

Computer Simulation of a Projectile Impacting a Metal Plate

L4 PHYSICS ACDB4007

Emalie Halifax

STUDENT NUMBER - 2222482

OME DEGREE APPRENTICESHIP

UNIVERISTY WALES TRINITY SAINT DAVID

Abstract

This report investigates how a steel bullet shaped projectile impacted metal plates of titanium alloy Ti-6Al-4V and aluminium alloy 6061 T6. Using computer simulation software Abaqus the stresses exerted by the projectile on the plates were analysed. It has been found that the projectile did not fully penetrate the titanium and the stresses on the plate did not cause failure. Whereas the steel projectile penetrated the aluminium plate causing tension on the underside of the plate that exerted the ultimate tensile strength of the material. This stress resulted in damage occurring on the aluminium plating.

Table of Contents

Abstract	1
Table of Figures and Tables.....	2
1. Introduction	3
2. Description of Problem	3
3. Model	3
4. Analysis and Discussion	6
4.1 Simulation One - Titanium Ti-6AL-4V	6
4.2 Simulation Two - Aluminium 6061 T6	7
4.3 Discussion.....	10
5. Conclusion	11
6.References	12

Table of Figures and Tables

Figure 1 - Sketches of the (a) Projectile and (b) Plate	4
Figure 2 - Assembled 3D model of (a) Projectile and Plate and (b) with applied Meshing	4
Figure 3 - Steel Projectile Impacting Titanium Alloy Plate in (a) Max Principle and (b) S23	7
Figure 4 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S23 at $4.5 \times 10^{-4}s$	8
Figure 5 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S23 at $7.5 \times 10^{-5}s$	9
Figure 6 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S23 at $1.002 \times 10^{-4}s$	10
Figure 7 - Velocity Graph for Steel Projectile Impacting Titanium Alloy Plate	10
Figure 8 -Velocity Graph for Steel Projectile Impacting Aluminium Alloy Plate	11
Table 1 - Steel Material Properties for Simulation	4
Table 2 - Aluminium 6061 T6 Material Properties for Simulation.....	5
Table 3 - Aluminium 6061 T6 Johnson-Cook Values.....	5
Table 4 - Titanium Alloy Ti-6AL-4V Material Properties for Simulation	5
Table 5 - Titanium Alloy Ti-6AL-4V Johnson-Cook Values.....	6

1. Introduction

The ability to be able to protect people and assets from projectiles is vital in the world of OME. There are many factors to take into consideration regarding what you use as ballistic protection, from the type of projectile, the velocity of the projectile and what you want to happen if a projectile hit the protection.

The use of computer modeling and finite element analysis provides an insight into the outcomes of projectiles impacting armored plating without needing to initially undertake a physical test.

This report will detail simulations conducted by a student as part of an OME Degree Apprenticeship L4 Physics module. The simulations will investigate how a steel projectile impacts two plates with different material properties.

2. Description of Problem

As part of the module, students were tasked with analysing the impact of a high-speed ballistic projectile onto a target plate. Students were given the opportunity to investigate different aspects of the problem. In this report the material properties of the plate were investigated. The student made a comparison between titanium alloy Ti-6Al-4V and aluminium alloy 6061 T6.

These two materials were used due to their current use in the defence sector. Aluminium is used for its lightweight and durable properties - including its resistance to projectile impact and corrosion. It has a high strength-to-weight ratio while maintaining its lightweight capability and ballistic performance. This combination allows aluminium alloys to be used in marine applications [1]. The 6000 series, which includes aluminium 6061 used in this report, is used directly as panels on armour systems such as the up-armouring of High-Mobility Multipurpose Wheeled Vehicles [1].

Titanium Ti-6Al-4V has seen an increased use in military driven by a need for increased ballistic performance in armour; weight reduction to increase mobility and tactical requirements [2]. Titanium is twice as strong as aluminium, but its high cost meant its use became very specialised [3]. Over the years the increased cost of advanced materials like composites and ceramics, along with low-cost alloys have enabled titanium to be a cost-effective option [2].

3. Model

The model used was provided by Kelvin Donne - University of Wales Trinity St David, Physics Lecturer [4] and consisted of a bullet shaped projectile approximately 0.09m in length and 0.07m in diameter, along with a 0.3m square plate with a depth of 0.03m. The sketches are shown in Figure 1.

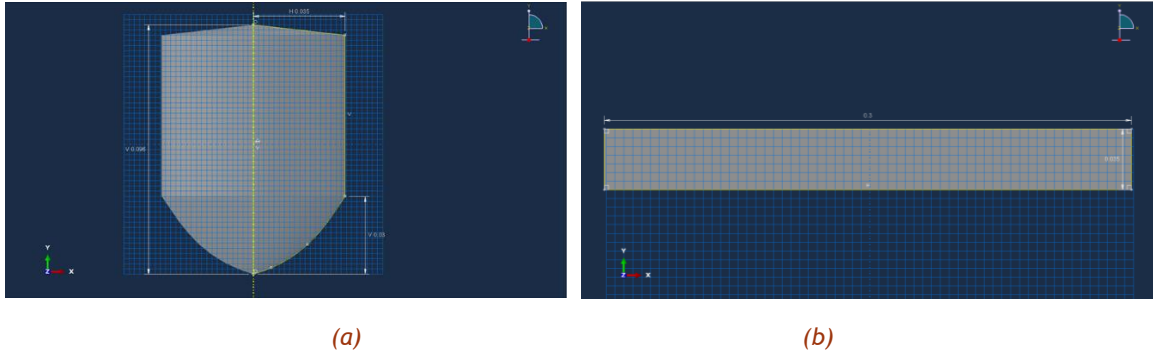


Figure 1 - Sketches of the (a) Projectile and (b) Plate

The sketches were revolved and extruded respectively to provide 3D models as shown in Figure 2. These models were assembled and assigned an impact motion in the Interaction section of the Abaqus software. In this study the projectile impacted the plate at a velocity of 940ms^{-1} with the results generating 200 frames over the $5 \times 10^{-6}\text{s}$ of interaction.

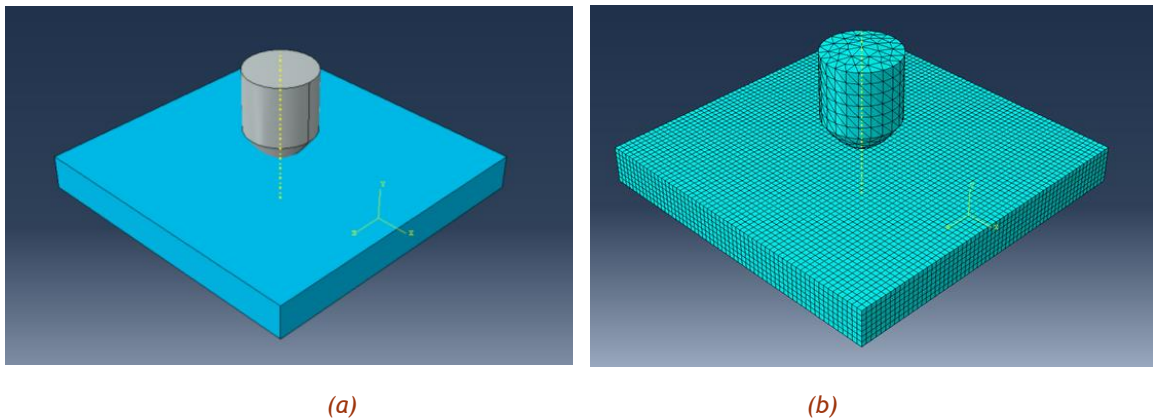


Figure 2 - Assembled 3D model of (a) Projectile and Plate and (b) with applied Meshing

To allow the simulation to model the projectile's motion accurately, material parameters needed to be assigned to the projectile and the plate. In the simulations the material of the projectile remained the same and the plate was changed for each test. The projectile material used was steel and the two plate materials were aluminium alloy 6061 T6 and titanium alloy Ti-6AL-4V. Table 1 shows the material properties for the steel used - these were provided in the original model, along with the properties for the aluminium in Table 2 [4]. To enable the simulation to show how the plate would damage on impact, Johnson-Cook Plastic and Damage values were inputted. Tables 2, 3, 4 and 5 show the values used for each plate material [4, 5]. As well as the material parameters a mesh was applied to the components to allow the simulation to show the damage and stresses.

Material properties	Symbol	Steel
Density	ρ (kg/m ³)	7860
Young's modulus	E (GPa)	210
Poisson's ratio	ν	0.3

Table 1 - Steel Material Properties for Simulation

Material properties	Symbol	Aluminium 6061 -T6
Density	ρ (kg/m ³)	2699
Young's modulus	E (GPa)	68
Poisson's ratio	ν	0.36

Table 2 - Aluminium 6061 T6 Material Properties for Simulation

Johnson-Cook Damage		
Material properties	Symbol	Aluminium 6061 -T6
J-C damage constant	d1	-0.77
J-C damage constant	d2	1.45
J-C damage constant	d3	0.47
J-C damage constant	d4	0.00
J-C damage constant	d5	1.60
Melting temperature	T _m (K)	925
Transition temperature	T (K)	293.1
Johnson-Cook Plastic		
Material properties	Symbol	Aluminium 6061 -T6
J-C yield strength	A (MPa)	324.1
J-C hardening coefficient	B (MPa)	113.8
J-C strain hardening exponent	N	0.42
J-C strain rate constant	C	0.002
J-C softening exponent	M	1.34
Melting temperature	T _m (K)	925
Transition temperature	T (K)	293.2
Reference Strain Rate	ϵ_0	1

Table 3 - Aluminium 6061 T6 Johnson-Cook Values

Material properties	Symbol	Ti-6Al-4V
Density	ρ (kg/m ³)	4428
Young's modulus	E (GPa)	109.8
Poisson's ratio	ν	0.31

Table 4 - Titanium Alloy Ti-6AL-4V Material Properties for Simulation

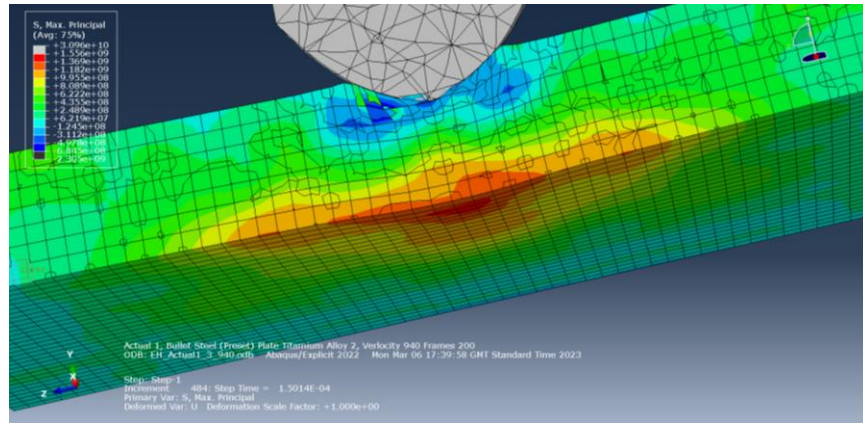
Johnson-Cook Damage		
Material properties	Symbol	Ti-6Al-4V
J-C damage constant	d1	-0.09
J-C damage constant	d2	0.27
J-C damage constant	d3	0.48
J-C damage constant	d4	0.014
J-C damage constant	d5	3.87
Melting temperature	T _m (K)	1878
Transition temperature	T (K)	298
Johnson-Cook Plastic		
Material properties	Symbol	Ti-6Al-4V
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
Transition temperature	T (K)	298
Reference Strain Rate	ε ₀	1

Table 5 - Titanium Alloy Ti-6AL-4V Johnson-Cook Values

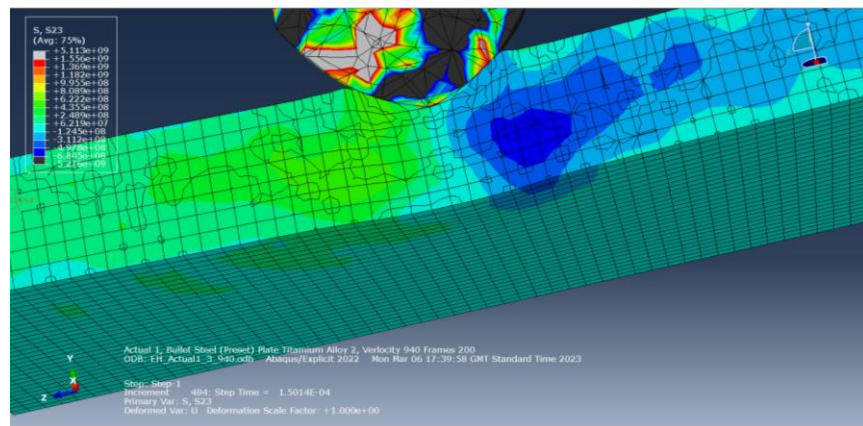
4. Analysis and Discussion

4.1 Simulation One - Titanium Ti-6AL-4V

Both simulations were conducted with the projectile having a velocity of 940ms^{-1} and any damaged nodes to be deleted. The initial test used the steel projectile and the titanium alloy Ti-6AL-4V plate. In the test the projectile impacted the plate and ricocheted off leaving an indentation. Figure 3 shows the projectile impacting the plate. Results are shown in Max Principle to show the stress due to tension and compression on the plate and S23 to show the shear stresses. In Max Principe, the negative values indicated stress due to compression and the positive due to tension.



(a)



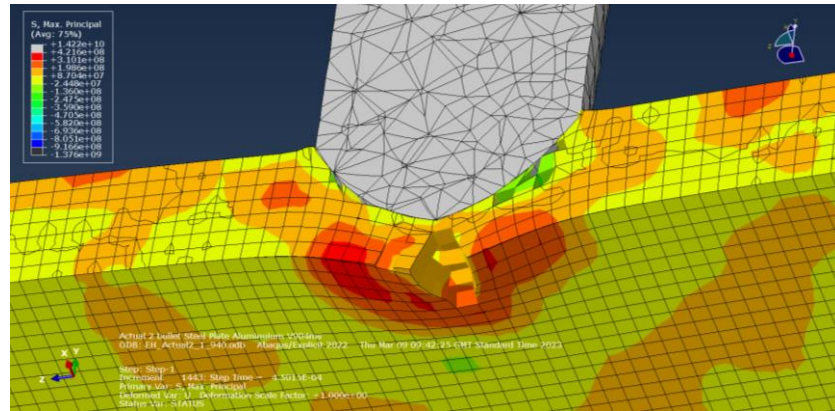
(b)

Figure 3 - Steel Projectile Impacting Titanium Alloy Plate in (a) Max Principle and (b) S23

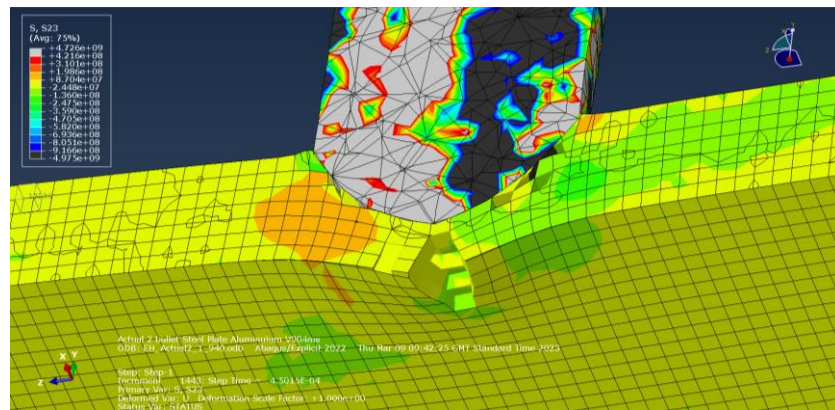
In Figure 3(a) it can be seen from the orange red colour that there is high tension at the bottom of the plate with values around $1.3 \times 10^9 \text{ Pa}$. The shear values shown in Figure 3(b) by the green and darker blue colours, are around $\pm 6 \times 10^8 \text{ Pa}$, ten times less than the tension. This indicated that if the material were to fail it would be from the tension of the projectile impacting the plate. The ultimate tensile strength (UTS) of the alloy used is approximately 1170MPa [6]. The values indicated the stress on the plate exceeded titanium's UTS, however the simulation did not show any damage. This could have come from a potential error in the Johnson-Cook data for titanium. If the stress on the plate exceeded the UTS it would be expected to see failure.

4.2 Simulation Two - Aluminium 6061 T6

Test two used the same projectile with aluminium 6061 as the plate. In this test the projectile impacted the plate and caused cracking and damage before ricocheting. Figure 4 shows the results of the impact. This occurred after $4.5 \times 10^{-4} \text{ s}$.



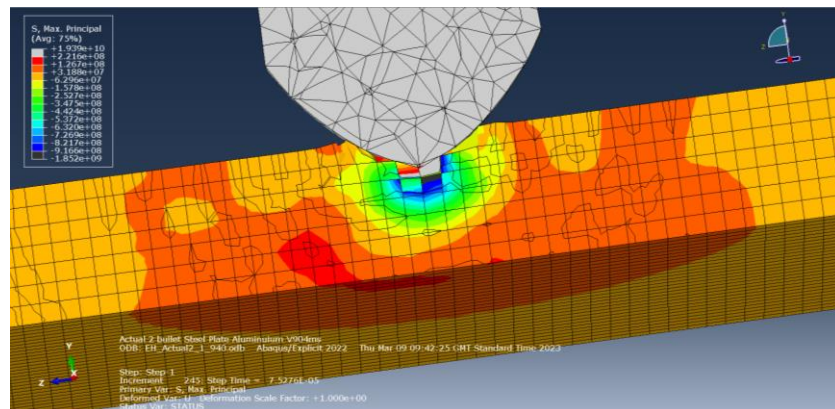
(a)



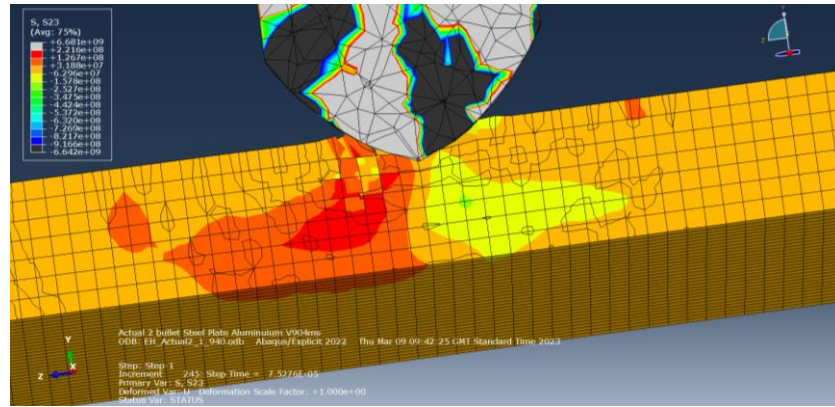
(b)

Figure 4 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S23 at 4.5×10^{-4} s

From these results some damage can be seen at the bottom of the plate. To determine if the damage occurred from tension or shear stress the results were analyzed just before damage started to appear after 7.5×10^{-5} s.



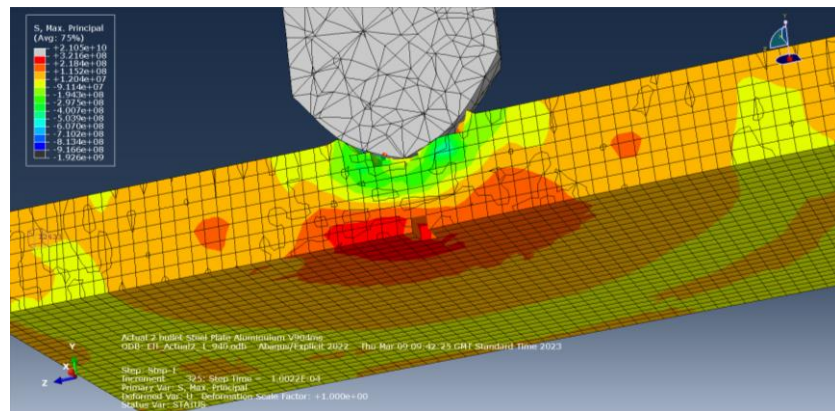
(a)



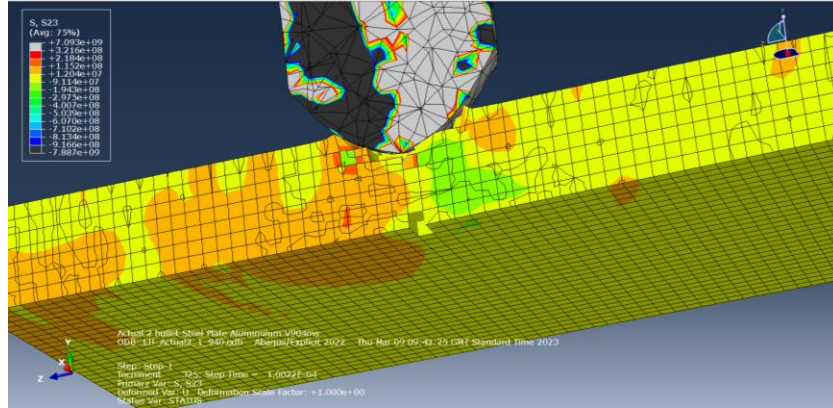
(b)

Figure 5 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S22 at $7.5 \times 10^{-5}s$

Figure 5(a) shows high tension at the bottom of the plate, a greater proportion than can be found in Figure 3(a). Here the tension has values of around $1.8 \times 10^8 \text{ Pa}$. Figure 5(b) shows the shear stress on the plate from the impact, which have values around $\pm 1.7 \times 10^8 \text{ Pa}$. The UTS of aluminium alloy 6061 T6 is approximately 290MPa [7]. As the plate has cracked, as seen in Figure 4, it can be presumed the stress exceeded the UTS. From this time stamp it is difficult to determine if the deformation was a result of tension or shear stress.



(a)



(b)

Figure 6 - Steel Projectile Impacting Aluminium Plate in (a) Max Principle and (b) S23 at 1.002×10^{-4} s

Further analysis showed the damage occurred after 1.002×10^{-4} s. Figure 6 shows higher tension at the bottom of the plate around values of 2×10^8 Pa compared to the shear values of $\pm 1.7 \times 10^8$ Pa. This indicated that it is likely the material failed due to stress from tension.

4.3 Discussion

The results of the simulations show the projectile exerted higher tensile stress than shear stress on both materials. Neither simulation caused total failure of the plate. The projectile caused no damage to the titanium plate, only a slight indentation before ricocheting off. However, the simulation indicated some error, as the stresses on the plate exerted the UTS of the material without causing damage. Whereas the projectile penetrated the aluminium plate causing damage to the underside of the plating before starting to ricochet out. This outcome was expected based on the known values and properties of the material.

Comparing the velocity graphs of the tests shown in Figures 7 and 8, it can be shown the penetration of the aluminium plate slowed the bullet down more than the interaction with the titanium. This indicates a higher risk of further damage due to high speed rebound fragmentation depending on the use of the armour plating.

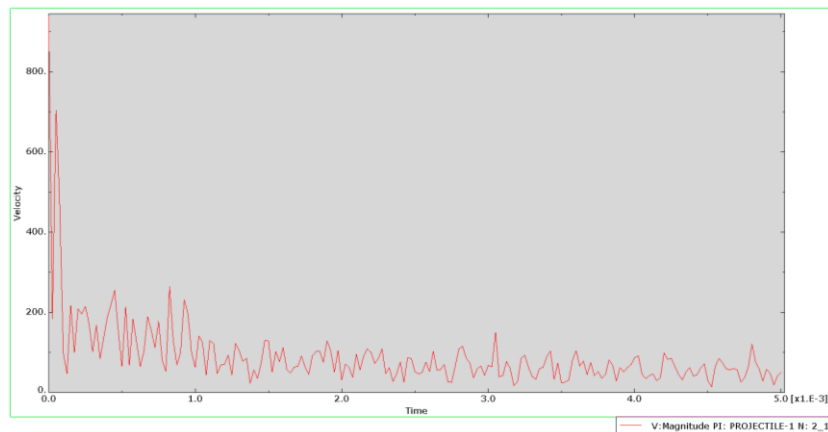


Figure 7 - Velocity Graph for Steel Projectile Impacting Titanium Alloy Plate

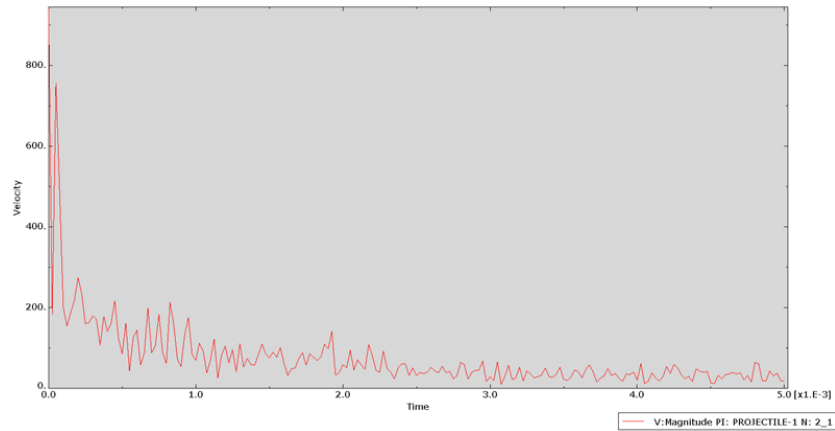


Figure 8 -Velocity Graph for Steel Projectile Impacting Aluminium Alloy Plate

Overall, the simulations provided an insight to how a bullet shaped steel projectile impacts target plating of different materials. The model provided was a simplistic representation of a bullet shaped projectile, a more scaled version to bullets used in firearms would provide results closer to physical interaction. Likewise, the mesh applied to the model could be improved by having a finer mesh at the point of impact. This would provide enhanced Max Principle and S23 results and could provide a more accurate failure point.

If the simulations were to be repeated other areas open to further insight include how the thickness of the material and the angle of penetration from the projectile impact the level of protection provided by the materials.

5. Conclusion

The simulations conducted showed how a steel projectile impacts metal plates of titanium alloy Ti-6Al-4V and aluminium alloy 6061 T6. Although the model was a simplistic representation, the results provided enabled an analysis of the two materials. It showed the projectile exerted higher tensile stresses than shear stresses on the plates, causing damage to the aluminium not the titanium. There are areas for improvement with the study, however, it has introduced the Abaqus software and finite element analysis to the student.

6. References

- [1] Clinton Aluminum, "Aluminium Applications For Armor Plating," 11 May 2021. [Online]. Available: <https://www.clintonaluminum.com/aluminum-applications-for-armor-plating/#:~:text=Armor%20plating%20is%20commonly%20used%20to%20protect%20military,and%20include%20tanks%2C%20troop%20carriers%2C%20and%20the%20like..> [Accessed 6 April 2023].
- [2] W. Gooch, "Potential Applications of Titanium Alloys in Armor Systems," in *International Titanium Association Titanium 2011*, San Diego, 2011.
- [3] J. Mitchell, "Ti-6Al-4V Titanium - Essential Reading," 24 October 2017. [Online]. Available: <https://www.engineeringclicks.com/ti-6al-4v-titanium-essential-reading/>. [Accessed 6 March 2023].
- [4] K. Donne, *Assessment Simulation Model axi_ballistics2.cae file*, Swansea: University of Wales Trinity Saint David, 2023.
- [5] X. Wang and J. Shi, "Validation of Johnson-Cook plasticity and damage model using impact experiment," *International Journal of Impact Engineering*, vol. 60, pp. 67-75, 2013.
- [6] N. Power, "Strength of Titanium Alloys," [Online]. Available: <https://www.nuclear-power.com/nuclear-engineering/metals-what-are-metals/alloys-composition-properties-of-metal-alloys/titanium-alloys/strength-of-titanium-alloys/>. [Accessed 13 March 2023].
- [7] Power, Nuclear, "Strenght of Aluminium Alloys," [Online]. Available: <https://www.nuclear-power.com/nuclear-engineering/metals-what-are-metals/alloys-composition-properties-of-metal-alloys/aluminium-alloys/strength-of-aluminium-alloys/>. [Accessed 23 March 2023].