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Computational Modelling of Ballistic Impact

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Abstract

This report is to identify key differences between specified materials when impacted by a steel bullet at 800m/s using Abaqus modelling software, analysing and evaluating the results. Areas which will be analysed and evaluated will be the effect of the material properties on bullet velocity, how the plate material is affected from initial impact through to after complete penetration with regards to stresses within the material, including compression, tension and shear.

This report will also elaborate on how the software is set up to simulate the problem, as well as how explicit solvers are used within the OME industry.

Keywords:

Johnson-Cook Material Properties

Stress

Compression

Tension

Abaqus

Copper

Titanium Alloy

Ductile/Ductility

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1 Introduction

Using Abaqus, a simulation was set up in order to understand the forces acting within a projectile and plate in the event of a ballistic impact.

This report will outline how the simulation was prepared, including creation of the simulated models, assignment of the material properties, meshing of the materials, application of load which will cause the ballistic impact, simulation of the impact and analysis of the results.

In order to provide further understanding, two different materials were used for the plate, Copper and Titanium Alloy Ti-6Al-4V. The material properties for the projectile were simple steel. These results were analysed and velocity of the projectile for each simulation plotted onto graphs for further understanding of effects different materials might have.

2 Setting up Abaqus for Simulation

2.1 Creating a Projectile

Firstly, a projectile shape was created on abacus using the 'Part' module. A Part was created using the 'Create Part' button, with the modelling base feature 'Revolution' selected. A shape was drawn for this, and the dimensions edited to create a projectile 0.032m in radius and 0.101m in length. The shape created was that of half of the cross section of projectile, which was then extruded by a 360-degree revolution, creating a cylindrical projectile.

2.2 Creating a Plate

Similarly to the projectile, a part was created for the plate, except this time the base feature 'Extrusion' was selected. This allowed for a rectangle to be drawn and extruded into a rectangular plate of dimensions Width/Depth/Thickness of 0.304m/0.304m/0.026m.

2.3 Creating and Assigning Properties

For this Simulation, 3 materials were chosen; simple steel, titanium alloy Ti-6Al-4V and copper.

The simple steel properties were provided by the lecturer and as follows:

Simple Steel	
Density(Kg/m ³)	7850
Youngs Modulus(GPa)	202
Poisson's Ratio	0.29

Table 1 - Simple Steel Properties

Only simple elastic properties were used for the projectile as it is the damage to the plate which will be identified later in the report.

The plates however were assigned Johnson-Cook properties, including temperature and damage model properties to ensure they acted or reacted

correctly. The original documentation of sources for these can be found in the appendices.

Titanium Alloy Ti-6Al-4V	
Density(Kg/m ³)	4428
Youngs Modulus(GPa)	119
Poisson's Ratio	0.33
A	987.8x10 ⁶
B	761.5x10 ⁶
C	0.01516
N	0.41433
M	1.516
T _{melt} (K)	1833
T _{Transition} (K)	298
Epsilon dot zero	1x10 ⁻⁵
D1	-0.09
D2	0.25
D3	-0.5
D4	0.014
D5	3.87
Fracture Energy	0

Table 2 - Titanium Alloy Ti-6Al-4V Properties [1,2,3]

Copper	
Density(Kg/m ³)	8960
Youngs Modulus(GPa)	124
Poisson's Ratio	0.34
A	90x10 ⁶
B	292x10 ⁶
C	0.025
N	0.31
M	1.09
T _{melt} (K)	1356
T _{Transition} (K)	298
Epsilon dot zero	1
D1	0.54
D2	4.89
D3	-3.03
D4	0.012
D5	1.12
Fracture Energy	0

Table 3 - Copper Plate Properties [3,4]

These properties were assigned to their respective parts using the 'properties' module within Abaqus.

Other properties included assembling the models together within the 'assembly' module, assigning the solution and solver using the 'step' module, creating and

assigning a load within the 'load' module, where the projectile was assigned a load of 800m/s, meshing the model using the 'mesh' module, and finally running the simulation using the 'job' module, allowing us to analyse the results of our simulation in the 'results' module.

3 Simulation Results

3.1 Titanium Alloy Ti-6Al-4V

The results of the simulation for the titanium alloy plate can be seen in the below screenshots, showing the stresses in the materials at each stage and including detailed descriptions.

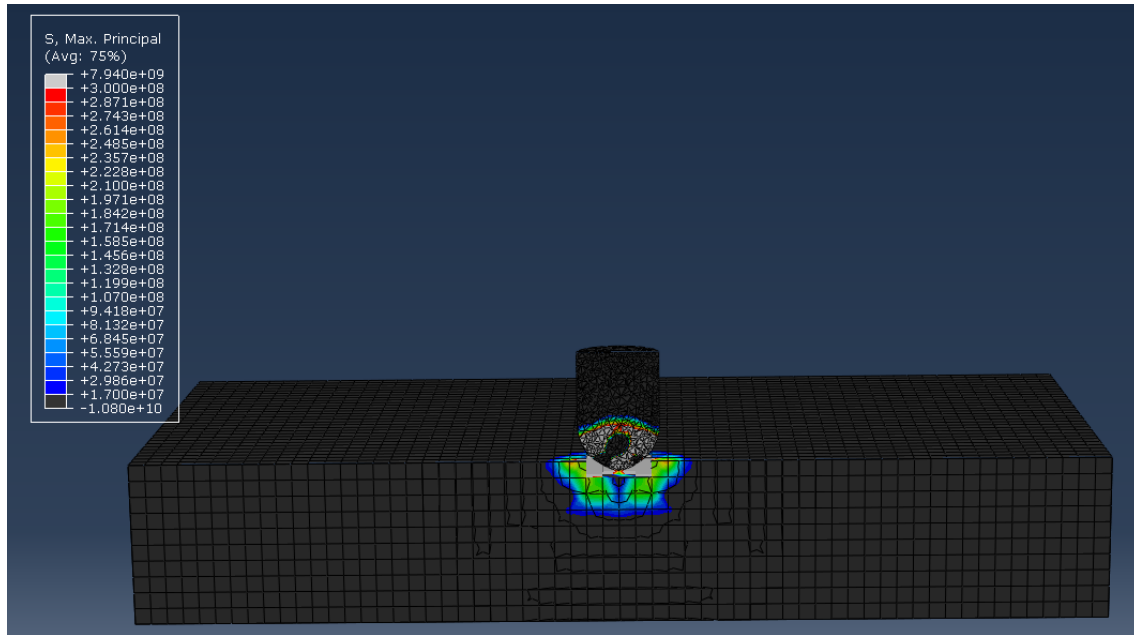


Figure 1 - Initial Impact of Projectile on Titanium Alloy Plate

This first screenshot shows the initial stresses in the materials upon immediate impact, where the stress is most focused not at the tip of the projectile, but in a circular area around the tip. This is due to shear stresses alleviating pressure buildup at the tip, however causing tensile stresses around in an outward fashion. Due to the strength and rigidity of the material the stresses have a short wavelength.

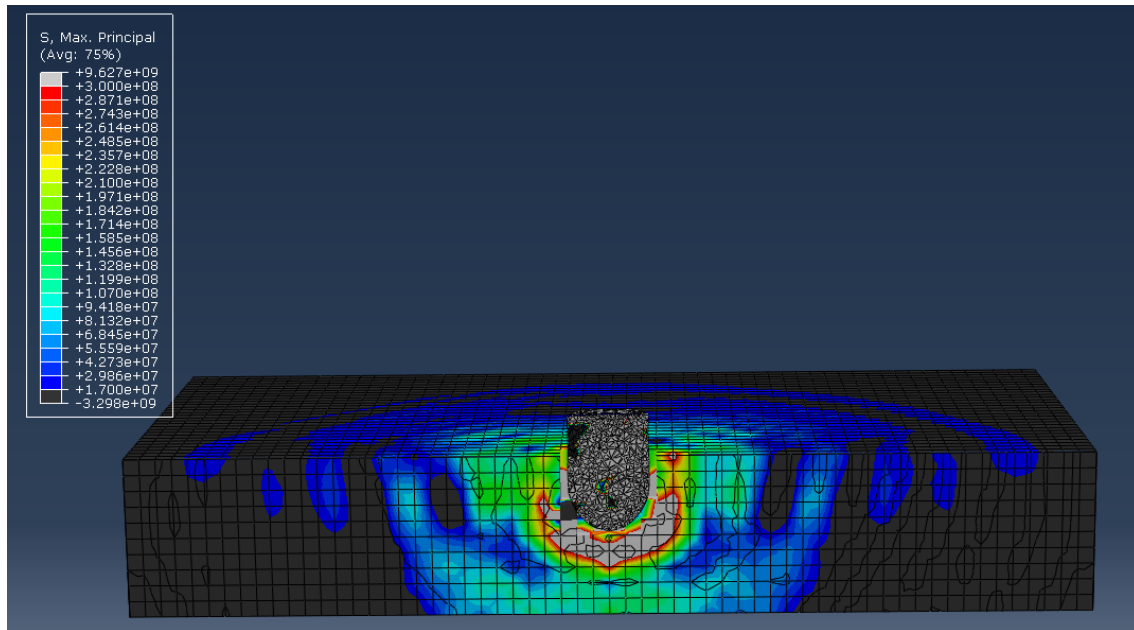


Figure 2 - Penetration of Titanium Alloy Plate

This screenshot describes the waves of extreme pressure through the body of the plate as the projectile continues to penetrate it. The highest pressure can be seen ahead of the vector of the projectile; this is due to the reaction of the alloy as it is compressed by tensile stress.

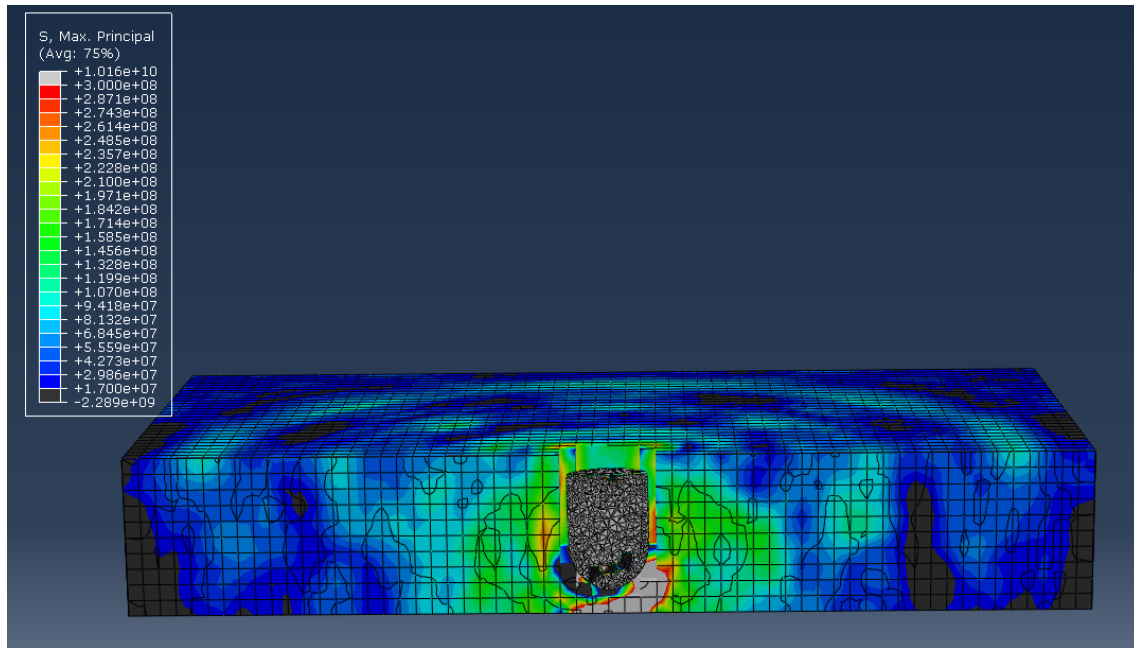


Figure 3 - Continued Penetration of Titanium Alloy Plate

As the projectile continues to penetrate the plate, the waves of stress travelling through the material intensify; it can also be seen that the focus of stress is shifted to one side more than the other, this is due to deflection within the material.

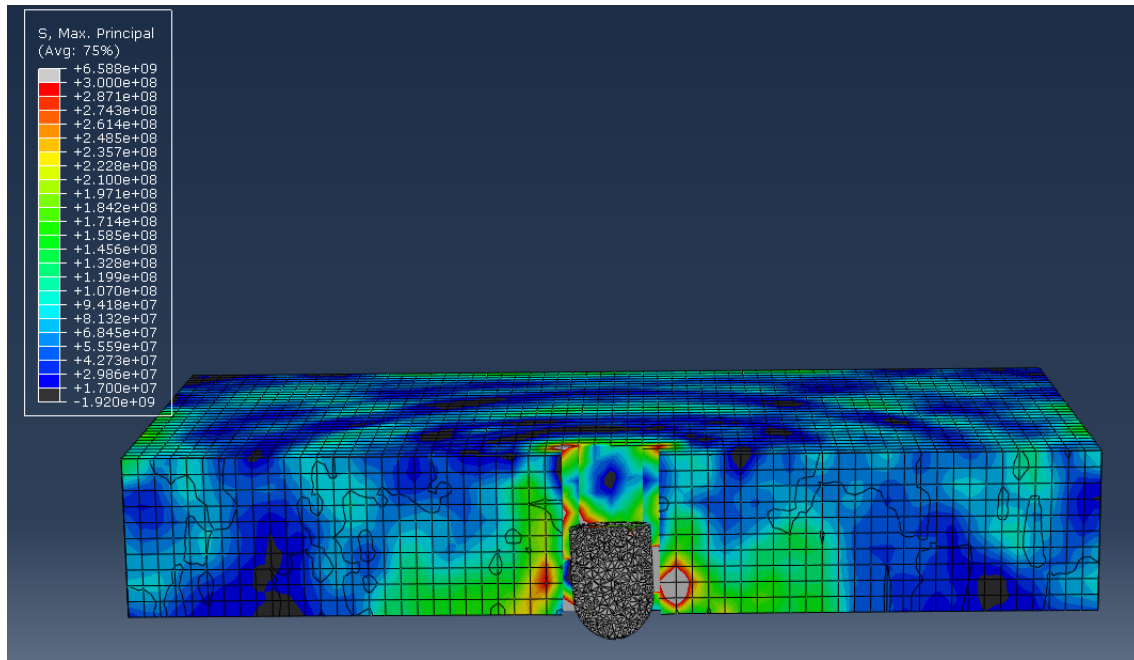


Figure 4 - Initial Breach of Titanium Alloy Plate

Upon initial breach it can be seen that the projectile has slightly deflected, thus causing an imbalance of tensile stress in the material shown on the right of the projectile within this screenshot. The stresses have travelled completely through the material at this point.

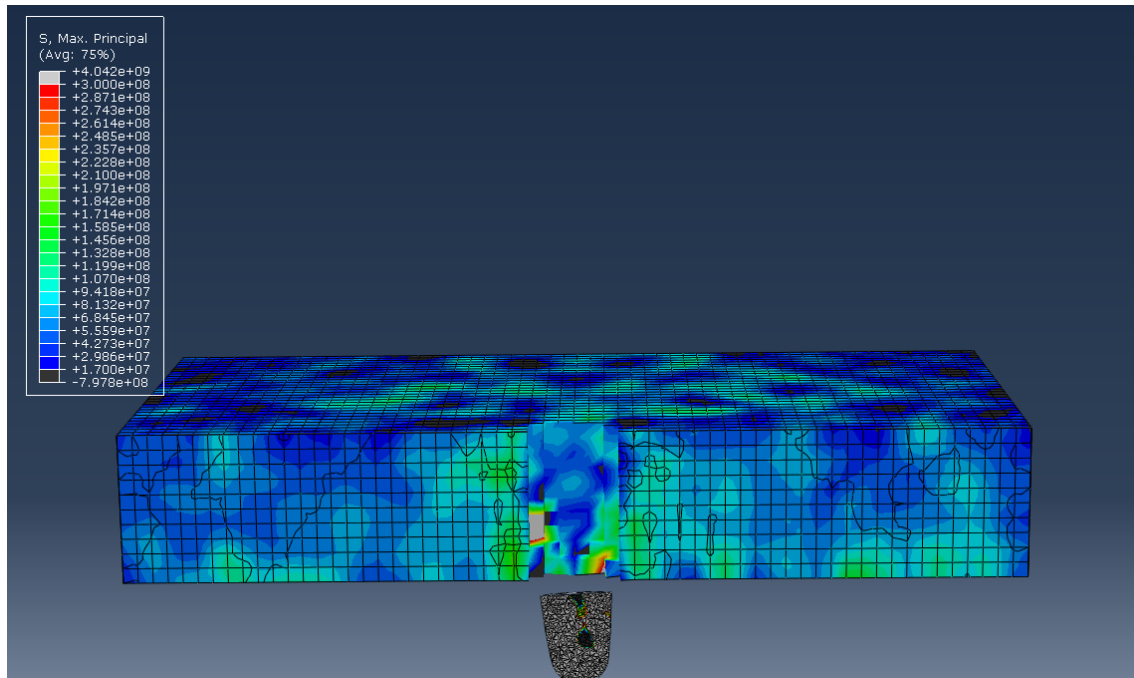


Figure 5 - Complete Penetration and Breach of Titanium Alloy Plate Including Deflection of Projectile

As the projectile has left the material, a clear deflection in the vector of the project can now be seen. Almost all extreme stresses have dissipated from the material, although the material is still at this point completely saturated by stress as the rippling waves of kinetic energy continue to move through the material.

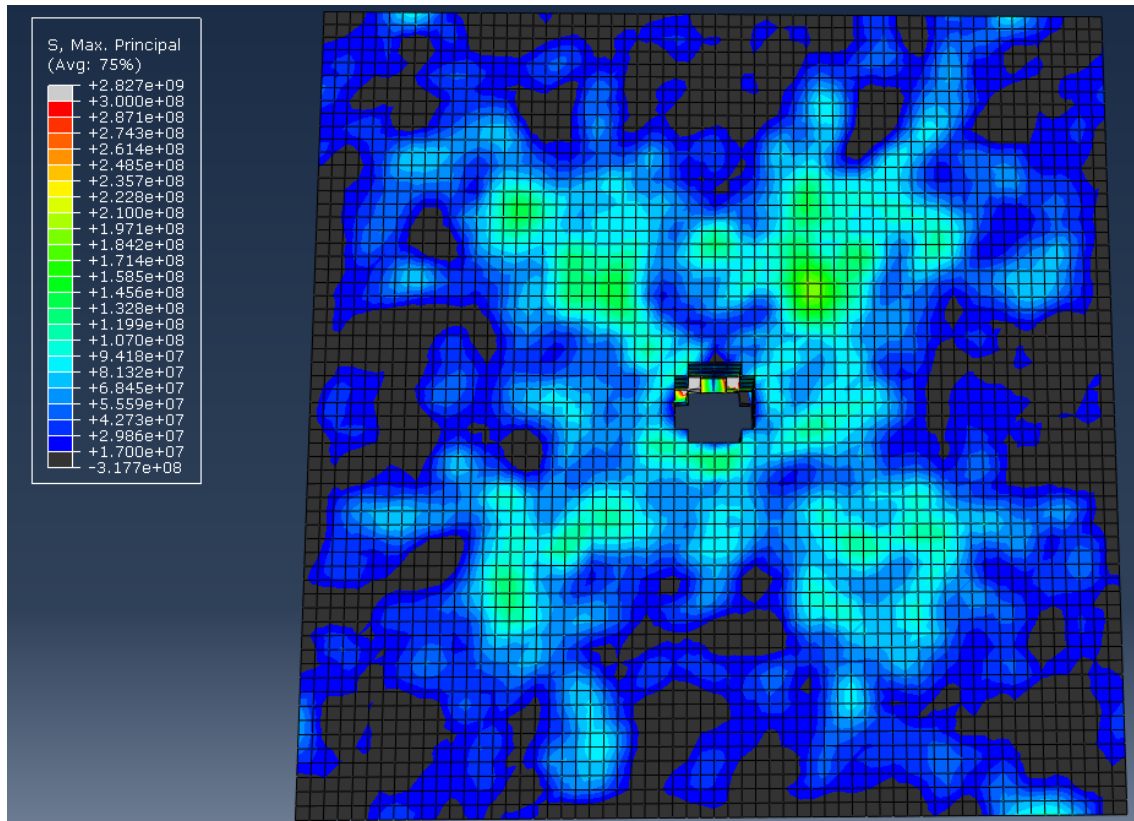


Figure 6 - Residual Stresses Through titanium Alloy Plate Following Penetration

This screenshot shows the aftermath of the projectile, with the stresses through the material beginning to return to a ground state. Around the penetration extreme levels of stress can still be seen, this is due to both the rigidity of the material and permanent deformation as a result of the impact and penetration.

3.2 Copper

The results for the simulation completed on the copper plate can be seen below at the same increments as was recorded and shown with the titanium alloy plate.

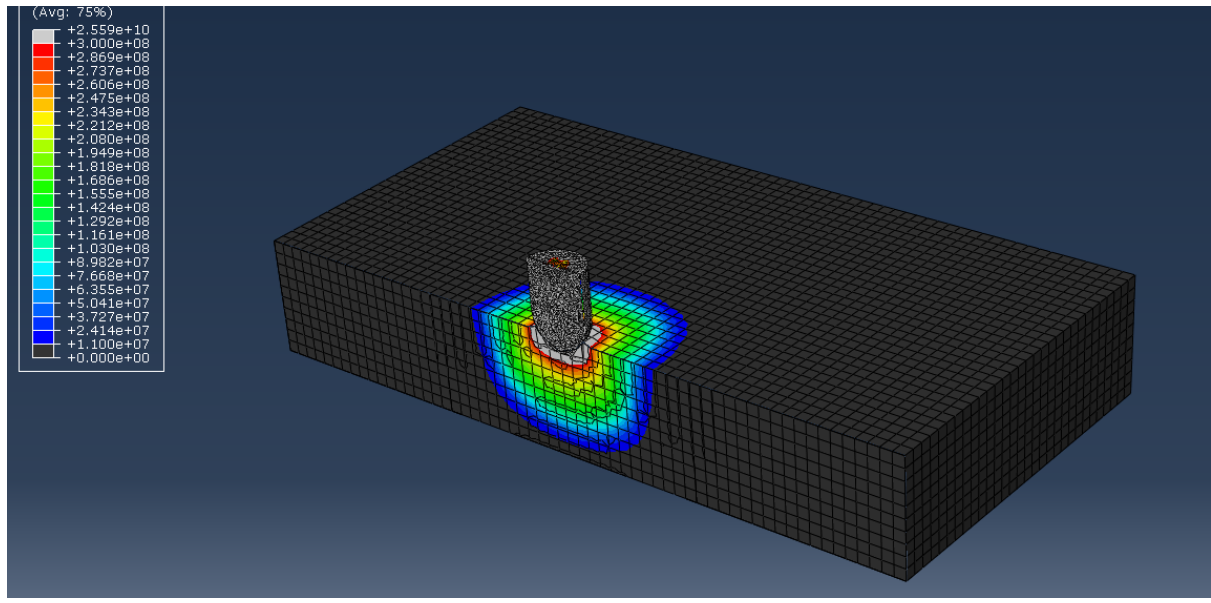


Figure 7 - Initial Impact of Projectile on Copper Plate

Upon initial impact the long wavelength of the stresses travelling through the copper plate could be seen. This is shown as uniformly distributed due to the ductile nature of the copper material absorbing vast amount of kinetic energy exhibited during the impact.

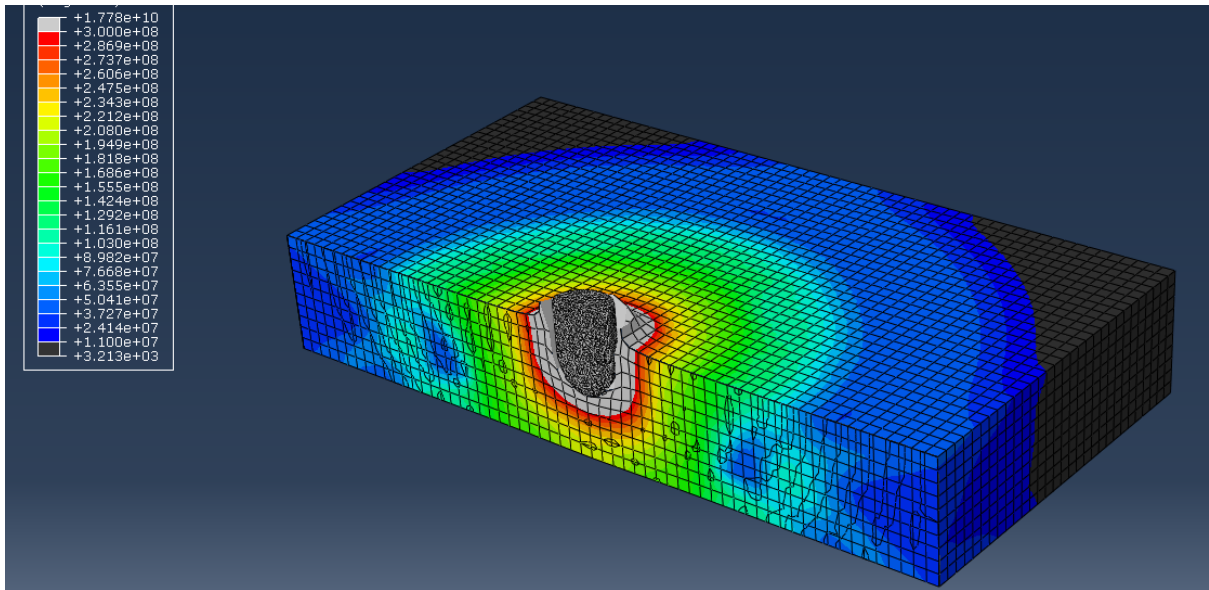


Figure 8 - Penetration of Copper Plate

Penetration of the copper plate can be seen here, with deformation around the opening due to the ductility of the copper material. This in turn has resulted in a long wavelength of stress.

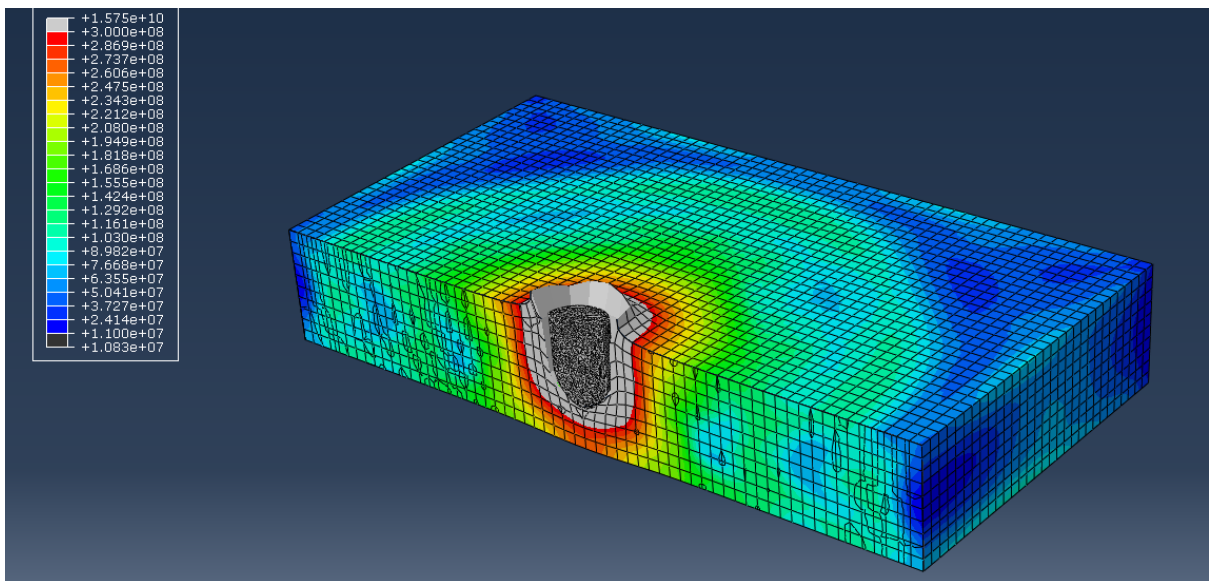


Figure 9 - Continued Penetration of Copper Plate

As the penetration continued, the absorption of kinetic energy can be represented by the illustrated volumes of stress occupying the material building up. At this point the entire plate had been subject to stress factors.

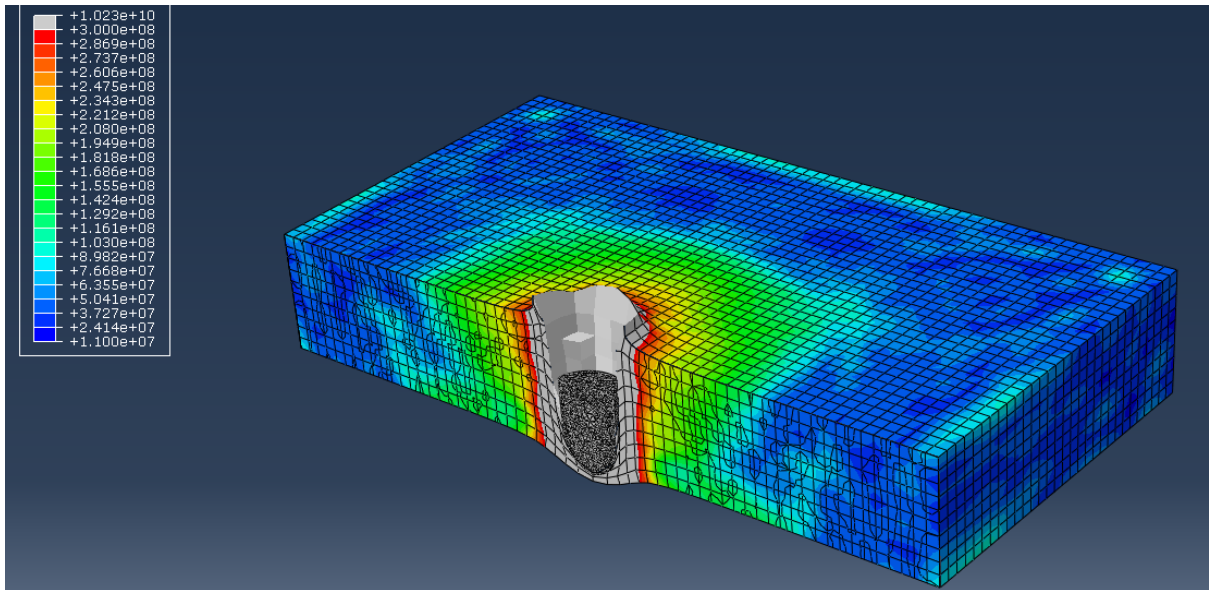


Figure 10 - Pre-Breach Deformation of Copper Plate

Prior to breaching the copper plate, the material was greatly stretched and deformed due to its ductility. This resulted in permanent deformations and residual stress around the penetration. A wave of reduced stress throughout the material can be seen here.

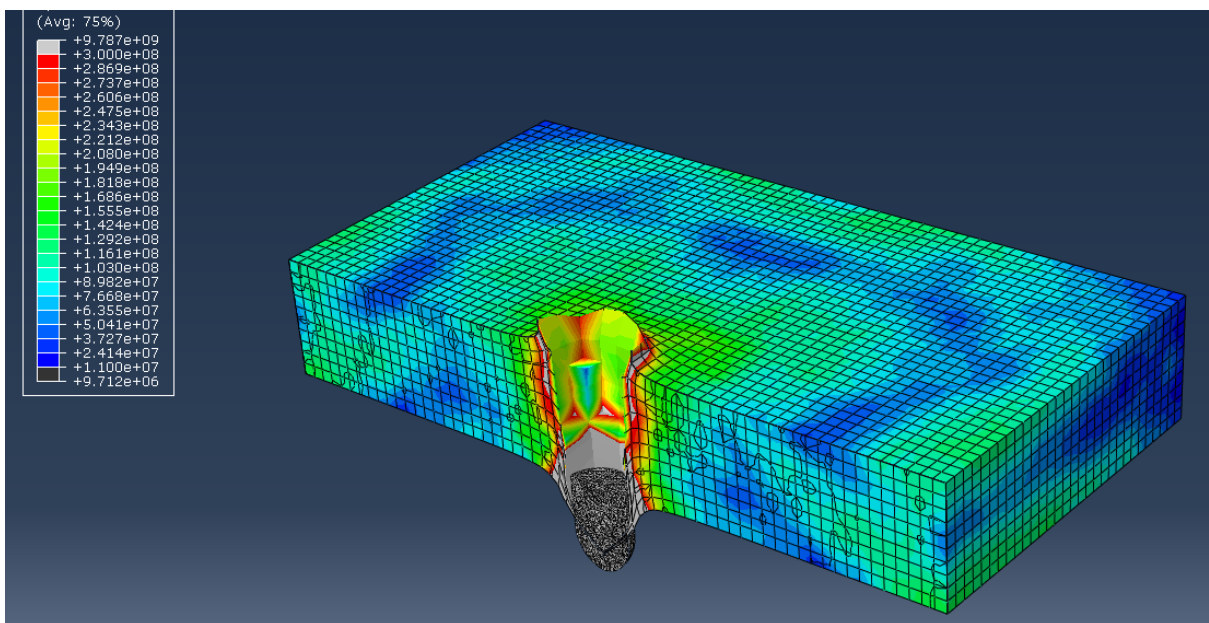


Figure 11 - Breach of Copper Plate

Once the copper plate was breached, the magnitude of deformation could be seen. It would be hard to tell at this point if the projectile was deflected at all just

be looking at the stresses, a measurement of the dimensions of the cross section of the projectile would need to be taken to understand what deflection there was, if any.

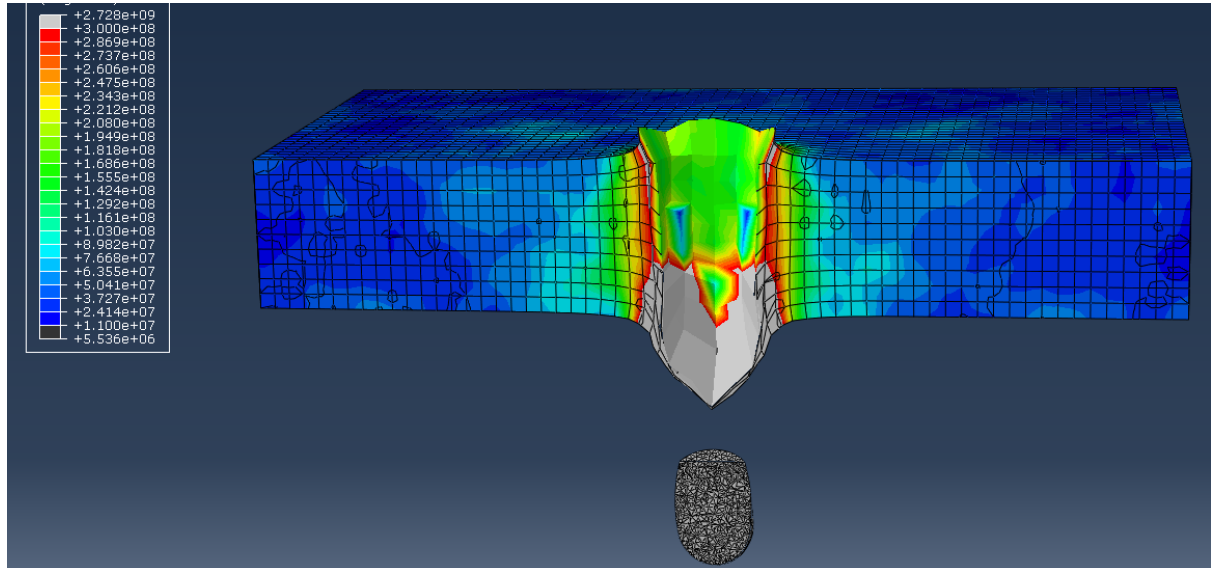


Figure 12 - Complete Penetration and Breach of Copper Plate

Following the complete penetration and breach of the copper plate, a full deformation of the material can be seen. A deflection of the projectile to change its vector away from the cross section can also be seen, both by the clear dimensions of the cross section of the projectile and by the profile of stresses in the penetration slightly above and central to the breach.

3.3 Plotting Velocity Graphs

3.3.1 Titanium Alloy Ti-6Al-4V

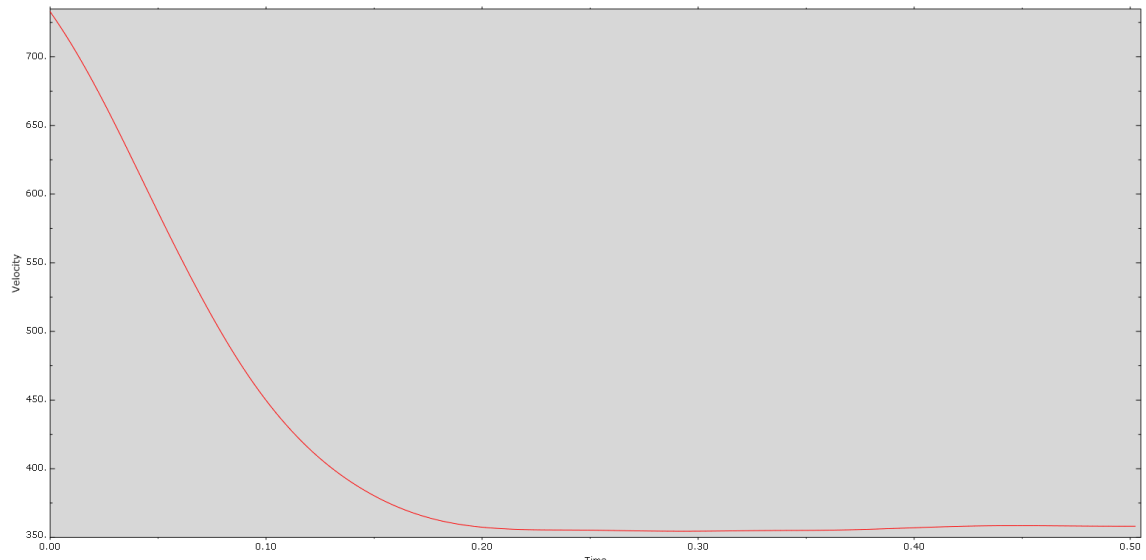


Figure 13 - Velocity Graph of Projectile Penetration Through Titanium Alloy Plate

This graph shows the plot of the velocity of the projectile from initial impact to complete penetration, through the titanium alloy plate. It can be seen that the initial impact of the projectile did not decrease the velocity by more than 40m/s, it was still travelling at a speed of around 360m/s following complete penetration.

3.3.2 Copper

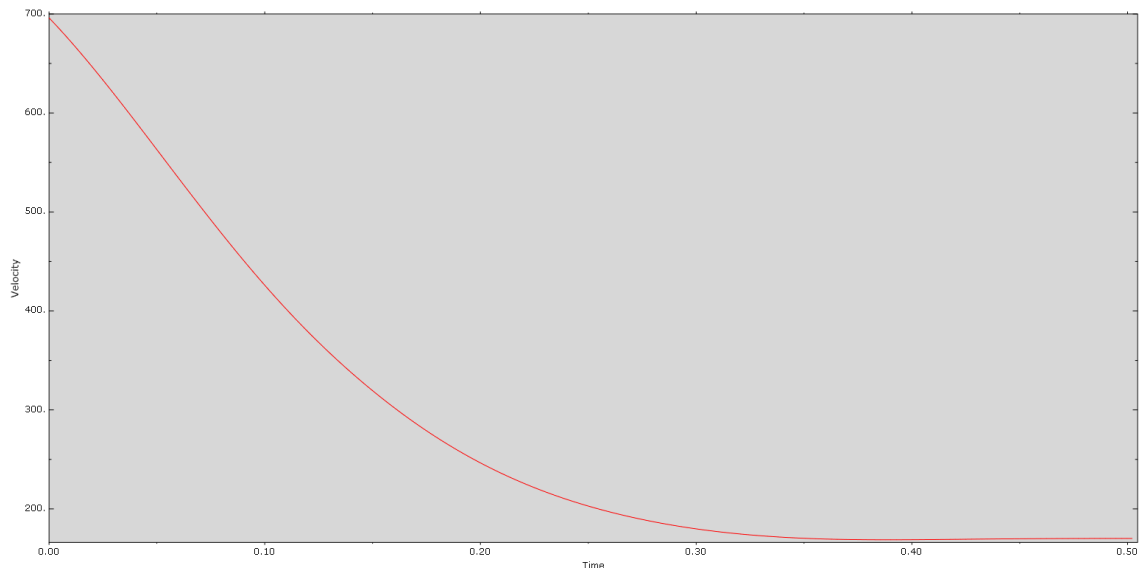


Figure 14 - Velocity Graph of Projectile Penetration Through Copper Plate

This graph shows the plot of the velocity of the projectile from initial impact to complete penetration, through the copper plate. It can be seen that the reduction in velocity of the projectile due to impact was far greater than that of the titanium plate, with the velocity after impact being decreased by more than 100 m/s, the final velocity is also far less at roughly 180m/s, demonstrating absorption of kinetic energy in the material having less deflection but more stopping power overall.

3.4 Comparison

3.4.1 Shear Stresses

In this section, a comparison between the two plate materials can be seen to analyse shear stresses. Each screenshot was a side by side of the same frame using abaqus' parallel port feature. The left simulation is the copper plate whilst the right is the titanium alloy.

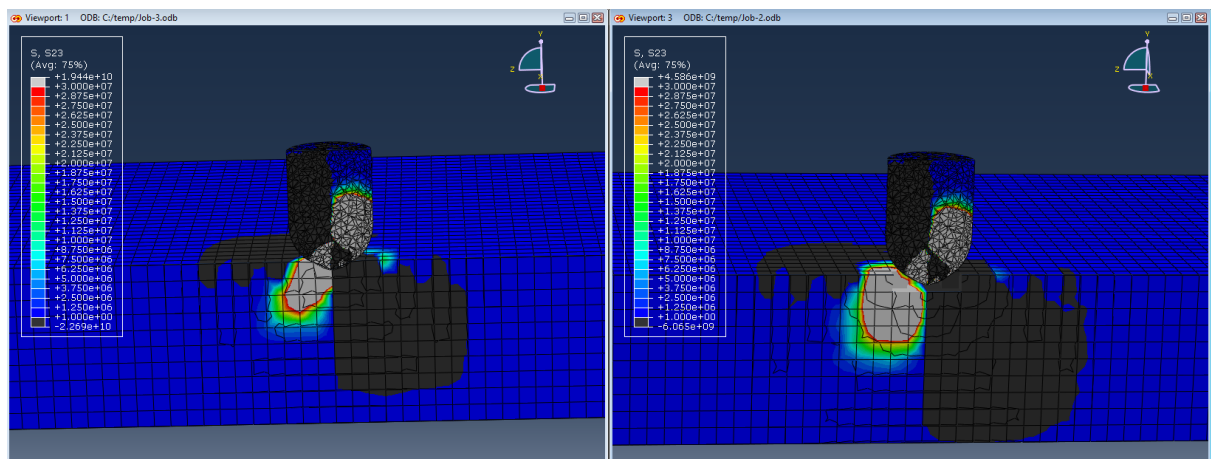


Figure 15 - Sheer Stress Comparison of Two Materials During Initial Impact

This screenshot shows the difference in shear stresses upon initial impact, where there was a far greater stress in the rigid and brittle titanium alloy, due to the ductility of the copper being able to absorb more of the stress throughout its structure.

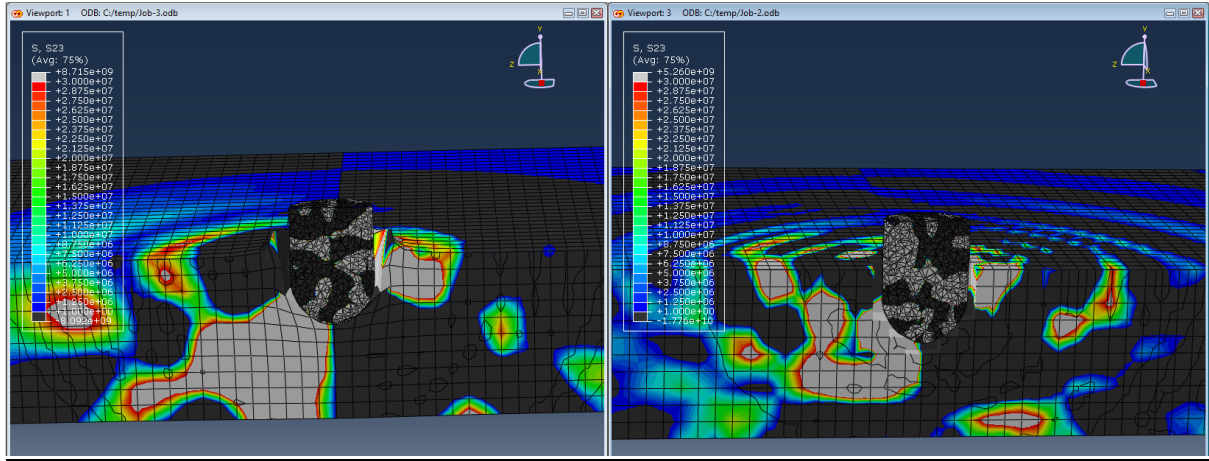


Figure 16 - Shear Stress Comparison of Two Materials During Penetration

During penetration of the two materials, the shear stress could be seen to reside in higher stresses more locally to the penetration in the titanium alloy than in the copper plate, which is to say shear stress dissipated more quickly for titanium.

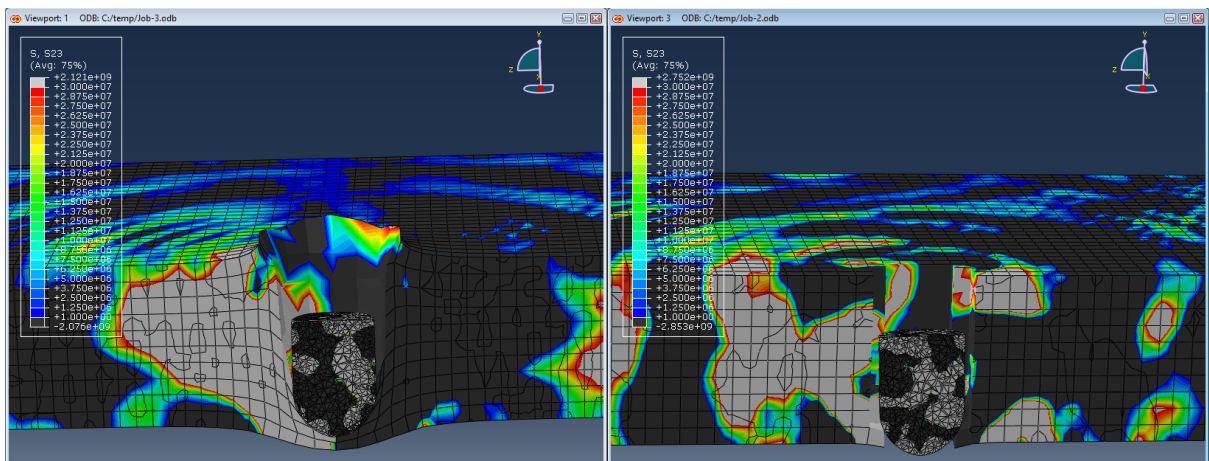


Figure 17 - Shear Stress Comparison Between Two Materials During Continued Penetration and Initial Breach of Titanium Alloy

During continued penetration, the copper plate absorbed more of the shear stress due to its conductivity, and as a malleable material it tended to plastically deform whilst the titanium alloys brittleness resulted in a clear breach and complete penetration earlier.

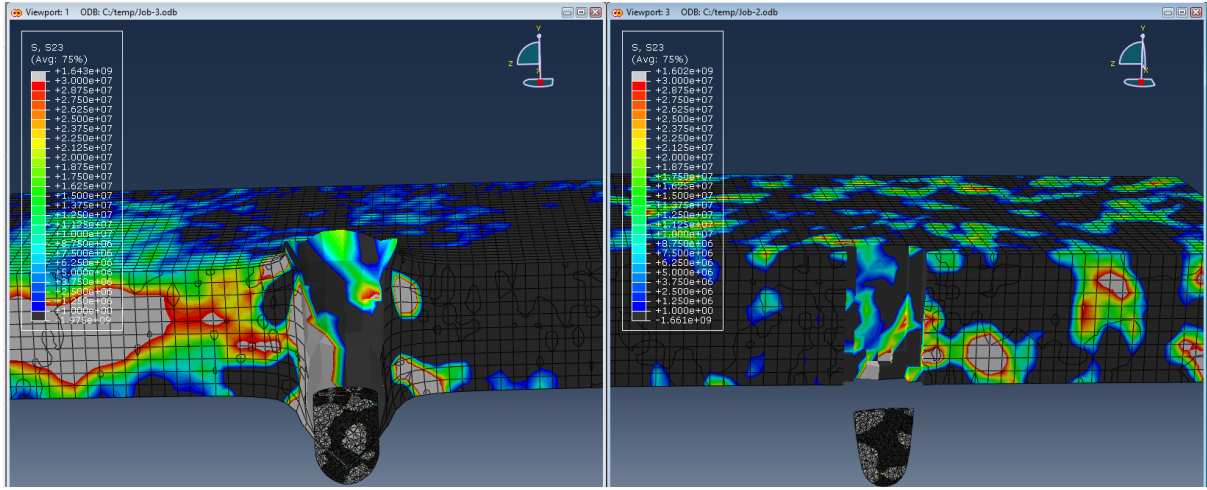


Figure 18 - Shear Stress Comparison Between Two Materials Following Breach and Clearance of Projectile

Once the projectile had completely penetrated both materials, it could be seen that the shear stresses remained throughout the copper plate for longer than in the titanium alloy.

3.4.2 Tensile Stresses

Similarly to the previous section, a comparison between the two plate materials can be seen, except this time to analyse the tensile stresses. As before each screenshot is a side by side of the same frame using abaqus' parallel port feature.

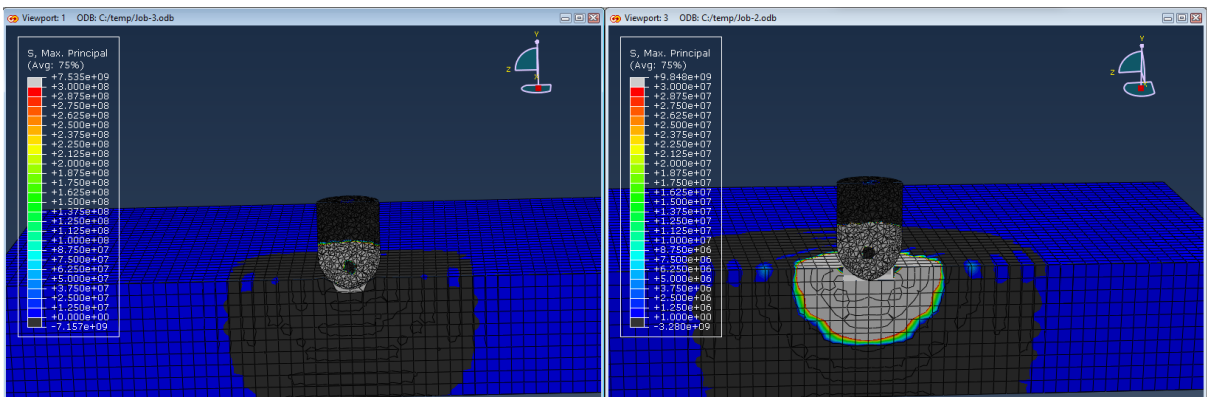


Figure 19 - Tensile Stress Comparison of Two Materials During Initial Impact

During the initial impact, the tensile stress was far greater in the titanium alloy, as its lack of ductility meant that compression of the material spread quickly throughout, whilst the copper plate absorbed the compression more locally.

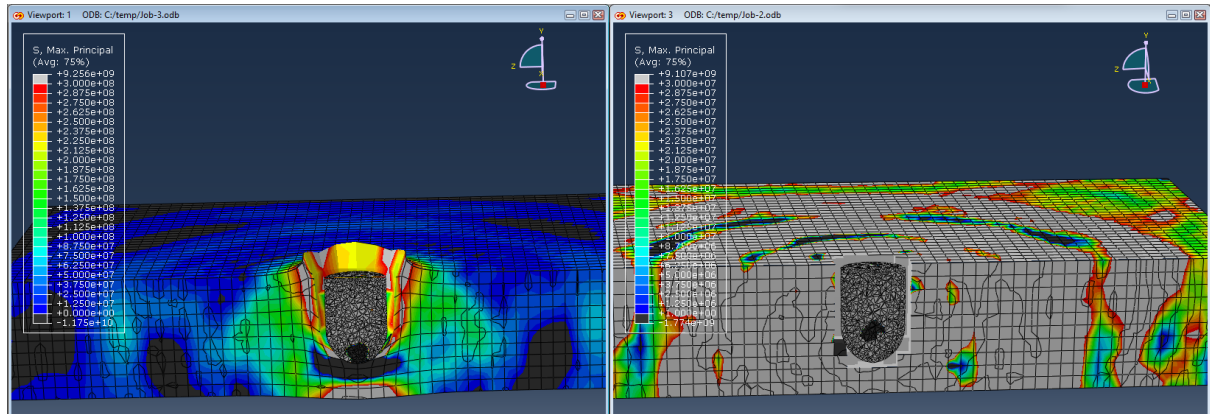


Figure 20 - Tensile Stress Comparison of Two Materials During Penetration

Furthering from the last screenshots description, the tensile stress can be seen here to be far greater throughout the titanium plate, whilst in the copper plate high levels of tensile stresses stayed local, with only low levels felt throughout the material.

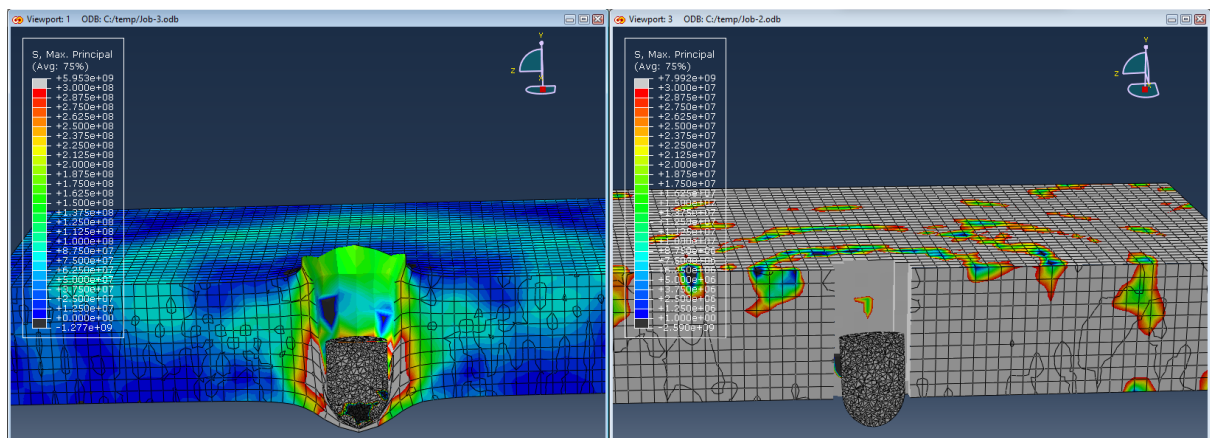


Figure 21 - Tensile Stress Comparison Between Two Materials During Continued Penetration and Initial Breach of Titanium Alloy

The tensile stresses continued to build through the titanium alloy, showing that the entire material felt the high pressures at the point in which the projectile first breached the plate, whilst the copper plate continued to absorb many of the stresses locally, with a slight increase in stress felt throughout the material.

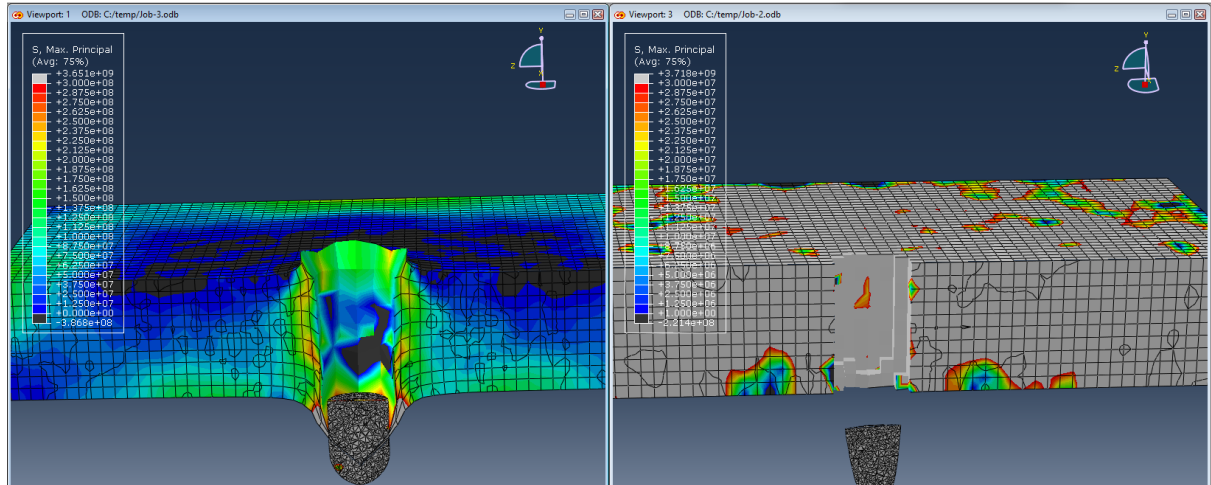


Figure 22 - Tensile Stress Comparison Between Two Materials Following Breach and Clearance of Projectile

Once the projectile had completely penetrated the plate, the tensile stresses can be seen to quickly begin to diminish within the copper plate, whilst in the titanium alloy the stresses remained throughout. The copper plate also can be seen to have exhibited higher levels of tensile stresses locally, as a result the material had deformed.

3.4.3 Tensile vs Shear Stresses (Probed)

During the analysis of the simulation, the materials were analysed on a finer scale by using the probe feature of abaqus to analyse the tensile and shear stress values of a single node for each material, to understand compression through the parallel and perpendicular planes of the material.

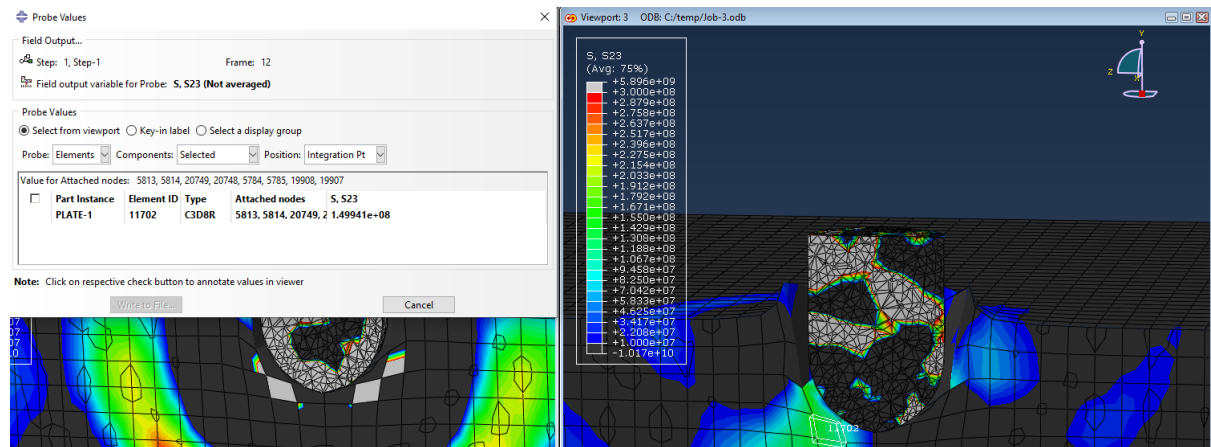


Figure 23 - Probed Shear Stress of Copper Plate During Penetration

The values here read that the shear stress at this point in the simulation was valued at 149MPa.

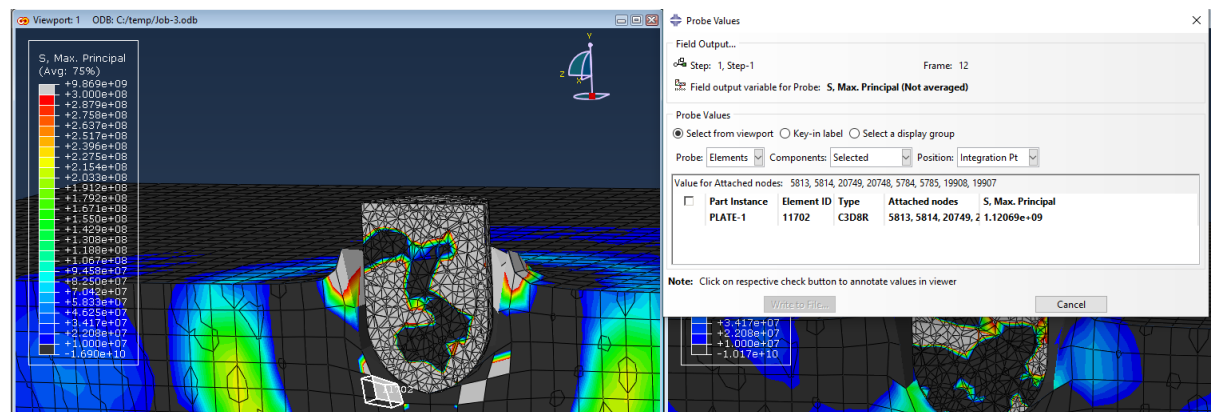


Figure 24 - Probed Tensile Stress of Copper Plate During Penetration

The values here show that the tensile stress read 1.12Gpa, just over 7.5 times more pressure felt by the shear stress, confirming that the material compressed more than it was cut by the projectile before splitting.

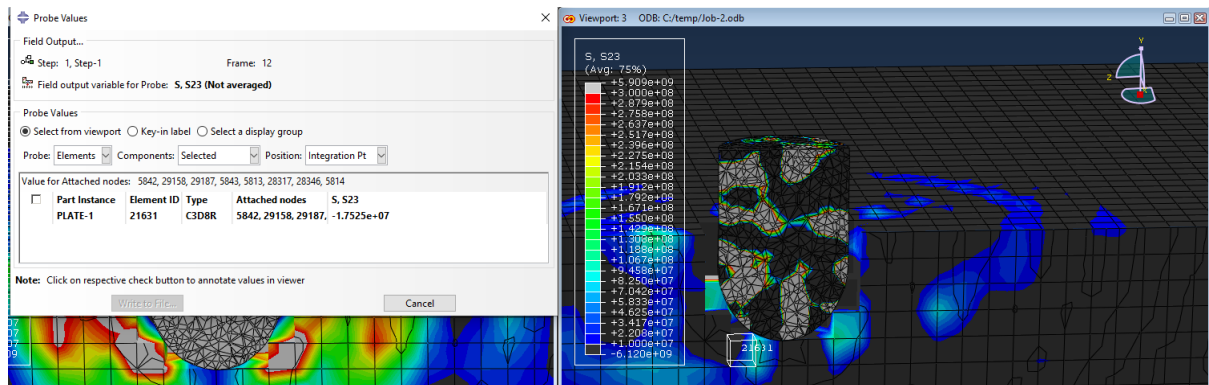


Figure 25 - Probed Shear Stress of Titanium Alloy During Penetration

The probe point used for the titanium at the same frame had to be taken from one layer lower, due to the fact that the material at the previously measure point had already been destroyed at this stage. The reading was 17.5Mpa, lower than the copper plate however this was a result of the difference in position.

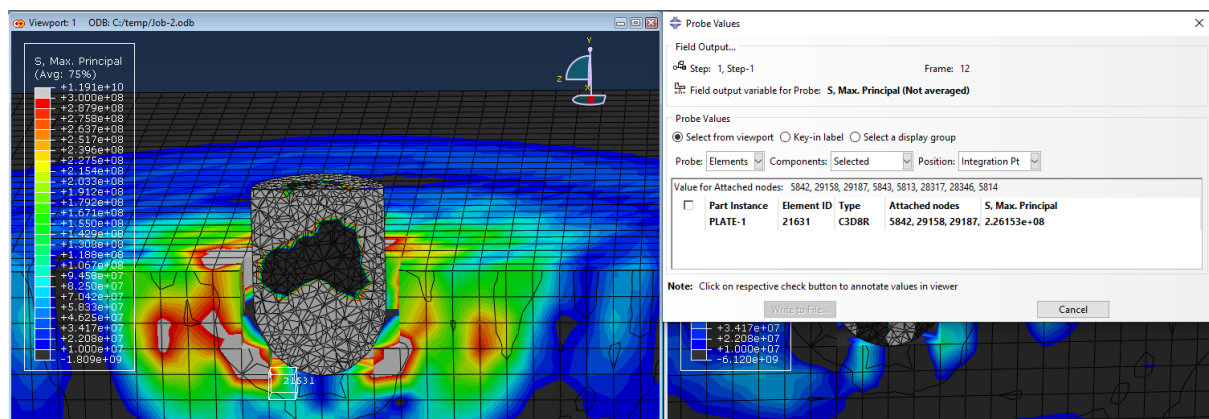


Figure 26 - Probed Tensile Stress of Titanium Alloy During Penetration

The Tensile stress felt at this same point was 226Mpa, which was more than 12 times that of the shear stress. This describes that the tensile stress felt throughout the titanium alloy, compared to the shear stress, was far greater than that of the copper plate, likely due to the ductility of the copper plate absorbing more of the tensile stress during the impact and penetration.

4 Summary and Evaluation

4.1 Summary

This simulation has looked at material properties of copper and titanium alloy, including how they react when impacted by a projectile moving at 800 m/s. It has clearly described the ductile and brittle natures of the materials, as well as elaborated on the shear and tensile stresses felt throughout the materials.

4.2 Applications in the OME Industry

Within the OME industry, two examples of explicit solvers are FLACS-CFD and EXSIM. [5, 6]

FLACS-CFD focuses on:

- Natural and forced ventilation as well as containment through leaks and dispersion of dangerous substances
- Vapour cloud explosions
- Jet and pool fires
- Hydrogen risks connected with the use of hydrogen as an energy carrier
- Blast wave propagation
- Industrial dust explosions

Whilst EXSIM looks at:

- How geometries and terrain affect explosions and their consequences
- Minimizing the impact of explosions through layout optimisation
- Optimising the design of explosion mitigation measures

These are important within industry when looking at component and whole system safety measures and applying operating procedures and boundaries or limitations so that catastrophic incidents are not exhibited.

4.3 Limitations and Approximations

Limitations of this type of simulation are that the program doesn't take into account any chemical reactions that may be experienced between the collision of the two materials and therefore could misinform of any damage or reaction as a result. An example of where this would be more important would be if the materials were made of aluminium and iron, where a thermite reaction may be experienced if the conditions were right vastly affecting the outcome of the simulation.[7]

Other limitations include the lack of fragmentation exhibited during the simulation, which would be important within the OME sector as fragmentation poses a significant threat to life.[8]

An approximation which can be understood by the software itself is that it assumes the materials are uniform throughout, whilst in the real-world materials are not uniform and instead are made up of grains, made as small as possible to try to achieve as close to uniformity as possible [9]. This can also be understood by the number of nodes available during the setup of the simulation, with the software being limited by the amount available to be used due to processing power.

4.4 Evaluation

In conclusion, the simulation provides a great baseline understanding of the different behaviours of different metal plates during the collision and penetration of a projectile, however there would need to be a higher level of accuracy to understand better the effects this would have in a real-world situation.

4.5 Future Direction of Simulation

Simulation is a great way to understand collision mechanics without the requirement to handle any potentially dangerous equipment or materials and provides detailed descriptions of a reaction between moving and static objects. It can be presumed that in the future, as computer programs become more and more

capable as well as the introduction of generative AI and AI learning programs, simulation programs will become more and more accurate until they almost completely replace field testing, with only the occasional assurance field test required to ensure the simulation software is calibrated correctly.

5 References

- [1] C.Salame, R.Bejjani and P.Marimuthu. "52nd CIRP Conference on Manufacturing Systems", *A better understanding of cryogenic machining using CFD and FEM simulation*. Page 1072. 2019.
- [2] X.Wei and J.Shi. "International Journal of Impact Engineering", *Validation of Johnson-Cook plasticity and damage model using impact experiment*. Pages 68-69. 2013.
- [3] R. Chakrabarty and J. Song. "Surface and Coatings Technology", *A modified Johnson-Cook material model with strain gradient plasticity consideration for numerical simulation of cold spray process*. Page 5. 2020.
- [4] H.B.Boubaker, A.Moufki, M.Nouari, P.Laheurte and A.Tidu. "18th CIRP Conference on modelling Machining Operations", *Thermodynamically consistent formulation coupling crystal plasticity theory and Johnson-Cook damage model to simulate micromachining of copper*. Page 510. 2021.
- [5] Gexcon. 2025. FLACS-CFD Solvers. Available at: <https://www.gexcon.com/gb/software/flacs-cfd/solvers/>. Accessed 20250514.
- [6] Det Norske Veritas. ND. EXSIM SOFTWARE. Available at: <https://www.dnv.com/software/services/plant/exsim-computational-fluid-dynamics-cfd-simulation-software-for-explosions/#:~:text=The%20EXSIM%20software's%20advanced%20explosion%20modelling%2C%20which,including%20hydrocarbons%20and%20emerging%20materials%20like%20hydrogen.&text=The%20EXSIM%20software%20can%20present%20overpressure%20predictions,wall%20failure%20and%20opening%20of%20blast%20panels>. Accessed 20250514.
- [7] Hird.S. 20241121. The Reactivity Series. Available at: <https://www.savemyexams.com/gcse/chemistry/aqa/18/revision-notes/4-chemical-changes/4-1-reactivity-of-metals/4-1-2-the-reactivity-series/>. Accessed 20250513

[8] Alameri.O and Elek.P. 20241015. Efficiency Analysis of Fragmentation Warheads Through Advanced Modeling Techniques: Experimental and Numerical Study. Available at:
<https://onlinelibrary.wiley.com/doi/full/10.1155/2024/3288510>. Accessed 20250513.

[9] Fu.M.W and Chan.W.L. 2011112. Geometry and grain size effects on the fracture behavior of sheet metal in micro-scale plastic deformation. Available at:
https://www.sciencedirect.com/science/article/pii/S0261306911004468?casa_token=rNGOmjnemdEAAAAA:RR5abfGggqKGal6SQVFrF25xuqqQzhCEG0pWhA6ljThYNTuaaW7Fj3jPEnlth8_5M15J8TdWIT4. Accessed 20250513.

6 Appendices

6.1 Screenshots of Johnson-Cook material and Damage Model Values Used

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face of the tool when compared to dry turning for the same cutting conditions [12]. When the cryogenic carbon dioxide exits through the delivery nozzle, it undergoes rapid expansion and a drop in pressure which causes a phase change according to the Joule-Thompson effect [13]. Based on the different parameters at delivery, the effect of the cryogenic fluid varies and affects the convection coefficient. This is why the nozzle diameter and position relative to the tool-chip interface play a critical role in determining the effect the fluid has on the machining process. These factors are largely overlooked in current literature and the effect on the convection coefficient is inconsistent and rarely mentioned in literature [14]. Values of the convection coefficient in literature vary from 3,500 to 74,950 W/m²K [14]. Pusavec et al. developed a finite differences model which calculates the convection coefficient in terms of the temperature difference between the workpiece and the cryogenic jet [14]. This model considers 1D heat transfer and ignores the heat generation due to machining, which is not the case in practice. In addition, Lequien et al. developed a CFD model to optimize the effect of the nozzle parameters while impinging a flat Ti64 plate and used it to determine the convection coefficient. However, this study does not take into consideration the tool-chip geometry and the heat generation during machining [15]. In this research paper, a 2D FE model is developed to determine the thermal conditions during orthogonal cutting of Ti64, mainly the temperature profile and heat generation rates in the primary, secondary and tertiary zones. These results are then used as initial conditions in a 3D CFD model, which simulates the cryogenic jet impinging on the tool-chip interface. The aim of this CFD model is to understand the effect of nozzle position on the physical parameters of the fluid coming in contact with the tool and workpiece, and the subsequent effect on cutting temperatures and tool wear.

2. Orthogonal cutting of Ti-6Al-4V

2.1. Modeling, meshing and loading

A 2D Finite Element analysis was used to model the orthogonal cutting of Ti64 using a thermo-coupled dynamic explicit analysis in ABAQUS v6.14. The tool material was set as uncoated carbide while the workpiece material was set as Ti64. The properties of each material are summarized below in table 1. Both the work piece and the tool are modelled as deformable bodies and provided with temperature properties. A plain strain model of 1mm thickness is generated. The tool has a 5 degree rake and a 5 degree clearance angle. Surface to node interaction is created between the tool and the work piece and simple Coulomb friction is assumed between the tool and the work piece. The value of the friction coefficient is taken to be 0.3, which was used in available literature [16,17]. The bottom part of the work piece is constrained in all degrees of freedom, whereas the tool is free to move only in the “x” direction with the cutting speed assigned. The speed is set as 150m/min while the feed rate is set as 0.3mm/rev. Both the work piece and the tool are meshed using Lagrange meshing. The meshing element used is the CPE4RT element, which is

a 4-node plane strain thermally coupled quadrilateral element with bilinear displacement and temperature.

Table 1. Material properties of work piece and the tool.

Parameter	Work Piece	Tool
Young's Modulus	119 GPa	686
Poisson's Ratio	0.33	0.22
Specific heat	570 J/kg/°C	197 J/kg/°C
Thermal Conductivity	7.3 W/m·C	162 W/m·C
Density	4512 kg/m ³	15800 kg/m ³
Friction Coefficient	0.3	

2.2. The Johnson-Cook material and damage models

The Johnson-Cook (J-C) material and damage model is applied to the workpiece to initiate the chip formation process and determine the flow stress of the material with respect to strain, strain rate and temperature effects. The Johnson and Cook equation, is of the following form, [18]

$$\bar{\sigma} = \left[A + B(\bar{\epsilon})^n \right] \left[1 + C \ln \left(\frac{\dot{\epsilon}}{\beta} \right) \right] \left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right] \quad (1)$$

Where $\bar{\sigma}$ is the equivalent stress, A is the initial yield stress at room temperature, B is the hardening modulus, C is the strain rate factor, n is the work hardening exponent, m is the thermal softening coefficient. The strain rate $\dot{\epsilon}$ is normalized with a reference strain rate $\beta = 1.0$. Finally, T_{room} and T_{melt} represent the room temperature and melting temperature. The first factor characterizes the strain hardening of the yield stress, the second represents the increase in the yield stress at elevated strain rates and the third factor models the reduction in the material's yield stress caused by thermal effects [18]. The damage model proposed by Johnson and Cook is used in conjunction with the J-C yield model. The damage model will govern when fracture occurs, and the concerned element is removed from computation. The Johnson Cook material and damage values for Titanium alloy Ti64, namely A, B, C, D_n, n and m, are summarized in table 2 below [18].

Table 2. Johnson Cook material and Damage model values for Titanium alloy

Parameter	Value	Parameter	Value
A	987.8 MPa	D ₁	-0.09
B	761.5 MPa	D ₂	0.25
C	0.01516	D ₃	-0.5
n	0.41433	D ₄	0.014
m	1.516	D ₅	3.87

2.3. FEM Results

2.3.1. Stress distribution

The Von Mises stress distribution is shown in fig. 1. First, the chip shape and segmentation of the chip are in agreement with available literature [20], which shows that the Johnson-Cook parameters used are accurate. The stress attains maximum values at the primary shear zone, lesser values at the secondary shear zone and the least values at the tertiary shear zone, which also proves the accuracy of the results.

Figure 27 - Johnson-Cook Material Properties and Damage Model Values for Titanium Alloy.

2.2. Experimental procedure

FOD tests were conducted at ambient temperature using a gas-gun apparatus available at the United Technologies Research Center (UTRC). The FOD test method is capable of introducing deformation and damage in the Ti-6Al-4V substrate that is representative of the real impact conditions such as high strain rate effects on material deformation. Fig. 1a shows a schematic of the FOD test

Table 1
Basic mechanical properties of target and projectile materials.

Material properties	Symbol	Alumina	Steel	Ti-6Al-4V
Density	ρ (kg/m ³)	3902.5	7971	4428
Young's modulus	E (GPa)	300	203.6	109.8
Poisson's ratio	ν	0.21	0.3	0.31
Yield stress	σ_y (MPa)	—	2340	1098

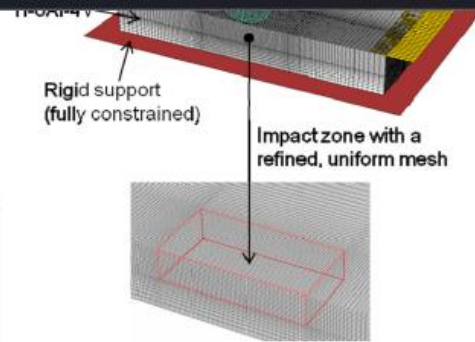


Fig. 2. FE model of the FOD test.

Table 2
Material parameters for Ti-6Al-4V.

Material properties	Symbol	Ti-6Al-4V
Density	ρ (kg/m ³)	4428
Shear modulus	G (GPa)	41.9
Poisson's ratio	ν	0.31
J-C yield strength	A (MPa)	1098
J-C hardening coefficient	B (MPa)	1092
J-C strain hardening exponent	N	0.93
J-C strain rate constant	C	0.014
J-C softening exponent	M	1.1
Melting temperature	T_m (K)	1878
J-C damage constant	d_1	-0.09
J-C damage constant	d_2	0.27
J-C damage constant	d_3	0.48
J-C damage constant	d_4	0.014
J-C damage constant	d_5	3.87
Elastic bulk wave velocity	C_0 (km/s)	5.13
Slope in u_x vs. u_y diagram	S	1.028
Grüneisen coefficient	γ_0	1.23
Fracture toughness	K_{IC} (MPa m ^{1/2})	49.9–100
Specific heat	c (J/kg °C)	560
Heat fraction	α_0	0.9

of the impact analysis. In other words, the chosen mesh needs to ensure that the model can provide a convergent solution (i.e., errors of displacement and plastic strains comparing with those from a finer mesh model are less than 5%), predict the experimental measurements, and allow the maximum saving of the computational cost. The results presented in this paper are based on this optimized mesh.

In the simulation, the alumina projectile was modeled as elastic and the steel one as elastic–plastic, with the parameters given in Table 1. A more sophisticated material model was employed for Ti-6Al-4V to simulate the dynamic response and will be discussed next.

3.2. Material models

In impact analysis, the material constitutive law should include strain rate dependency for both material deformation and failure. This study investigates the J–C material model in conjunction with Mie–Grüneisen equation of state (EOS) model to simulate the response of Ti-6Al-4V under FOD impact conditions.

Figure 28 - Johnson-Cook material Properties for Titanium Alloy

Table 1

Simulation and material parameters for Copper, Al6061-T6 and Ti-6Al-4V. (* marked parameters are determined by fitting experimental stress-strain rate data with Eq. (3)).

Parameters	Copper [60,76]	Al6061-T6 [34,63,77,78]	Ti-6Al-4V [61,79,80]
Density (g/cc)	8.96	2.70	4.43
Young's modulus (GPa)	124	70	110
Poisson's ratio	0.34	0.33	0.33
Heat capacity (J/KgK)	383	875	670
Melting temperature (K)	1356	775	1833
A (MPa)	90	324	724
B (MPa)	292	114	683
n	0.31	0.42	0.47
C	0.025	0.002	0.035
m	1.09	1.34	1
$\dot{\epsilon}_0$	1	1	1e-5
T_{ref} (K)	298	298	298
*Fitting Parameter D	0.1532	0.2902	0.032
*Fitting Parameter $\dot{\epsilon}_c$	451.6	3.243	247.1
α	0.5	0.3	0.4
Shear Modulus (GPa)	39	26	44
Burgers vector (nm)	0.256	0.286	0.3

2.3. Material parameters

Based on mechanical properties, different materials undergo distinct deformation behaviors during cold spray [14,18]. For instance, Schmidt et al. [65] reported different critical velocities for hard and soft materials, with harder materials like titanium and steel having higher critical velocities than softer materials like copper and aluminum. Consequently, in the present study we considered both soft (copper, Al6061-T6) and hard (Ti-6Al-4 V) materials, to show the general validity of our material models. The relevant material parameters used in the simulations are given in Table 1.

3. Results and discussions

Given the difference in available experimental data and material responses, below we present results and discussion separately for different material systems examined.

3.1. Copper

Fig. 4a shows the cross-section image of a copper particle sprayed on a copper substrate at 500 m/s, from the work of Li et al. [76]. Using Eq. (10), and the splat width and height measurements from Fig. 4c, the initial diameter of the spherical copper particle can be inferred to be about 41 μm . The parameters for the modified JC model were determined by curve fitting the experimental stress vs. strain rate data (see Fig. 4b) using Eq. (3). R-squared measure of the closeness of the data to the fitted regression line is also given in Fig. 4. The comparison between experimental data and the JC model predictions can be seen in Fig. 4c.

It can be seen from Fig. 4b that our modified JC model enables an accurate representation of the high strain rate increase in strength as the material experienced in experimental results. The predicted stress-strain behavior on the base of our modified model is shown in Fig. 4c, in comparison with the one predicted by the original JC model and experimental data. We can see that our modified model yields a stress-strain response much better agreed with the experimental data than the original JC model. Meanwhile, Fig. 5 shows the morphologies and stress evolution for the deformed copper particle for the original JC, modified JC w/o SGP and modified JC w/ SGP.

As previously described, our modified JC models would provide improved deformation responses than the original JC model, in particular, higher strength and less deformation at high strain rates. This is well demonstrated in the comparison shown in Fig. 5, where the modified JC models show far lesser jetting and much higher stresses in the particle. The higher stress predicted by the modified JC models resulted in lower strain and consequently lower flattening of the particles. This also resulted in the different stress distribution within the

Figure 29 - Johnson-Cook Material Properties for Copper and Titanium Alloy

[24], the polycrystalline copper workpiece contains equiaxed grains with average size of 0.8 mm and random crystallographic orientation.

The workpiece is divided into two regions: the first one, which represents the cutting domain ($3 \times 0.213 \times 0.5$ mm) is meshed with uniform C3D8RT elements with mesh size about $0.02 \times 0.02 \times 0.05$ mm. The second domain, which is not machined, is meshed with non-uniform C3D8RT elements for reducing the computation costs. The friction at the tool/chip interface is modeled using the Coulomb friction law. The friction coefficient is estimated for each cutting simulation using the experimental cutting and thrust forces data. The parameters used to formulate the constitutive equations are reported in Table 1. Table 2 lists the parameters of the damage model used in the current micromachining simulation of polycrystalline copper.

$\frac{k}{h^3}$ (MPa/K)	μ_0 (MPa)	n	$g_{0\epsilon}$	q_ϵ	p_ϵ
0.823	42000	20	1.60	1.0	0.66
τ_{ex0} (MPa)	$\dot{\epsilon}_{ex0}$ (s^{-1})	κ	τ_a (MPa)	$g_{0\epsilon x}$	$\dot{\epsilon}_{ex}$ (s^{-1})
667.66	$5.66 \cdot 10^{10}$	2	8.24	0.235	10^4

Table 1. Parameters used to formulate the constitutive equations [22, 21].

D_1	D_2	D_3	D_4	D_5	Y_0	m
0.54	4.89	-3.03	0.012	1.12	0.01	9

Table 2. Parameters of the J-C damage model [13, 25].

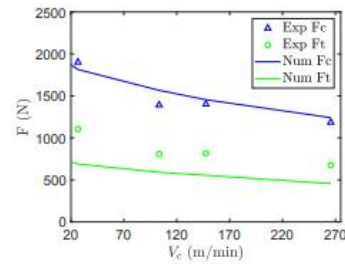


Fig. 3. Comparison between experimental and numerical average values of cutting and thrust forces for orthogonal cutting of FCC copper over a wide range of cutting velocities.

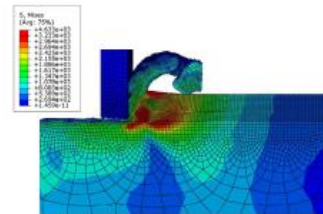


Figure 30 - Johnson-Cook Damage Model Values for Copper