Application of insensitive energetic materials in shaped charge (analytical and numerical)

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Abstract. Over the past two decades, significant advancements have been made in energetic materials, particularly in developing insensitive munition explosives (IMXs) by research institutions such as the Swedish Defence Research Agency and the Picatinny Arsenal in the US. These advanced IMXs have progressively replaced conventional explosives like Comp B and TNT in various military applications, including mortar and artillery shells, as well as grenades. The most commonly used IMX formulation in this research consists of 50% NTO, 35% DNAN, and 15% RDX which is loaded into shaped charge of 70 mm diameter. Theoretical studies have been conducted to assess the influence of loading density on the explosive performance and shaped charge characteristics and its penetration capability. The density of the explosive has been varied from 1.6 to 1.81 g/cm^3, the latter being the theoretical maximum density (TMD). Results indicate that increasing the density enhances the detonation velocity from 7015 m/s to 8050 m/s, as determined using the Explo5 code. Additionally, JWL parameters derived from Explo5 were applied in Autodyn simulations, demonstrating that jet velocity increased from 6030 to 7150 m/s. Correspondingly, penetration depth into rolled homogeneous steel (RHA) improved from 14.5 to 18.9 cm.

1. Introduction

In 1973, an accident occurred in the state of California, which was caused by fire on 18 boxcars that were carrying 250,000 kg of bombs that were filled with Tritonal explosives and this led to the explosion of these bombs sympathetically [1]. In 2020, a massive explosion occurred at Beirut port, Lebanon [2]. Ammonium nitrate was being stored in the warehouse when the explosion happened. Although over 6500 people were injured and around $15 billion was lost financially, this explosion was regarded as the worst of its type and the worst calamity of this decade.

The significance of insensitive energetic materials is acknowledged in an expanding corpus of literature. As a result, several scientists and technicians researched the creation of high explosives to create explosives that are extremely resistant to impact, stress, friction, and high temperatures [3]. An explosive that has high performance and insensitivity to be safe in handling, storage, and transportation is considered a perfect explosive. Therefore, conventional explosives like TNT, RDX, and HMX are no longer suitable for ammunition because of the number of accidents involving the initiation of ammunition by unplanned stimuli. The primary objective of munitions development is to minimize the risk of inadvertent detonation. Insensitive munition (IM) denotes ammunition or explosives that reliably fulfill performance, readiness, and operational requirements while reducing the risk of unintentional initiation when subjected to unforeseen stimuli. In the case of an accident, IM is not expected to respond

vigorously. IMs are munitions designed to enhance safety, primarily through the incorporation of energetic elements characterized by exceptional insensitivity. Insensitive munitions (IMs) [4] are created by combining these IHEs with conventional explosives to further enhance safety. This is typically done using casting methods, where one or more explosives like RDX or nitroguanidine (NQ) are mixed with a melted, less sensitive explosive like NTO. The resulting compound maintains the necessary explosive power while being more resistant to unintentional detonation. Examples of such IMs include PAX families [5], IMX101, and IMX104 [6]. These innovations aim to provide effective explosive materials for military use while minimizing the risks associated with handling, storage, and transport, ultimately improving overall safety. One of the most significant events of the 2010s was the production of IMX-101, which replaced TNT in munitions [7]. Time Magazine ranked it as one of the greatest fifty inventions of this year. The US Army and BAE Systems developed the insensitive explosive mixture known as IMX-101 to take the place of TNT in artillery shells. It is based on DNAN, NTO, and NQ and has been considered the main fill for the new IM M795 155-millimeter artillery munition. IMX-104 is an insensitive explosive composite mixture based on DNAN, NTO, and RDX. It has been developed as a substitute for Comp B. It has been regarded as the primary fill for 81mm, 60mm, and 120mm HE mortars [8, 9].
The hollow charge, which has excellent armor penetration, has been used in military and civilian applications [10]. It can be filled with insensitive explosives to be efficient and highly safe against unexpected initiation. EXPLO5 is a computer program that uses the chemical equilibrium, steady-state model to calculate detonation parameters for explosives. The program employs the Becker Kistiakowsky-Wilson (BKW) equation of state for gaseous detonation products. The analysis of shaped charge jetting focuses on understanding the processes involved in jet formation and its penetration capabilities. When a shaped charge detonates, the liner material collapses and transforms into a high-velocity jet, which plays a crucial role in penetrating targets. Several factors, including the explosive's properties, liner geometry, and loading density, influence jet formation and its effectiveness. Higher loading densities typically result in increased jet velocity, leading to greater penetration depth. Computational tools such as Explo5 and Autodyn are widely used to model and analyze these phenomena, providing insights into detonation characteristics, jet dynamics, and material interactions. This study aims to demonstrate the effects of varying the loading density of IMX on detonation characteristics through analytical methods utilizing the Explo5 thermochemical code, while also examining the shaped charge characteristics and its penetration into RHA targets through numerical simulations with Autodyn software.

2. Analytical calculations

The material models inherent in the code were used in the modelling. The equation of state (EOS) for the high explosive is "Jones Wilkins Lee" (JWL) equation which was defined by Kury et al., 1965; Lee et al., 1968 [11, 12]. The Jones-Wilkens-Lee (JWL) equation of state (EOS), shown in (1), for IMX with different densities was used to model the explosive charge.

$$P = \mathrm{A}\left(1-\frac{\omega\,\mathrm{V_o}}{\mathrm{R_1 V}}\right)e^{(-\mathrm{R_1 V}/\,\mathrm{V_o})}+B\left(1-\frac{\omega\mathrm{V_o}}{\mathrm{R_2 V}}\right)e^{(-\mathrm{R_2 V}/\mathrm{V_o})}+\frac{\omega E}{\mathrm{V}} \qquad (1)$$

The initial density is represented by $1/V_0$, while ω denotes the Gruneisen coefficient. The constants A and B are expressed in pressure units, whereas R_1, R_2, and ω are dimensionless. Pressure is denoted by P, the relative volume by V/V_0, and specific internal energy per unit mass by E. The JWL parameters for IMX at varying densities were determined at the Chapman-Jouguet (CJ) point using the EXPLO5 code. These parameters define the explosive properties, which are summarized in **Table 1**.

Table 1. The JWL parameters and detonation characteristics for the IMX at different densities.

Density (g/cm^3)	1.6	1.67	1.74	1.81
Parameter A (Mbar)	23.24	21.29	18.3	15.28
Parameter B (Mbar)	0.924	0.874	0.712	0.562
Parameter R1 (-)	7.84	7.65	7.21	6.431
Parameter R2 (-)	3.38	3.32	3.21	2.75
Parameter W (-)	1.04	1.041	1.021	0.99
C-J Detonation velocity (m/s)	7015	7230	7685	8050
C-J pressure (Kbar)	209.5	216.4	232.8	260.4
C-J Energy / unit volume (kJ/cm^3)	8.26	8.88	9.09	10.1

3. Numerical simulations

Multiple methods exist for the theoretical establishment of jet characteristics in a shaped charge configuration. Most methods commenced by delineating the velocity profile of the liner over time and analyzing the progression of the collapse angle for each segment throughout the collapse process. Subsequently, variations of the Pugh-Eichelberger-Rostoker(PER) are presented. The theory determines the mass and velocity components of both the jet and the slug. Three separate simulation models in Autodyn were utilized for the analysis. The initial model, jetting analysis, was employed to ascertain the velocities and masses of both the jet and the slug. The second model, known as the jet formation model, facilitated the acquisition of jet profiles at different time intervals. Finally, the jet interaction model was utilized to analyze the penetration of the jet into the RHA target.

3.1. Autodyn-2DTM Jetting Analysis

The 2-D version of the numerical finite difference code Autodyn includes an integrated jetting routine that performs a PER-type calculation once the conical liner collapse is finished. The charge can be represented using either a Lagrangian or Eulerian grid, but the liner must be modeled as a Shell with 33 designated mass points are shown in **Figure 1** and are used as "jetting" points.

A Lagrangian grid was employed to model the charge, and Shell elements were used to represent the aluminium casing where needed. IMX is an explosive main charge of shaped charge with 70mm caliber and the detonation point is indicated at the axis of liner apex. The charge and liner at first were modeled with (0.1×0.1) mesh size 1501 I-lines (covering the axial space) and 251 J-lines (covering the radial space) but due to computational complications, this was later changed to (0.2×0.2) mesh size 751 I-lines and 126 J-lines.

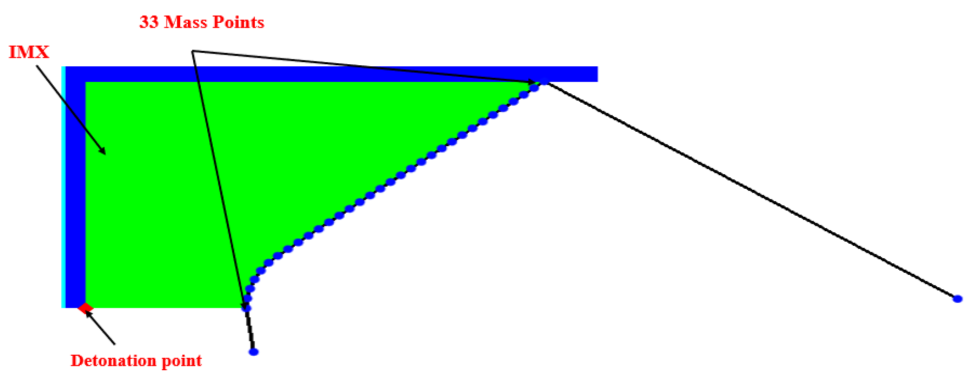

Figure 1. The 2-D jetting analysis of shaped charge using Lagrangian solver which imagines the conical liner as a Shell in which 33 specified mass points.

3.2. Autodyn-2DTM Jet Formation

IMX and the aluminium case material were used to model the explosive charge and were indicated in **Figure 2**. During the detonation of a high explosive, the detonation wave (DW) would be generated and it was accelerated toward the liner apex to cause the collapsation of the liner, and then the jet and the slug were formed with different velocities. The jet formation model depends on continuum mechanics using the Euler method to indicate the stretching shape of the jet at different times and the starting breakup of the jet at a specific time. The produced jet and slug were accelerated with a non-uniform velocity gradient toward the target. The output of the jet formation model will be used as the input of the lagrange-lagrange penetration model.

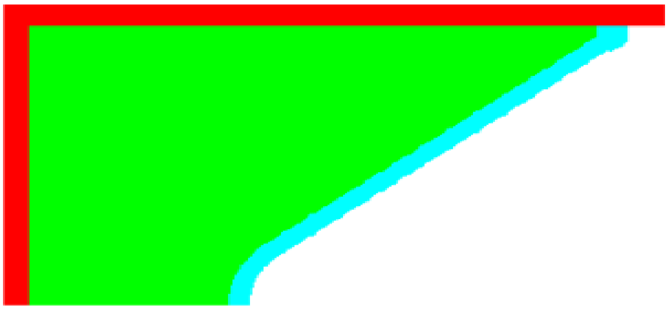

Figure 2. IMX and the aluminum case material were used to model the explosive charge.

3.3. Autodyn-2DTM Jet Penetration

In this model, we obtained the crater profile and calculated the depth of penetration through the transformation of Euler to the Lagrange solver using Autodyn software, then the formed jet from the jet formation interacts with the target, as shown in **Figure 3** to create a crater in the target. The jet penetration with steel and RHA targets was achieved using the Lagrange method.

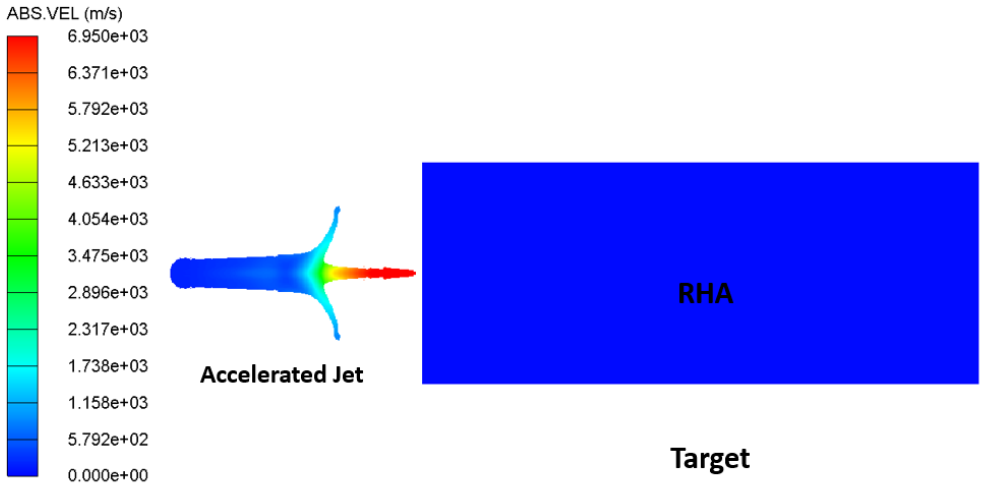

Figure 3. The remapped jet was accelerated toward the RHA target for IMX filler at 1.74 g/cm^3.

4. Results

4.1. The summary of shaped charge jetting analysis, jet formation, and jet penetration

The jet formation numerical simulations depict the stretching copper jet during the liner collapse until it touches the target surface at the assigned stand-off distance (i.e., three times its caliber). velocity vectors have been shown to denote the liner collapse as shown in **Figure 4**. The output results from the jetting analysis were indicated in **Figure 5**, whereas a sample of results of IMX at 1.74 g/cm^3 were 7-3 km/s for the jet tip and its rear velocity whereas the cumulative jet mass was found to be 36 g for this case. Figure 6 represents a sample of the predicted shaped charge liner collapse and jet formation using the IMX charge for 1.67 g/cm^3 at different times from the detonation moment. The jet started to form at 6 µs and its breakup after 18 µs as per **Figure 6**.

Figure 7 depicts the velocity contours during and after jet formation for the same explosive charge. The contours display the collapse of the liner and the initiation of jet formation at 6 µs. Subsequently, the jet starts to elongate, exhibiting a velocity gradient of approximately 6530 m/s at the tip and 1900 m/s at the slug. The formed jet started to breakup at different times for each case as shown in **Figure 8**. A sample of numerical penetration is illustrated in **Figure 9** that describes the jet's penetration depth into the RHA target at different times using an IMX charge of 1.67 g/cm^3. The entire penetration depth is achieved at 70 µs, after which the jet element velocity falls below the cutoff velocity, at which the jet does not become effective anymore, which means successive penetration stop.

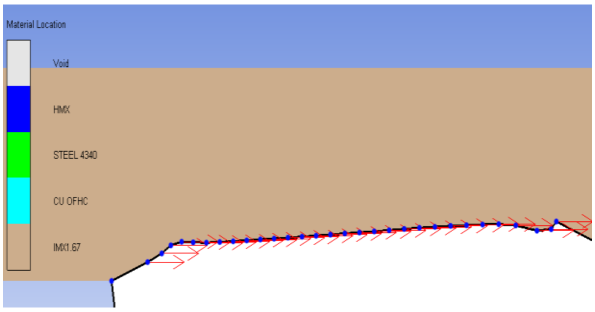

Figure 4. Liner collapse is indicated with vectors at each point.

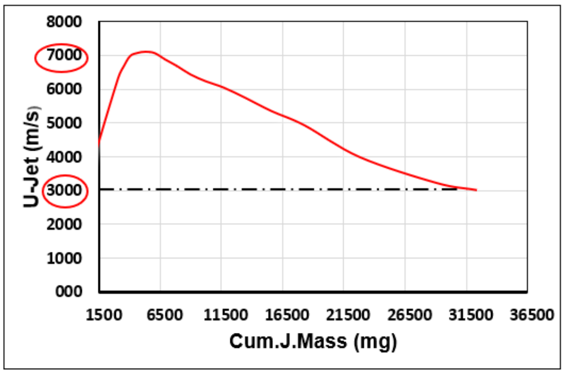

Figure 5. The output profile of jet velocity against cumulative jet mass.

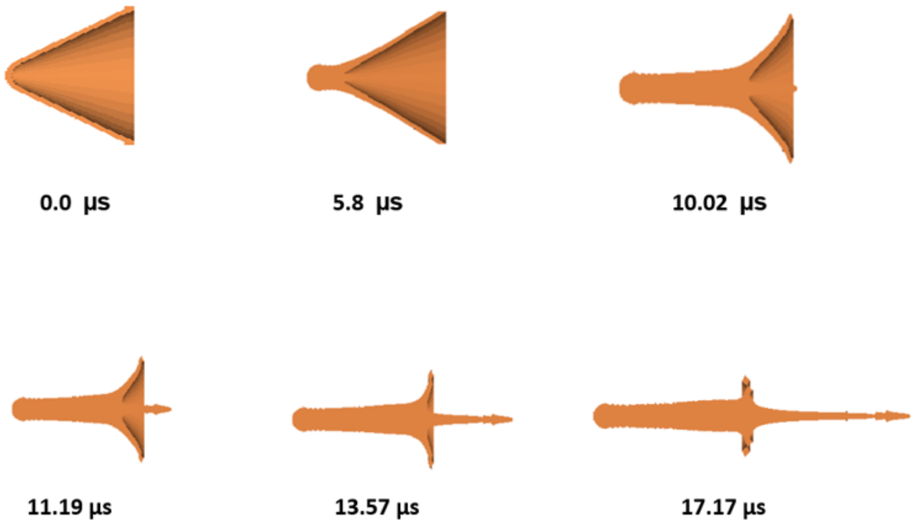

Figure 6. The impact of detonation wave (DW) on Liner collapse and jet creation at varying periods utilizing an IMX charge.

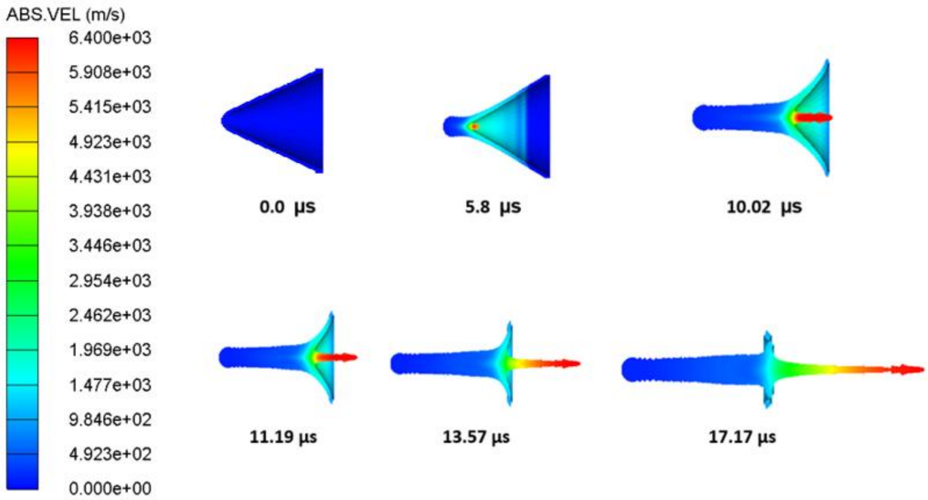

Figure 7. The absolute velocity contours at various timings after detonation of IMX charge at 1.67 g/cm^3.

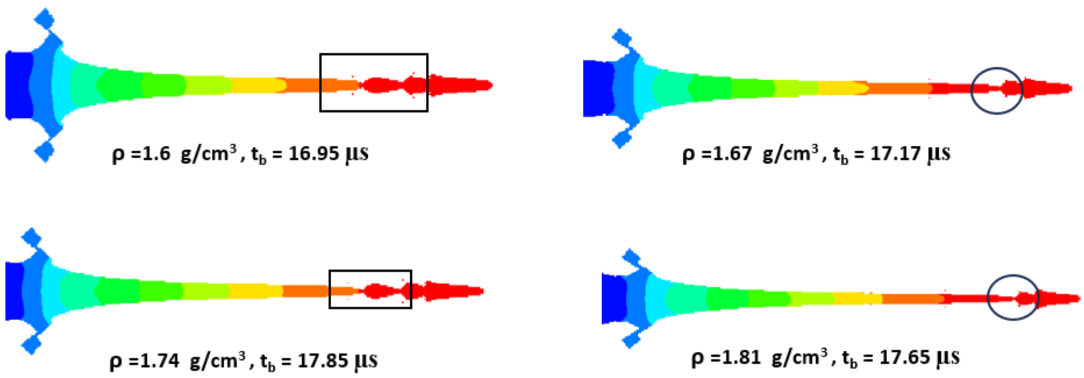

Figure 8. The formed jet starts to break-up at different times for each density of IMX explosive charge.

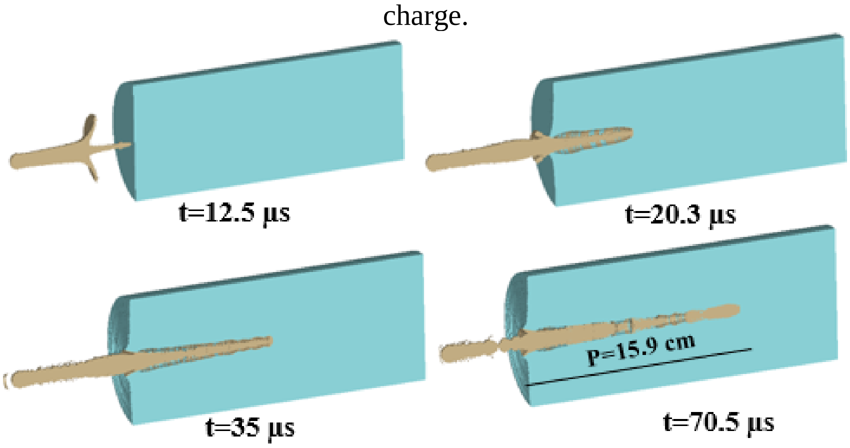

Figure 9. The penetration of jet into RHA target at different time for IMX filler at 1.67 g/cm^3.

What stands out in **Table 2** is to illustrate the results of Autodyn software jetting analysis; whereas the IMX with higher density has the largest penetration depth into the RHA target based on the jet penetration model. The results of the estimated jet tip velocity for IMX at 1.81 g/cm^3 were found to be 7150 m/s and 27.4 % jet mass to liner ratio, which achieved a penetration depth of 18.9 cm into the tested steel target material.

Table 2. The impact of changing the density of IMX filler on the shaped charge characteristics.

Density (g/cm^3)	Jet tip velocity (m/s)	Jet mass (g)	Jet mass to liner ratio (%)	Jet kinetic energy (KJ)	Jet penetration (cm)
1.6	6030	30.1	23.7	407.5	14.5
1.67	6460	33.2	26.1	470.9	15.9
1.74	6850	36.5	28.7	483.4	17.8
1.81	7150	34.9	27.4	549.6	18.9

Further analysis of the results reveals that the improvement of shaped charge characteristics was achieved by increasing the density of the explosive, therefore the most powerful explosive was IMX for 1.81 g/cm^3 (TMD) because it produced a detonation wave (DW) with the highest velocity and detonation pressure. If we now turn to the influence of changing the density on two parameters the DW and detonation pressure, there is a clear trend of increasing these parameters with increasing the density of IMX as shown in **Figure 10**. Of interest here in **Figure 11** is the increase in the penetration depth into the steel target (RHA) by increasing the jet tip velocity and density of the IMX filler.

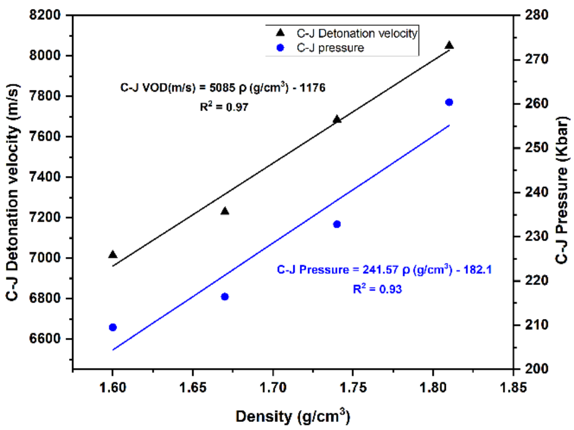

Figure 10. The impact of density on C-J VOD and C-J pressure.

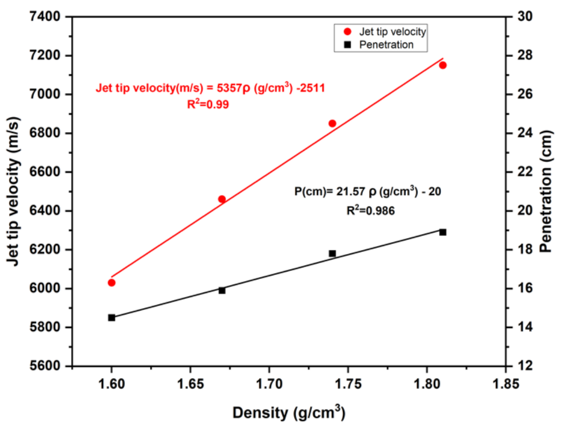

Figure 11. The impact of density on jet tip velocity and penetration.

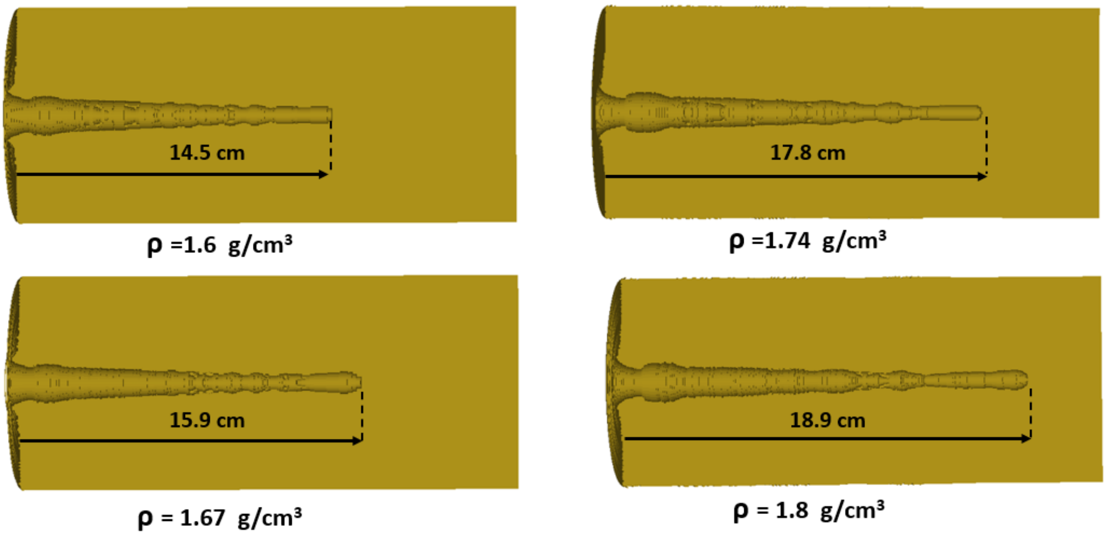

Figure 12. The penetration depth of IMX filler at different densities into rolled homogenous steel (RHA) target.

Autodyn software is used to calculate the depth of penetration through the transformation of Euler to the Lagrange solver. The most interesting aspect of **Figure 12** is to show that the crater depth of RHA target with the different four densities for IMX filler numerically based on Autodyn software; then the IMX for 1.81 g/cm^3 could create a crater depth of 18.9 cm. It can be seen from the data in **Figure 13** that the kinetic energy (KE) of the jet increased at different four densities of IMX explosive filler from 1.6 to 1.81 g/cm^3 to be 407.5 and 549.6 KJ respectively. The jet mass increased from 30.1 to 36.5 g for IMX with density from 1.6 to 1.74 g/cm^3 whereas, an abrupt change in this trend has occurred then the jet mass decreased to 34.9 g for IMX with 1.81 g/cm^3 because of the significant increase in jet tip velocity that resulting in the lack of jet mass but the KE still increased because the increase in jet velocity was more dominant than the decrease in jet mass.

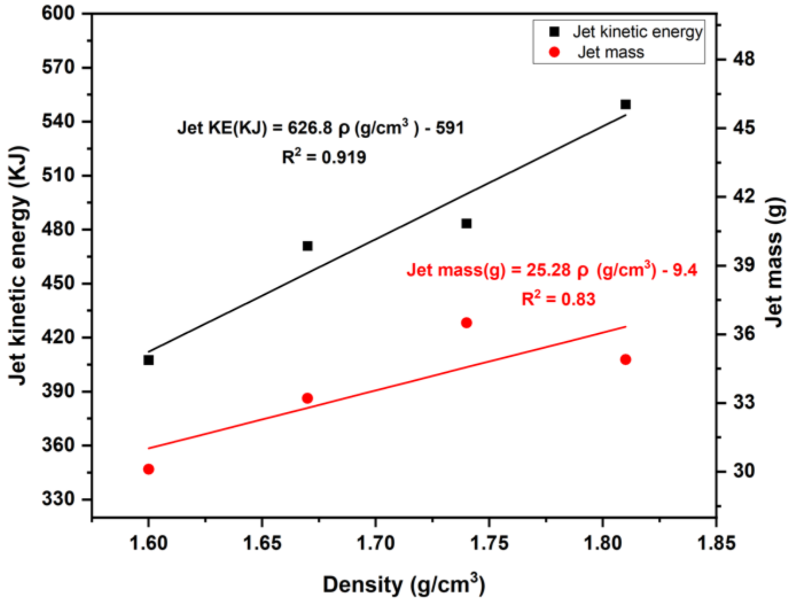

Figure 13. The relation of jet characteristics (Jet KE, Jet mass) as a function of loading density.

5. Conclusions

The current research work was devoted to study the effect of IMX loading density when used as at shaped charge explosive load. The analytical results of this study indicate that increasing in density for IMX was proportional with detonation velocity and detonation pressure theoretically using Explo5 thermochemical code. The current numerical calculations showed that increasing the density of IMX from 1.6 to 1.81 g/cm^3 increased the jet tip velocity from 6030 to 7150 m/s which indicated the importance of the loading density on the shaped charge performance. Besides, the importance of the jet tip velocity and its mass which were shown to vary significantly with the loading density of the IMX. The penetration potential estimated by Autodyn hydro code has shown clearly increase in its depth of shaped charge loaded with the largest IMX density of 30 % when compared with the baseline loading density of 1.6 g/cm^3.

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