum direct stresses of tension and compression are ten times higher than the shear stresses acting on the plate. This is because shear stress acts parallel to the load whereas direct stresses act perpendicular to the load.

At 350 ms^{-1} the projectile is embedded in the plate, at 400 ms^{-1} the projectile perforated the plate. From these two simulations it can be deduced that the ballistic limit of aluminium 7050 is between 350 ms^{-1} and 400 ms^{-1} .

Although not shown in the results images scabbing was observed at the edges of the plate at higher velocities. This scabbing is caused by the fixed boundaries on the edges of the plate. If the plate was larger this energy would be lost as the waves travelled a greater distance and the scabbing might not be observed.

Figure 13 shows the projectile velocity at all of the velocities simulated. From this it can clearly be seen that 400 ms^{-1} perforates the plate compared to the three other velocities. It can be seen that at the higher velocities the projectile slows down at a similar rate as the gradients of the curves are similar.

Recommendations

If this investigation were to be carried out again there are a number of recommendations I would suggest:

Using a quarter simulation would have two advantages. This involves modelling a quarter of the plate and a quarter of the projectile. As only a quarter is being used less nodes are required to mesh the components. Having only a quarter of the nodes would speed up the simulation run time. However these extra nodes could be used to give a finer mesh around the projectile impact area. The finer mesh would give better and more accurate results.

As the ballistic limit of the material was found to be between 350 ms^{-1} and 400 ms^{-1} running simulations at closer intervals would give a more accurate ballistic limit. This would greatly reduce the boundaries in which the ballistic limit falls.

Conclusion

From the simulations run and research carried out a number of conclusions can be drawn. The first being that even at a low velocity direct and shear stress are observed in the material as they were at higher velocities but the embedment depth was different. From the scales on the images it is seen that direct stress is ten times higher than shear stresses acting on the plate. By the projectile embedding at 350 ms^{-1} and perforating at 400 ms^{-1} it was observed that the ballistic limit must be between these two velocities.

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