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Design and Development of Novel AA7075-T6 based Armor Plate through Numerical and Experimental Approach

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Abstract

The materials used for ballistic applications have always taken a special spot in the manufacturing and study of protective amours. Although metals like steel provide adequate ballistic protection, they compromise the mobility of the soldier and since high mobility is a primary requirement for soldiers during combat. Therefore, at present most of the researchers are currently focusing on materials with properties like high impact resistance and high strength to weight ratio. In recent times, Aluminum alloys are recognized as the alternative materials which can provide good impact resistance and have a high strength to weight ratio and having better corrosion resistant properties which ultimately make it a suitable material for several military applications. In this research, one of the toughest aluminum alloys AA7075-T6 is considered for designing an armor plate and studied for its ballistic resistance. Initially, the monolithic AA7075-T6 alloy of 18 mm was tested for its ballistic resistance limit and further it is designed with the ceramic plate of 3 mm and base alloy AA7075-T6 of 15 mm was tested to evaluate. Later the monolithic alloy of 18 mm was surface reinforced up to a thickness of 3 mm with different types of reinforcements and evaluated the bullet residual velocity after penetration of the armor piercing projectile. Numerical simulation was conducted using the prominent non-linear dynamic analysis software i.e., Ansys AUTODYNE version 19.2 and the respective values for the surface reinforced metal matrix composites revealed excellent results for the depth of penetration and residual velocity of the projectile.

Keywords: *AA7075-T6 Aluminum Alloy, Ansys Autodyne, Armor Piercing Projectile, Design of Armor Plate, Surface Reinforced Metal Matrix Composites*

1.0 Introduction

Ballistic protection of soldiers and military vehicles has become a fundamental requirement and priority in today's age of modern warfare[1]. Ballistic protection is used to protect individuals from the impact of bullets and other projectiles. This can include body armour for military and law enforcement personnel[2-3]. Ballistic protection can also be used to protect vehicles, such as armoured cars and trucks, which are used to transport valuable goods or individuals at risk[4-6]. In the recent years there have been drastic developments in ballistic materials/armour technology, with the use of materials such as ceramic and advanced composites[7]. These materials are used to make

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armours that provide protection against high powered bullets. Although today's bullet proof armours provide sufficient ballistic against majority of the bullet types, they still have some drawbacks to them. Bullet proof armours can be hefty making them difficult to wear for extended periods of time[8-10]. In addition to that some bullet proof armours can be stiff and confining which compromises on the mobility of soldiers. Although, bullet proof armours provide a high level of ballistic protection, there are areas where improvements can be made to synthesise a bullet proof armour which can be more effective[11-14].

Recent studies have found the functionality of AA7075 alloy for ballistic protection because it absorbs and dissipates energy. The material has a high yield strength and relative high stiffness, which allows it to absorb and spread the impact created by the bullet across a larger area. Additionally aluminium alloys tend to be light in weight and corrosion resistant[15-20]. This material is hence significantly lighter in weight than metals like steel due to its low density. Further the corrosion resistance of AA7075 helps maintain its structural integrity through time even in harsh combat environments[21-25]. In addition to that, AA7075 can easily be fabricated into any desired shape allowing it to be used in a variety of ways for ballistic protection.

Ceramic reinforcements are materials that are used to enhance the strength and impact resistance of a selected material[26-28]. These materials are generally used in conjunction with other materials such as Kevlar to create multi-layered/multi stacked armour plates that provide enhanced protection than a wide range of metals. Ceramics can be used in several ways to reinforce a composite material. One way is to use ceramic fibres, which can be added to a polymer matrix to improve the material's tensile strength and stiffness. Another way is to use ceramic particles, which can be added to a polymer matrix to improve the material's compressive strength and toughness[29]. For the following study we have used ceramics like Alumina, Boron Nitride, and reduced graphene oxide. These ceramics are extremely hard and provide a high level of impact distribution[30]. Alumina has a high level of toughness which makes it crack resistant which helps it in absorbing and dissipating energy at impact[31]. Ceramics can also be used as a reinforcement in metal matrix composites. Ceramic particles can be added to a metal matrix to improve the material's wear resistance and hardness. Additionally, ceramic fibres can be added to a metal matrix to improve the material's thermal conductivity, electrical conductivity and to reduce the coefficient of thermal expansion[32]. The following study has also made the use of the same and made a unidirectional composite as they are able to withstand high impact forces and penetration of bullets. This is due to the orientation of all fibres in one direction which allows them to distribute the force of a bullet along a single axis, reducing the chances of the composite taking damage or shattering. Additionally, they also have a high strength-to-weight ratio making them ideal for use in body armour and other ballistic applications.

Ceramic fibres can facilitate in saving weight by improving the material's strength-to-weight ratio. The use of ceramic fibres or particles in a composite material can increase the material's overall strength simultaneously while keeping its weight to a minimum. Ceramic particles can also be used to reduce weight in composites. They are often smaller and denser than fibres, so they can be used in smaller quantities to provide the same strength benefits. Using the same principal ceramic particles reinforcement has been provided to a metal matrix, which can increase the material's strength and hardness while keeping its weight low[33].

As mentioned before the present study has been conducted in ANSYS v19.2 as it is one of the prominent CAE software used by engineers to solve complex problems. The following software has been used to study Ballistics to create an understanding of how different ceramic reinforcements and alloys and other factors perform under different ballistic systems. Some of the factors that come under consideration are:

i. Bullet Design: The design of the bullet for instance its shape, size and the material being used plays a major role on the performance of the bullet upon impact.

ii. Muzzle Velocity: The velocity of the bullet at which it is fired from the gun will have a significant effect on the bullet's performance and the materials behaviour. A bullet fired at higher velocity will have higher kinetic energy.

iii. Target Material: The type of material that the impact is going to happen on plays a major role in the study of ballistics protection. Hard materials such as the correctly chosen alloys or ceramics or a combination of both can either deform or fragment the bullet.

In summary, the design of the bullet, the material for the bullet as well as the target, the distance between the plate and the bullet all such factors have been taken into consideration for the present study to obtain accurate results.

2.0 Materials and Methodology

Using Finite Element Methods (FEM) which is a numerical technique used to solve complex engineering problems. It is an efficient tool used to analyse and simulate a wide range of physical occurrences, such as heart transfer, fluid flow, structural mechanics, etc. FEM is a process of breaking down a complex problem/ system into smaller parts or elements. These elements are later used to represent the system. The nature of each element is modelled using mathematical equations. Finite Element Method helps us understand and solve complex geometries and boundary conditions while also helping us simulate nonlinear systems. The following method is also opted for solving systems involving deformations and contact problems.

In this study, explicit dynamics was used, as it is used to simulate dynamic or transient which include impacts and explosions. This tool is particularly suited for high speed and highly nonlinear systems such as ballistic impacts considered in this study. This method uses a set of equations and integral methods than traditional FEA which make them accurate for simulation high speed systems. The main advantage of this is that it can simulate the behavior of a modelled system at a selected time providing accurate predictions of the forces and energies involved and the behavior of the target material during and after the impact. In ANSYS explicit dynamics uses a fixed time-step integration method to simulate the behavior of the system in real time, providing accurate predictions of the forces and energies involved.

In this study the model was created using ANSYS v19.2. This was done using ANSYS AUTO-DYNE which is finite element analysis software in ANSYS. The following model/system consists of a bullet and a target plate. The following system has been imparted with physical and mechanical properties of appropriate materials to obtain accurate results. Further the rotation of the bullet and any other external agents have not been considered for the following study as the focus of this study is the impact behavior of the target plate at the impact region. The study has been divided into 4 phases in which the target plate has been given a constant thickness of 18 mm and while in a few phases of the study the target plate has been divided into two parts each of thickness 3 mm and 15 mm respectively where the 3 mm is the ceramic reinforcement and the remaining 15 mm has been imparted with the properties of AA7075.

2.1 Projectile Modelling

For the analysis of a 7.62 x 39 mm bullet was considered where the bullet has a diameter of 7.62 mm and a length of 39 mm. This bullet is light in weight and is designed

Table 1. Dimensions of the Bullet

Land diameter	Neck diameter	Base diameter	Rim diameter	Rim thickness	Case length	Overall length
7.62 mm	8.60 mm	10.07 mm	11.35 mm	1.50 mm	38.70 mm	56.00 mm

Table 2. Material Properties of the STEEL 1006 Bullet

Property	Density	Tensile Strength	Yield Strength	Shear Modulus	Poisson’s Ratio
Value	7.872 g/cm^3	330 MPa	285 MPa	80 GPa	0.27

Table 3. Material Composition of the STEEL 1006 Bullet

Element	Fe	Mn	C	S	P	Total
Content	99.43	0.25	0.0080	0.0050	0.04	100

to provide good penetration upon impact. These types of bullets are used in popular rifles like AK-47, SKS and many other machine guns. For the following simulation physical and mechanical properties of STEEL1006 have been imparted to the bullet. Although the bullet consists of a hard steel core covered with a copper sheath, a steel core and as the penetration is only due to steel core hence only STEEl1006 properties have been imparted. In this simulation the whole bullet has been taken as a single body which has a mass of 28.85 gm. The bullet has been given a velocity of 500 m/s in the direction of the target plate (x-axis). The projectile has been given a 1mm high quality meshing with linear tetrahedral elements (Table 1,2 and 3).

2.2 Target Plate Modelling

A rectangular target plate has been designed with the length and width being 50 mm each and the plate has been given a thickness of 18 mm. The plate has been positioned 150 mm away from the projectile in the direction of its trajectory (x-axis). The mentioned dimensions have been taken for further refinement of the mesh to obtain accurate results of the impact the bullet makes on the target plate. The impact region has been set to the centre of the plate in the direction of the x-axis. The target plate has a quadrilateral meshing with a 1 mm high quality mesh size. Additionally fixed supports have been applied at the edges of the target plate and at the midpoints of each side for the plate to stay in place during impact. For the target plate mechanical and physical properties of AA7075 have been imparted (Table 4, 5 and 6).

3.0 Numerical Simulation

The impact analysis for the bullet plate system has been broken down into five stages. These five steps have been adopted to approach finer ballistic protection.

Model Specifications/Boundary Conditions for Phase - 1

- Temperature: Room Temperature.
- Type of the bullet: 7.62 x 39 mm.
- Distance (Tip of the bullet to Plate): 150 mm.
- Velocity of the Projectile: 500 m/s.
- Material used for Armour Plate: AA7075.
- Material used for Projectile: STEEL 1006.
- Target Plate Dimensions: 50 mm x 50 mm.
- Optimum Thickness for the Armour Plate: 18 mm.
- Ceramics Used: None.
- Optimum Thickness for Ceramic: 3 mm.
- Total Plate Thickness: 18 mm.
- Mesh Size: 1 mm.
- Mesh Quality: High.
- Point of Contact: Centre of the Plate.
- Type of mesh for Target Plate: Quadrilateral.
- Type of mesh for Projectile: Tetrahedron.
- Type of Support for the Target Plate: Fixed supports at the edges and nodes that represent the midpoints of the target plate.

Table 4. Dimensions of the Target Plate

Dimension	Length	Width	Thickness
Value	50 mm	50 mm	18 mm

Table 5. Material Properties of the AA7075 Target Plate

Property	Density	Tensile Strength	Yield Strength	Shear Modulus	Poisson's Ratio
Value	2.81 g/cm^3	572 MPa	503 MPa	26.9 GPa	0.33

Table 6. Material Composition of the AA7075 Target Plate

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Total
Content	0.4	0.5	2.0	0.3	2.9	0.28	6.1	0.2	87.32	100

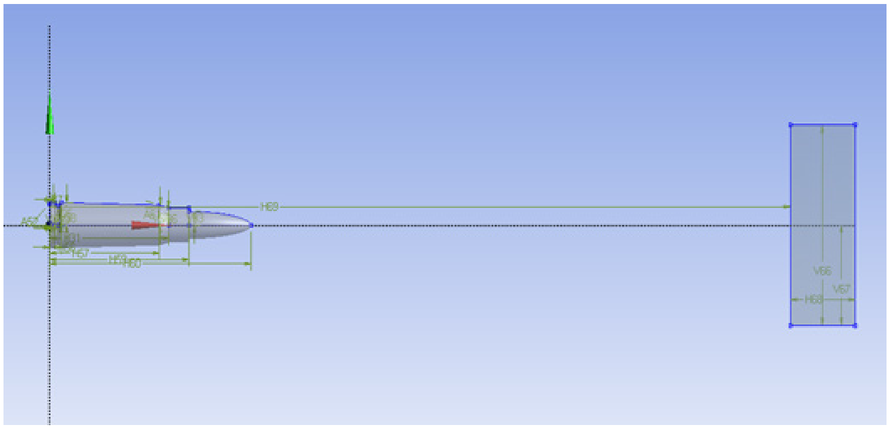
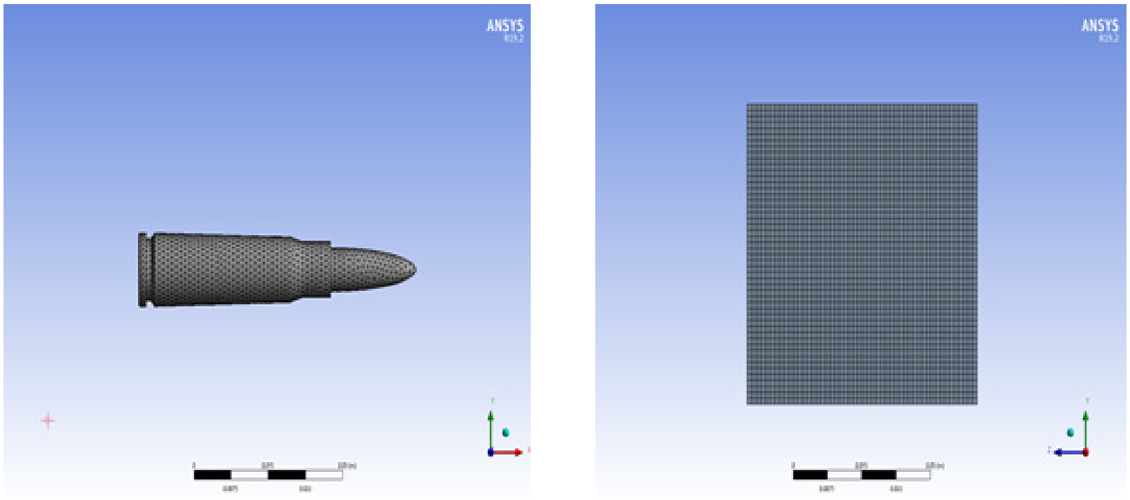


Figure 1. Geometry used in the study.



(a) (b)

Figure 2. Meshing of (a) STEEL 1006 Bullet, (b) Target Plate.

- End Time: 0.000336 s.

The first step includes performing impact analysis on a 50 x 50 mm AA7075 plate with a thickness of 18 mm. A 7.62 x 39 mm bullet has been considered for impact analysis. The distance from the tip of the bullet to the plate is taken as 150 mm.

The bullet has been given a velocity of 500 m/s, the main reason for taking bullet speed as 500 m/s is because it is a realistic speed for ballistic and firearms applications. This speed is also good for safety reasons as it represents high speed but not extreme speed. Hence, this speed provides effective computational results. The material properties of STEEL 1006 have been imparted to the bullet. For the simulation to generate accurate and trustworthy findings, a high mesh quality was used. The type of meshing used for the plate is block or square type meshing. This type of meshing has been used for the plate as it provides more reliable results while also preserving the geometry of the plate. Further a tetrahedral meshing has been employed for the bullet as it is a flexible method to mesh complex geometries with curvatures and varying sizes.

Model Specifications/Boundary Conditions for Phase - 2

- Temperature: Room Temperature.
- Type of the Bullet: 7.62 x 39 mm.
- Distance (Tip of the bullet to Plate): 150 mm.
- Velocity of the Projectile: 500 m/s.
- Material used for Armour Plate: AA7075.

- Material used for Projectile: STEEL 1006.
- Target Plate Dimensions: 50 mm x 50 mm.
- Optimum Thickness for the armour plate: 18 mm.
- Ceramics used to create the composites: Boron Nitride, Alumina, and Reduced Graphene Oxide.
- Optimum Thickness for Ceramic: 3 mm
- Total Plate Thickness: 15+3 = 18 mm
- Mesh Size: 1 mm
- Type of mesh for Target Plate: Quadrilateral.
- Type of mesh for Projectile: Tetrahedron.
- Mesh Quality: High.
- Point of Contact: Centre of the Plate.
- Type of Support for the Target Plate: Fixed supports at the edges and nodes that represent the midpoints of the target plate.
- End Time: 0.000336 s.

In the second phase of the numerical simulation, the 18 mm plate thickness is divided into parts where 3 mm ceramic is reinforced, and the other 16 mm of the plate has been imparted with properties of AA7075. For the second phase, various ceramics have been used to see which perform the best in the test conditions. The thickness of the ceramic reinforcement depends on the type of applications, the threat level, weight requirement, and mobility requirement. For the following study a thickness of 3 mm has been given as it gives an equal balance between weight and protection. Thin layer of ceramic reinforcements may not provide protection against higher velocity projectiles, and thick layers of ceramic reinforcements may compromise mobility. For providing ceramic reinforcement the material designer feature was used to make unidirectional composites out of selected metal matrix and ceramic materials. The geometry used to scrutinise the unidirectional composite was square with a fibre volume fraction of 0.5 and a fibre diameter of 5µm additionally, a block type mesh has been used b which adapts around the edges. The material has been made orthotropic in nature. Further the linear elasticity of the material has been computed and the material properties were imported to the engineering data of the existing project and used as 2 mm reinforcement in the target plate for further simulation.

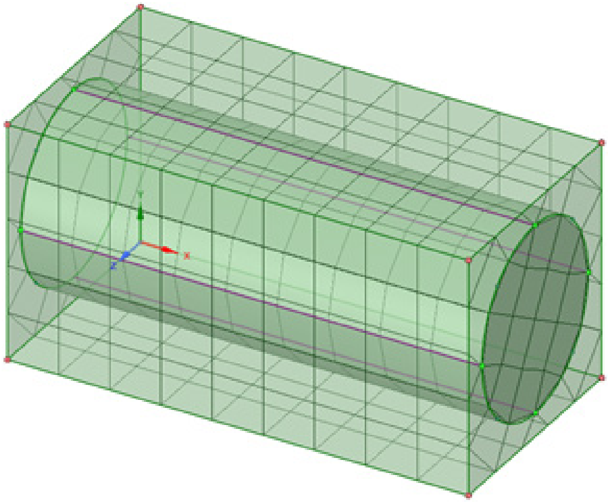


Figure 3. Unidirectional Composite made by using Material Designer.

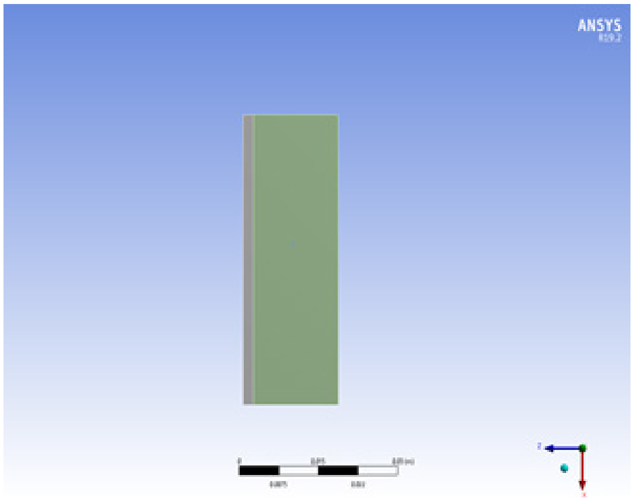


Figure 4. Ceramic and Metal Matrix partition of the Target Plate.

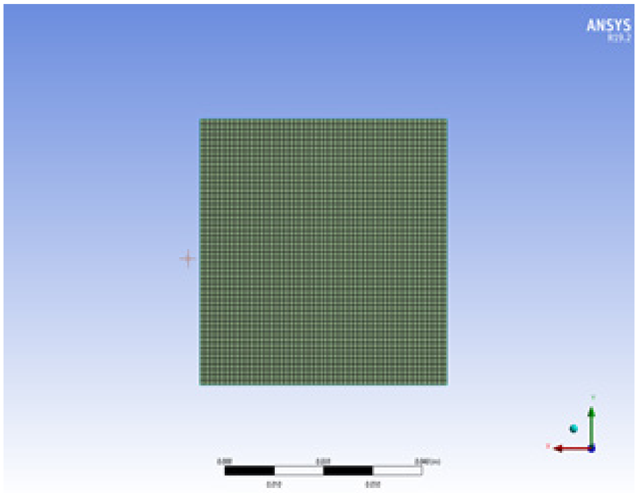
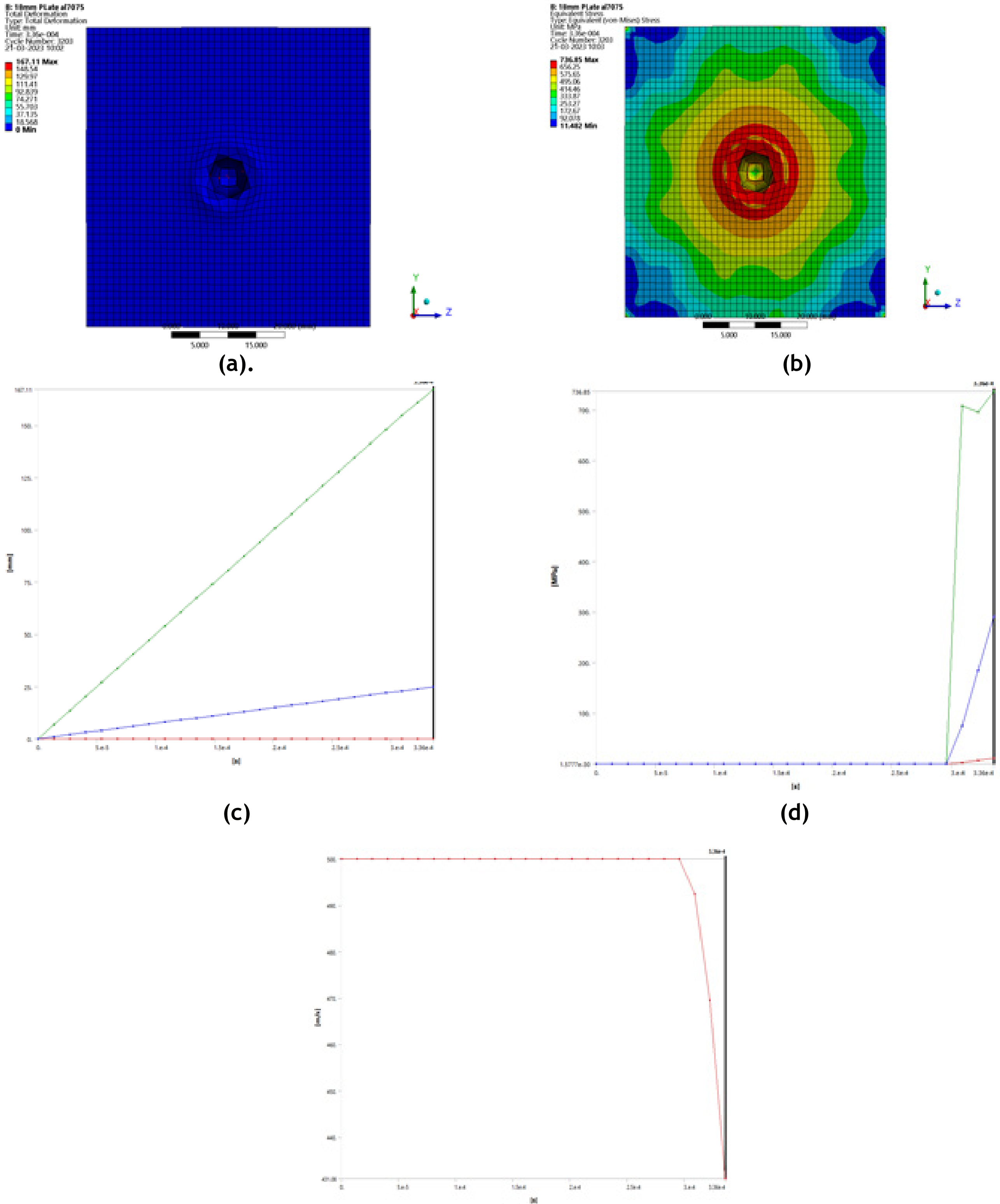


Figure 5. Meshing of the Ceramic and Metal Matrix partition of the Target Plate.



(a).

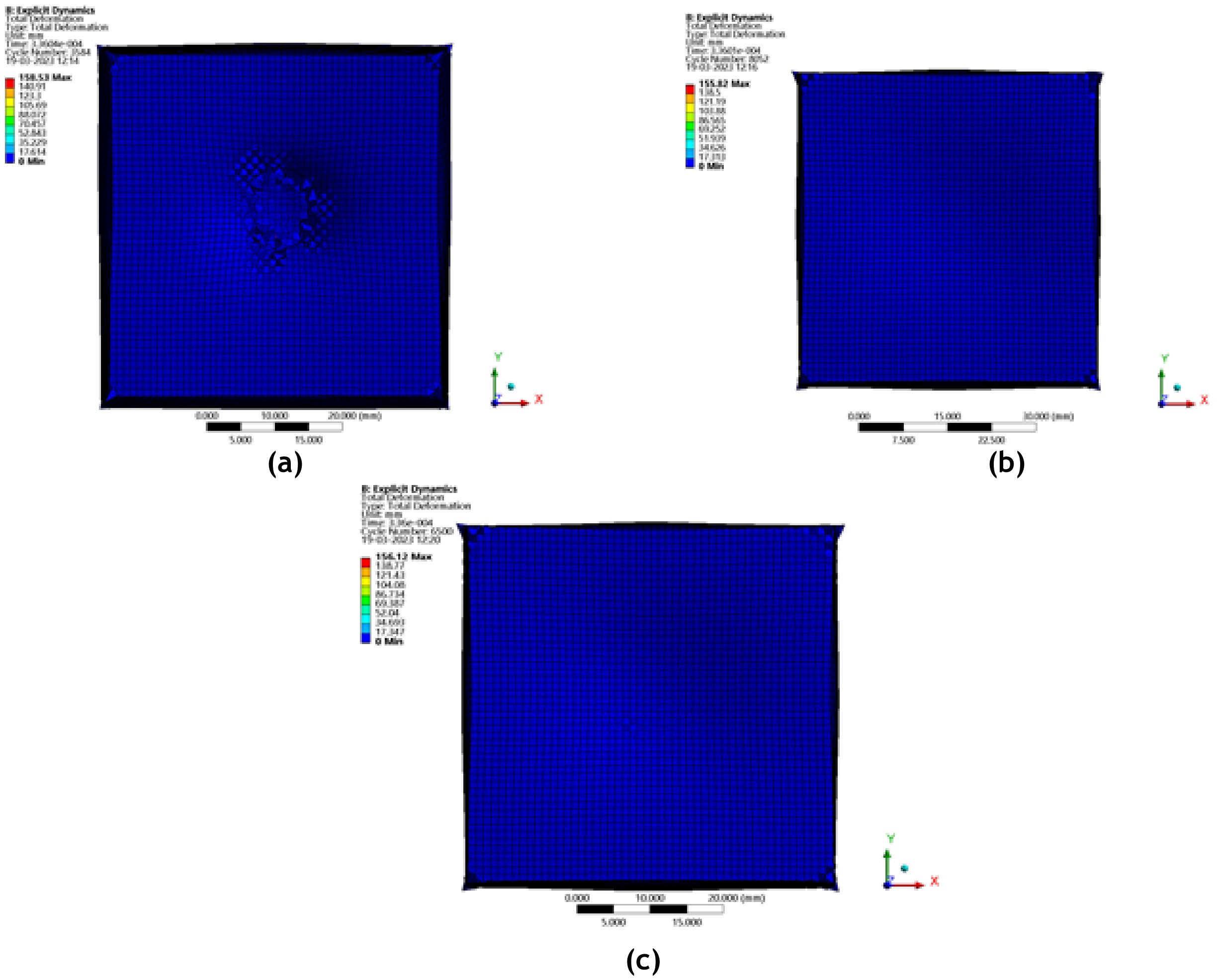
(b)

(c)

(d)

(e)

Figure 6. Ansys results of 18 mm AA7075 Armor plate: (a) Total deformation, (b) Equivalent stresses, (c) Total deformation graphical result, (d) Equivalent stresses graphical result, (e) Residual velocity of the bullet.



(a)

(b)

(c)

Figure 7. Total Deformation results for different reinforcements: (a) Al_2O_3, (b) hBN, (c) RGO.

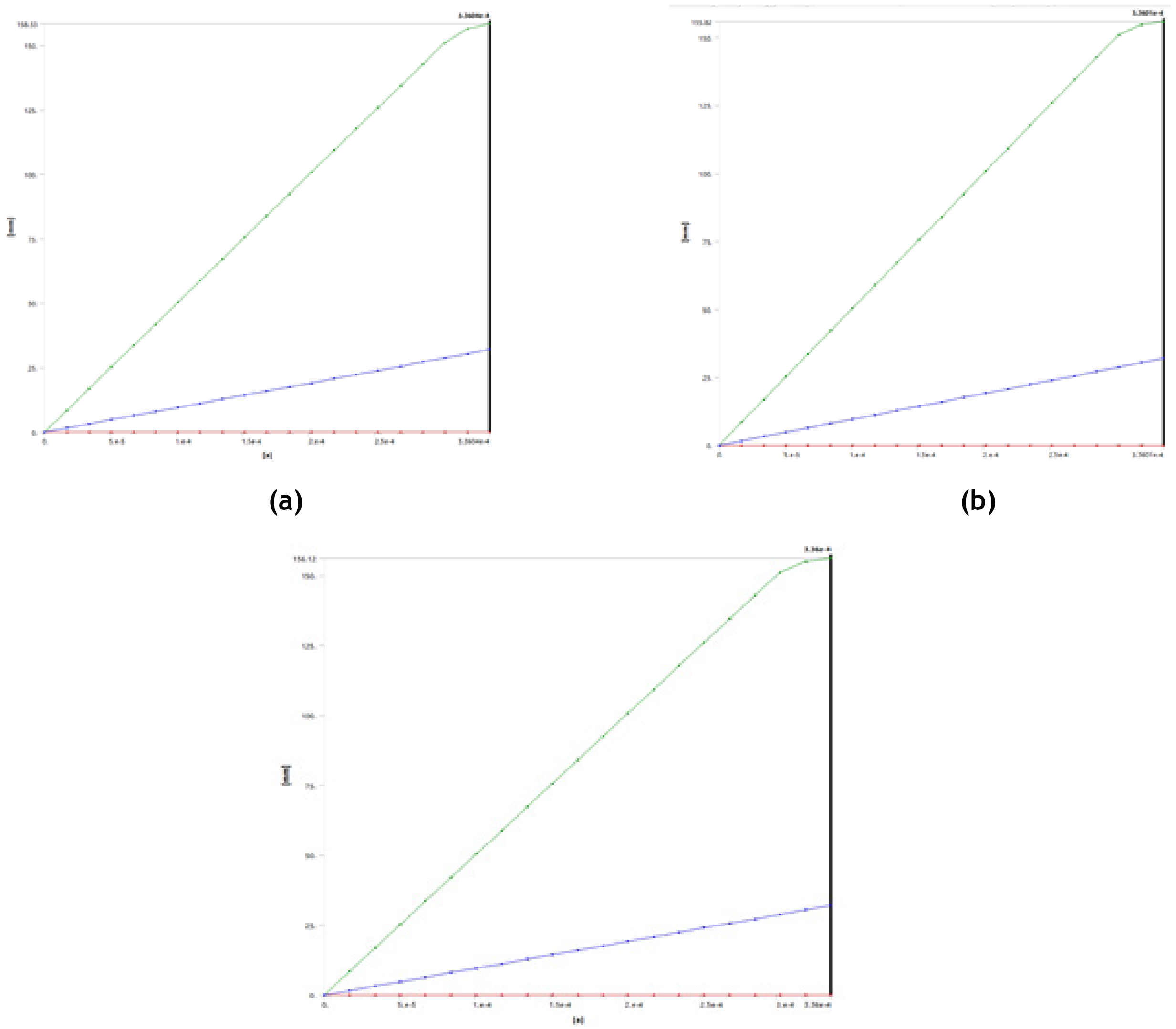
The following numerical analysis has been done to obtain the following results:

1. **Total Deformation:** The depth of indentation the bullet will create on the centre of th or the impact point upon impact.
2. **Equivalent Strain:** The strain that the bullet will cause on the plate upon impact.
3. **Equivalent Stress:** The stress on the target plate upon impact.
4. **Probe Velocity/Residual Velocity:** The velocity of the bullet after the end time of the simulation.

It's worth noting that for the following study spin and air drag and actual projectile of the bullet have not been considered. Air drag has not been considered for such scenarios as the object kept under study is moving at very high speeds hence, the object can experience a minor slow down due to air resistance. The effects of air drag is minimal because this slowing is often tiny in comparison to the object's overall speed as the distance assumed for the following simulation is 150 mm. This spin of the projectile does not have any significant effect on the results for such small distances.

4.0 Results and Discussions

An impact analysis was done to determine how well an armour plate stopped bullets. The goal of the study was to evaluate the effect of a bullet on the armour plate and find out if there were any significant changes in the structural integrity and ballistic performance of the plate. The results of the impact analysis utilising 7.62 x 39 mm bullet are as follows:



(a) (b)

(c)

Figure 8 Graphical results of the total deformation after adding the surface reinforcements: (a) Al_2O_3, (b) hBN, (c) RGO.

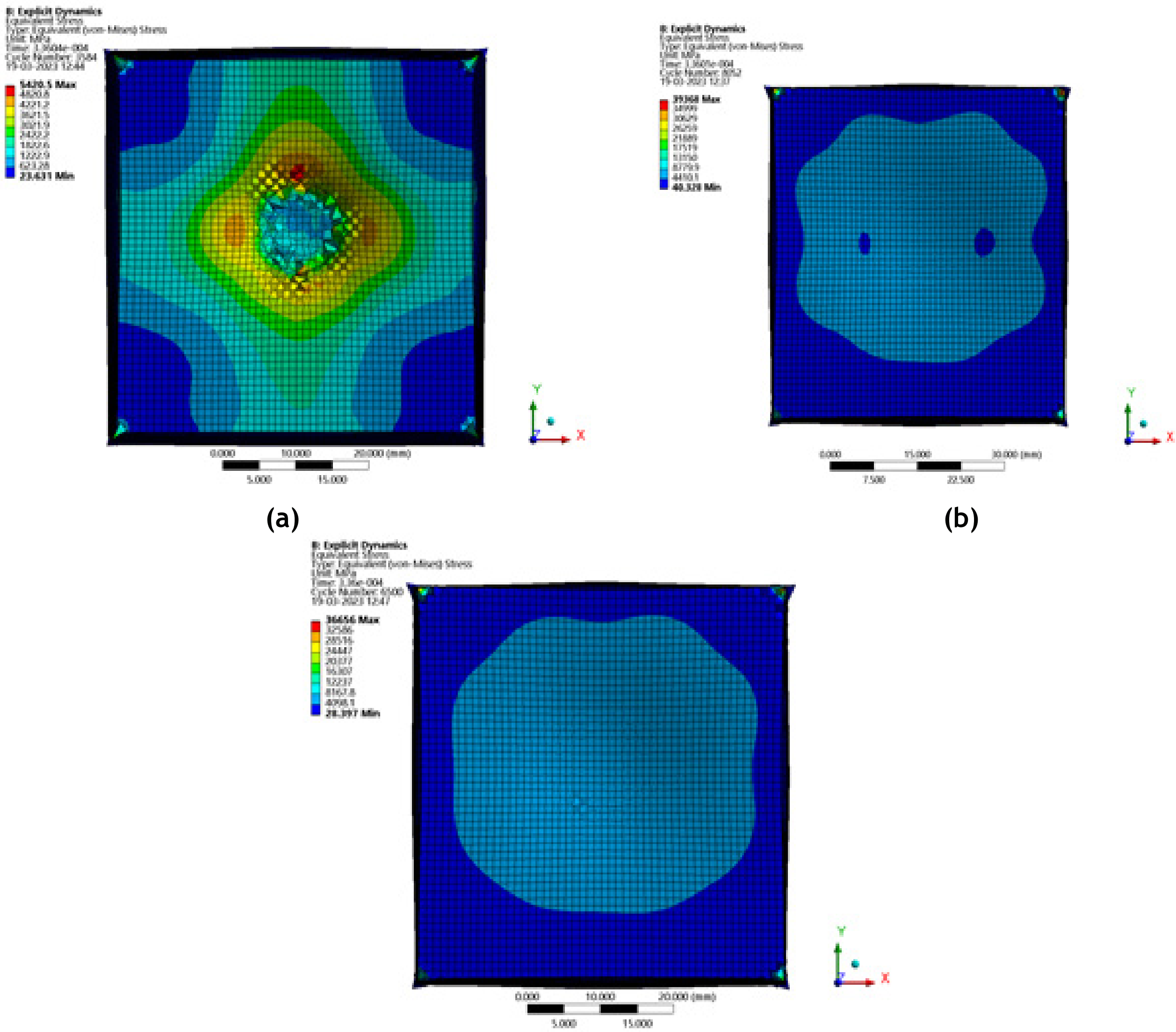
Phase - 1: It was carried out using with a 7.62 x 39 mm bullet travelling at a speed of 500 m/s that strikes the plate at the centre and a 18 mm AA7075 plate without any ceramic reinforcements, as was described in the previous section. The results for phase 1 are as follows:

From the above-mentioned values, AA7075 plates by themselves fail to provide sufficient ballistic protection. Hence, in phase - 2 of the study simulation was conducted after adding ceramic reinforcements like Boron Nitride, Aluminium Oxide and Reduced Graphene Oxide before performing the numerical analysis.

Phase - 2: A similar AA7075 plate was used for Phase 2, however this time a 3 mm layer of ceramic reinforcements was added, and the remaining 15 mm of the plate was a metal matrix. To determine which sort of ceramic will yield the best results under similar test conditions, many ceramics were used. The following simulation's outcomes are as follows:

Graphical results of the total deformations observed in the study with different surface reinforcements:

From the results obtained we observe that AA7075 plate without ceramic reinforcement produces a larger deformation upon impact. Further, the reduction in bullet velocity after impact is considerably less after impact which implies that AA7075 plate without reinforcement does not provide sufficient ballistic protection. On the



(a)

(b)

(c)

Figure 9. Equivalent stresses results for different reinforcements: (a) Al_2O_3, (b) hBN, (c) RGO.

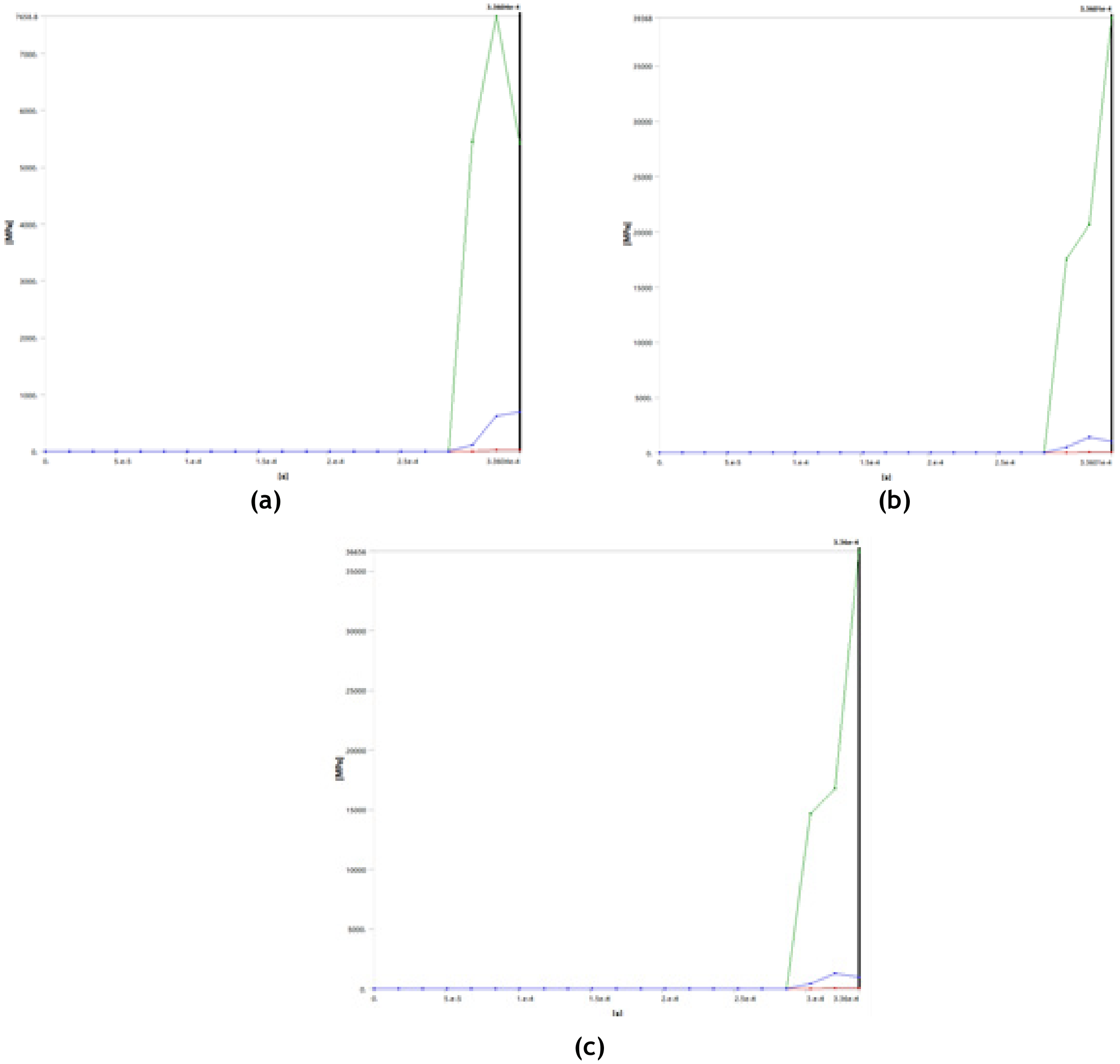
Table 7. Total deformation of Different Reinforcements

Reinforcement	Total Deformation (mm)
Aluminium Oxide	158.53
Boron Nitride	155.82
Reduced Graphene Oxide	156.12

other hand, when we use ceramic reinforcements on the AA7075 plates we notice that the total deformation caused by the bullet upon impact reduces drastically and the velocity of the bullet upon impact also reduces in a similar manner. Further, out of the three ceramics that were put under similar test conditions we see that Boron

Nitride produces optimum results and hence enhances the ballistic protection for the AA7075 plate.

The energy summary diagram depicts the impact resistance of the plate since, we see that the kinetic energy of the bullet remains constant until the point of impact whereas after the impact we observe that the internal energy and the hourglass energy have increased with a simultaneous decrease in the kinetic energy. For this phase of the study where ceramic reinforcements were used to perform impact simulations. Ceramics like Aluminium oxide, Boron Nitride and Reduced Graphene oxide were used, out of which Boron Nitride has shown optimum results. In the energy summary diagrams we see that the drop in kinetic energy is greater than the drop we noticed in the previous phase and a higher increase in internal energy and hourglass energy. Thus, giving providing finer ballistic protection.

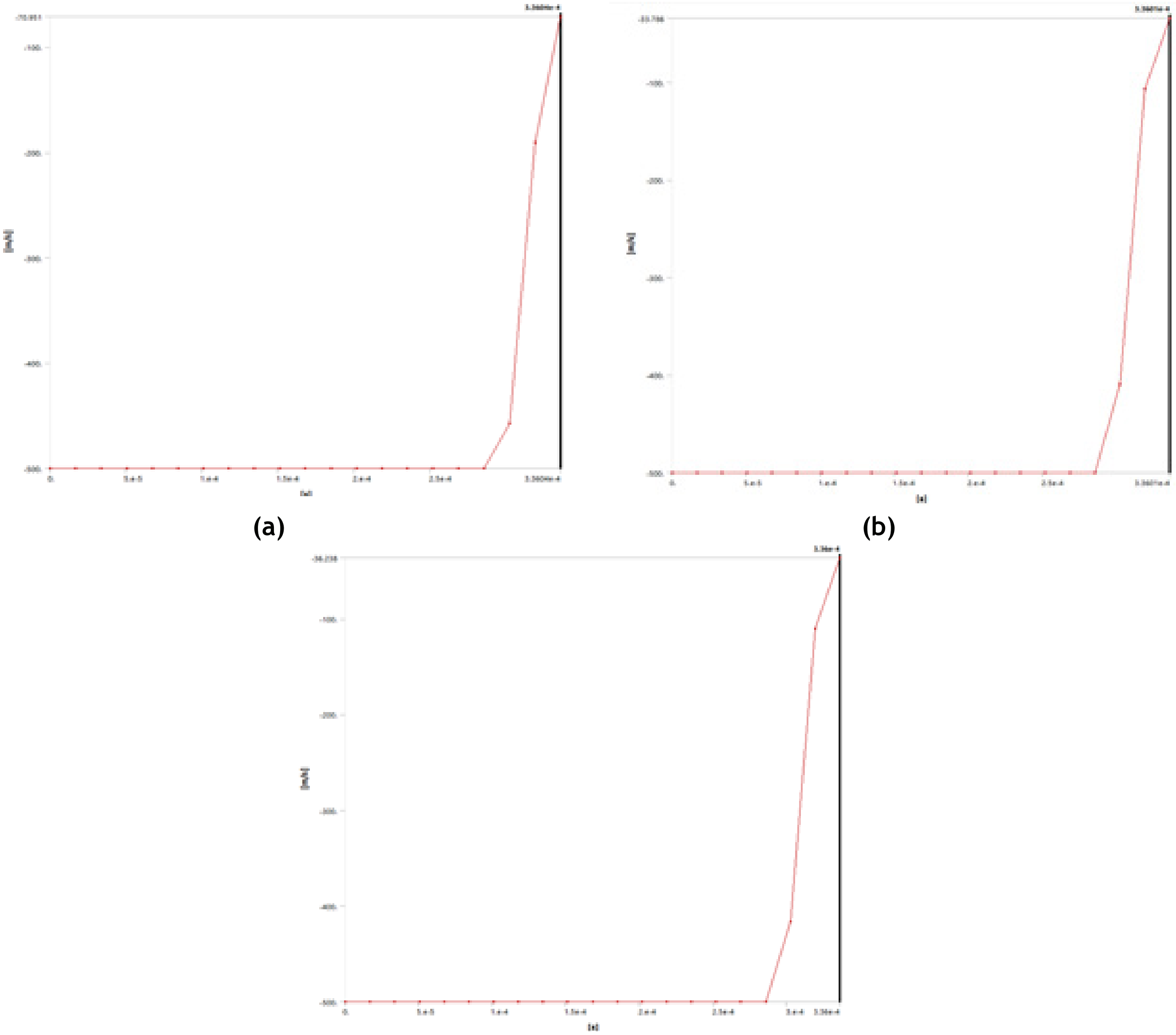


(a)

(b)

(c)

Figure 10. Graphical results of the equivalent stresses after adding the surface reinforcements: (a) Al_2O_3, (b) hBN, (c) RGO.



(a)

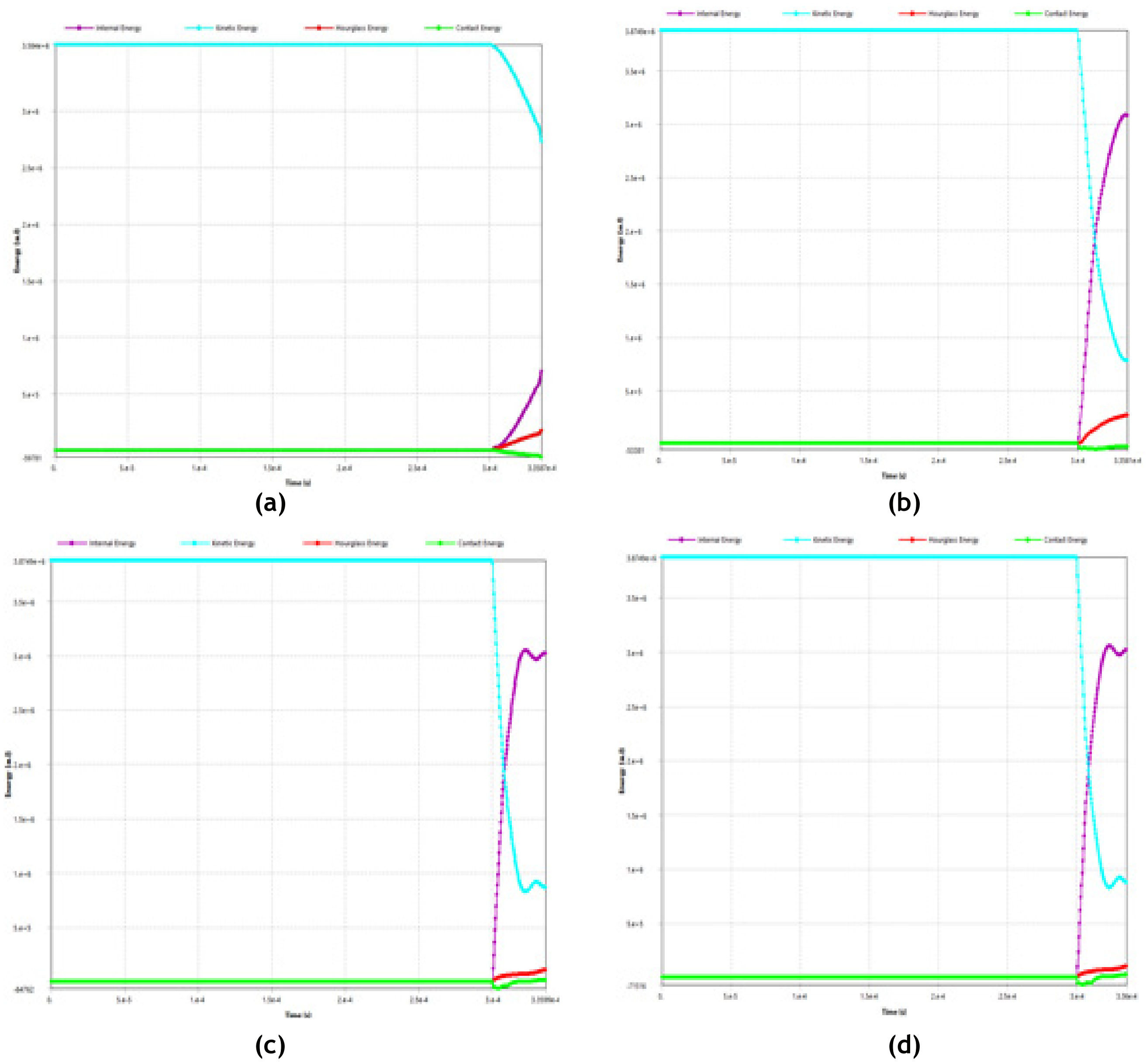
(b)

(c)

Figure 11. Graphical results of the residual velocities after adding the surface reinforcements: (a) Al_2O_3, (b) hBN, (c) RGO.

5.0 Conclusions

The ballistic resistance of the AA7075 target plate subjected to the impact of a 7.62 x 39 mm bullet projectile travelling at 500 m/s with and without reinforcement has been studied using numerical simulations in ANSYS 19.2 Explicit Dynamics. The impact analysis results, which are shown below, indicate that the metal matrix composite plate has a high ballistic resistance. Boron Nitride yielded the most effective results when used as ceramic reinforcement. Since it exhibits lesser DOP and Residual Velocity upon impact within given end time. The metal matrix composite's ceramic boron nitride reinforcement vastly enhances ballistic protection. As we observe that the kinetic energy and the velocity of the bullet drops exponentially after the impact. The reduction in the velocity probe of the bullet and the penetration depth demonstrates that a significant amount of energy was utilized to deform



(a)

(b)

(c)

(d)

Figure 12. Energy summaries after the impact of the projectile after hitting the target plate: (a) 18 mm thick AA7075 plate without any reinforcement, (b) Al_2O_3, (c) hBN, (d) RGO.

the target plate. The hourglass energy and internal energy have dramatically increased, according to the energy summary data. As a result, the ceramic reinforcements have enhanced the counterforces or resistive forces. The AA7075-T6 and ceramic reinforcement combination is also lightweight, which lowers density and enhances strength to weight ratio. It is vital to conduct experiments and apply practical methods to obtain these constants since, when ceramic reinforcements are included, the mathematical model constants vary depending on the alloys and configurations. After the numerical simulation, a properly planned experimental approach can be used to compare the experimental results to the analytical model. The AA7075-T6 metal matrix composite target plate can be produced utilising friction stir processing for the experimental technique. The bullet's drag, spin, and heat dissipation before, during, and after the impact will all be considered in future scope of this research.

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