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PARTICLE SIZE SENSITIVITY IN SMOOTH PARTICLE HYDRODYNAMICS NUMERICAL SIMULATION OF NATURAL FRAGMENTATION PHENOMENA

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Abstract: *Smoothed Particle Hydrodynamics (SPH), a computational method as part of ANSYS Autodyn software is widely employed for simulating natural fragmentation phenomena and all others process follow with large deformations. The goal of this study is to investigate the impact of particle size on key parameters such as fragment velocity and the total number of fragments. The research focused on the 105 mm M1 artillery projectile, aims to examine the relationship between particle size and fragmentation phenomena. The Johnson-Cook failure model was applied to the projectile case and Johnson-Cook strength model was applied to all metal parts of the artillery projectile. Furthermore, the research aims to underscore the importance of validation against available experimental data to ensure the reliability and applicability of SPH simulations. It is noted, however, that the available experimental results provide limited information. As a result, the comparison is restricted to the total number of fragments rather than a detailed analysis of fragment mass group numbers. Through systematic simulations with varying particle sizes, the study reveals a distinct trend: decreasing particle size correlates with increase of total number of fragments and no significant changes in fragment velocities within the specified material model behavior. By offering comprehensive insights into the relationship between particle size and fragmentation behavior, the study aims to emphasize the necessity of considering multiple factors in SPH simulations to enhance their accuracy and utility in predicting natural fragmentation phenomena.*

Keywords: *high explosive projectiles, natural fragmentation, numerical simulation, SPH simulation*

1. INTRODUCTION

The determination of mass, number, and velocity of fragments during the development phase can be accomplished using a numerical method in ANSYS Autodyn software through the Smooth Particle Hydrodynamics (SPH) simulation. Nowadays, very few research papers can be found on the topic of numerical investigation on natural fragmentation of artillery projectiles larger than 57mm caliber. The topic of the present research on natural fragmentation using SPH solver is primarily based on a 105mm projectile, mainly due to the availability of information. The available information relates to the known geometry of the projectile and approximate characteristics of the material that could be found in [1]. However, the material Č1635VP intended for the casing is defined with a minimal set of properties, where only the yield strength is known. Matching was done based solely on the yield strength, leading to the selection of AISI 1045 material, which is widely present in research papers dealing with natural fragmentation issues. The AISI 1045 material has approximately similar characteristics in the elastic zone as proposed by the author [1] and is well supported in available research papers [2-7], defined by Johnson-Cook strength model and various failure models. In the papers [2-7], the Johnson-Cook model was used as a strength model, describing the behavior of materials under high strain and high strain rate conditions. Regarding failure models, there are various approaches to modeling material fracture behavior using numerical analysis. Authors Luo et al. [8] conclude after testing various failure models available in ANSYS Autodyn that the principal strain failure model provides good results for thick cylindrical shells undergoing pure shear fracture. Additionally, some

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authors have used the principal strain failure model and stochastic failure model [3,7,8] for the natural fragmentation of cylindrical shells, or just the principal strain failure model [4]. On the other hand, there are studies where the behavior of cylindrical shell is considered using the Johnson-Cook failure model, with satisfactory agreement with experimental data. Authors Ping et al. and Elshenawy et al. [6,9], for example, state that using SPH analysis eliminates the need to consider failure and erosion criteria for natural fragmentation problems of cylinders made of the same material previously mentioned, which is opposite conclusion to the findings of the aforementioned authors. When it comes to the influence of particle size on result convergence, completely opposite conclusions can be found from numerical simulations conducted using the same ANSYS Autodyn software. For example, in the study by Elshenawy et al. [9], it is concluded that decreasing particle size decreases the initial fragment velocity of a mortar shell sample until convergence is achieved. However, in the work of Wei Li et al. [3], it is found that the fragment velocity of a cylinder increases with decreasing particle size. Vignjević et al. [10] use the SPH solver for natural fragmentation purposes, based on well-known experiments conducted by Mock and Holt and the case of the MK82 bomb. The authors specify the number of particles per shell thickness, which is crucial for analyzing the influence of particle count on result convergence. For instance, for the MK82 bomb with an average shell thickness of 12.7mm, there are 6 particles per thickness, resulting in a total 1.2 million particles. The total number of particles is contained within a quarter of simulated models. Under these particle count conditions, the authors report that the results align with experimental findings within an acceptable margin of error. However, the authors Ugrčić et al. [11,12] demonstrate ANSYS Autodyn software's natural fragmentation capabilities with 105mm, 120mm mortar shells, and 128mm unguided artillery rocket warheads. Their approach combines Euler-Lagrange interaction: Lagrange solver for fragmentation and Euler solver for detonation modeling. Results cover fragment velocity, number, and mass distribution, but their solver focus diverges from this research paper's scope. Experimental results are available for the 105mm M1 artillery projectile [11,13], providing information on the total number and mass distribution of fragments. However, these studies lack sufficient detailed information about the projectile material itself for numerical simulation and experimental testing. This limitation makes it challenging to verify the numerical model. The aim of this research is to study influence of the particle size (PS) on the convergence of results, such as fragment velocity and total number of fragments. Other phenomena are also included, such as shell interaction with the detonation products and kinetic energy of the detonation products. The paper also examines the sequences of shell expansion through a visual review of the fragmentation process. The work in this paper provides insights into the capabilities of SPH solvers within the ANSYS Autodyn software, emphasizing that result accuracy depends on precisely defined material behavior models and well-defined fragmentation properties in the simulation setup.

2. NUMERICAL MODEL

Artillery projectile configuration

Based on the dimensions of the artillery projectile taken from [1], a 3D model of a quarter cross-section has been designed. The model includes a projectile case, a driving band, an explosive charge, and a fuze. The fuze, modeled as a solid part, is crucial in simulations, particularly at the start, to establish the detonation front and prevent early leakage of detonation products. Figure 1 shows a 3D quarter cross-section of the considered model with materials corresponding to each component of the projectile in ANSYS Autodyn environment.

Numerical setup

The entire process of natural fragmentation is simulated using the SPH solver, where all components of the artillery projectile are simulated within the SPH domain. This research study does not go into the details of the SPH solver itself, where fundamental information can be found in [14]. Also, the same approach to modeling natural fragmentation phenomena can be found in research papers [2-10] involving the SPH solver. The study focuses on investigating the influence of PS on natural fragmentation phenomena. Reducing PS or increasing the total number of particles in the considered model directly affects computational requirements. Decreasing particle size leads to an increase in the number of nodes and significantly raises computation

Figure 1. Artillery projectile 105mm M1, 3D quarter numerical model with material assignment

time strongly affecting on the decreasing time step. Priority was given to the total number of particles and the number of cores used for parallel processing, and their impact on required RAM memory space. Figure 2 shows a 3D model with 10 subdomain decomposition, prepared according to the guidelines in the ANSYS Autodyn user manual [15] for parallel computation. Each simulation was set to record sequences every 25 μs within a total time interval of 350 μs. Several examples were run with the next properties:

- PS 5, case nodes 2940 and total nodes 6128,
- PS 2, case nodes 47004and total nodes 97093,
- PS 1, case nodes 375799 and total nodes 778385,
- PS 0.7, case nodes 1096360 and total nodes 2163301,
- PS 0.6, case nodes 1742818 and total nodes 3605391,
- PS 0.5, case nodes 3010833 and total nodes 6232289.

Material models

The Johnson-Cook (JC) model was selected to characterize the behavior of a cylindrical casing made from AISI 1045 steel, a driving band made from Cu-OFHC2 and fuze made from AL 2024 - T4. This model is extensively employed to describe materials that undergo large strains, high strain rates, and thermal softening. Additionally, to enhance its capability in capturing the material's response under diverse conditions, the Gruneisen equation of state was integrated with the JC model,

$$\sigma = (A + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon}^{*})(1 - T^{*m}) \qquad (1)$$

Here, the constants A, B, n, C, and m are material properties, where ε represents the equivalent plastic strain, ε^* denotes the dimensionless effective plastic strain rate, and T^* signifies the dimensionless temperature, where all data are given in Table 1. Gruneisen EOS contains next parameters: Grun. Coeff. is 2.17, C1 is 4.569 km/s, S1 is 1.49 and specific heat is 452 J/kgK. The JC model for strain at fracture incorporates key parameters such as stress, strain rate, and temperature to predict the material's behavior under dynamic loading conditions. The higher stresses relative to a reference stress led to increased strain at fracture, assuming other factors remain constant. The influence of strain rate sensitivity determines how the plastic strain rate affects fracture behavior. Additionally, the term for thermal softening indicates that higher temperatures relative to a reference temperature reduce the material's strength and ductility. The JC failure model which predicts the strain at fracture (ε_f) using the following equation:

$$\varepsilon_f = [D_1 + D_2 \exp(D_3\sigma^*)]\left[1 + D_4 ln\left(\frac{\varepsilon}{\varepsilon_0}\right)\right][1 + D_5 T^*] \qquad (2)$$

where constants D_1, D_2, D_3, D_4 and D_5 is given in Table 2. The JC failure model is applied only on AISI 1045, driving band and fuze are excluded. The Jones-Wilkins-Lee (JWL) equation of state serves as a widely adopted model in the explosives phenomena and is incorporated into ANSYS Autodyn software. It characterizes the detonation behavior of explosives, emphasizing the energy release and resulting pressure-volume relationship, expressed by the following equation:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{(-R_1 V)} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{(-R_2 V)} + \frac{\omega e}{V} \qquad (3)$$

Here, p stands for pressure, V denotes relative volume, and constants A, B, R1, R2, and ω are given in the Table 3, with e representing the specific internal energy per cubic meter.

Table 1. Johnson-Cook strength model parameters

Material	A (MPa)	B (MPa)	n	C	m	T_m (K)
AISIS 1045 [2-7]	507	320	0.28	0.064	1.06	1793
Cu-OFHC2	90	292	0.31	0.025	1.09	1356
AL 2024- T4	203	398	0.65	0.015	1.1	859

Table 2. Johnson-Cook failure model, damage constants for AISI 1045 [5]

D1	D2	D3	D4	D5

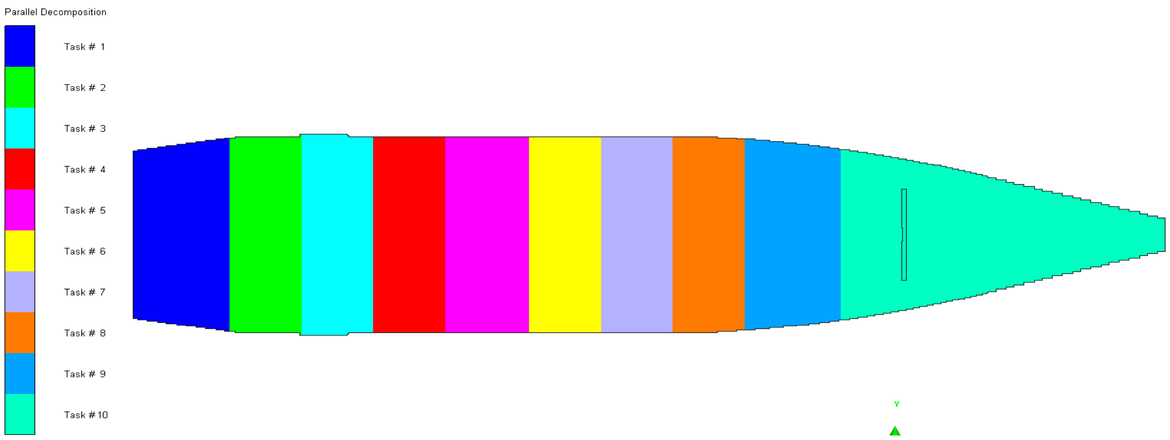

Figure 2. Artillery projectile 105mm M1, 3Dquarter numerical model (mirror function applied) with 10 subdomain parallel decomposition

0.1	0.76	-1.57	0.005	0.84

Table 3. JWL equation of state model for TNT (from Autodyn material library)

ρ (g/cm3)	D_{c-j} (km/s)	P_{c-j} (GPa)	A (GPa)	B (GPa)	R_1	R_2	ω
1.63	6.93	21	373	3.747	4.15	0.9	0.35

3.NUMERICALRESULTS AND ANALYSIS

The following section provides an analysis of the results obtained from numerical simulations based on six considered examples. The illustrated results from Figure3, up to Figure 7 correspond to the example with the highest achieved convergence. The detonation front propagation can be observed in Figure 3, moving from right to left. The complete detonation process from the detonator to the bottom of projectile is completed in approximately 50 µs. Figure 4 it is shown fragmentation process at 250 µs and it is visible detonation products leaking and interaction with fragments. In accordance with findings from prior research papers, the fragmentation process of projectiles is typically considered complete when the projectile's lower section increases radially approximately twice its radius, observed to occur around 250 µs, as visually depicted in Figure 5. Figure 5 serves to illustrate a comparative analysis between the resulting fragments and the initial configuration of the projectile casing.

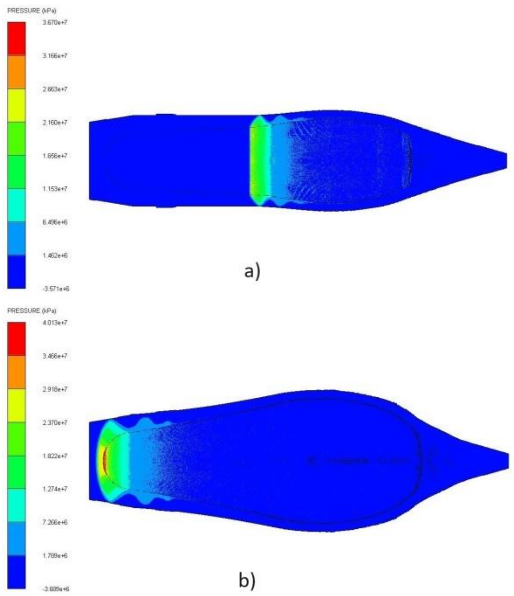

Figure 3. Detonation wave propagation in artillery projectile:a) 25 µs and b) 50 µs

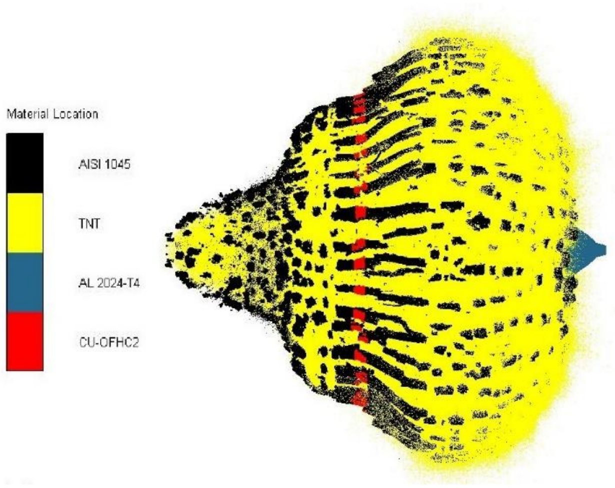

Figure 4. Completed fragmentation process with detonation products interaction 250 µs

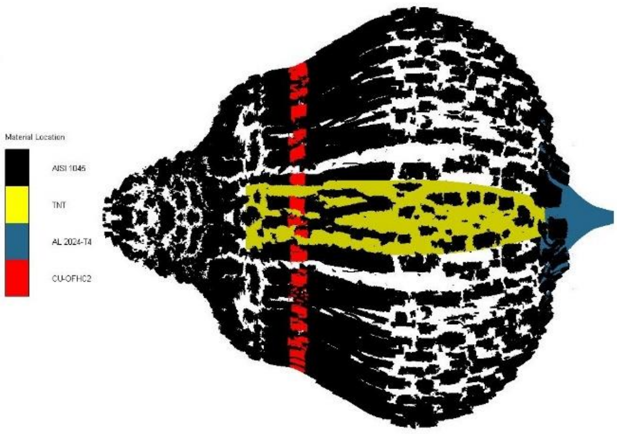

Figure 5. Completed fragmentation process compared to initial case volume (yellow color)

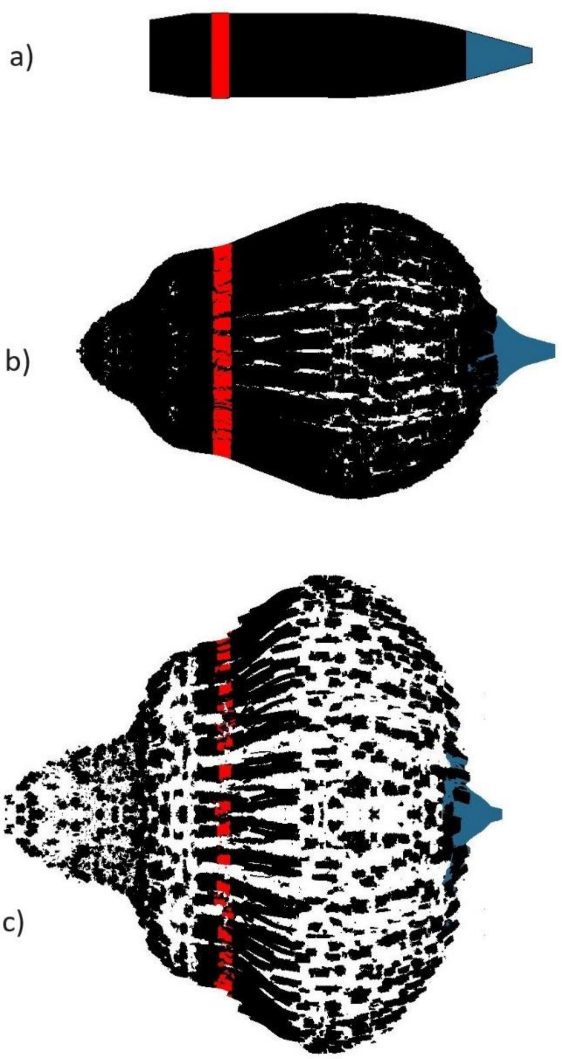

Figure 6. Fragmentation progression: a) 0 µs, b) 125µs and c) 250 µs

Figure 6 provides a detailed sequence showcasing the phases of both case expansion and fragment formation throughout the observed process. Specifically, it captures significant time points at 0 µs, 125 µs, and 250 µs, offering a comprehensive view of the dynamic evolution of fragments. The entire fragmentation process was tracked until 350 µs, with the determination of its completion grounded in the consistent total count of fragments observed up to approximately 250 µs. Notably, the assessment also incorporates the structural dynamics involving the rupture of the driving band and the deformation of the fuze, both contributing to the overall fragmentation profile. Figure 7 further enhances the understanding by presenting a detailed velocity distribution across various fragment zones along the projectile casing. In the zones characterized by a higher ratio of explosive mass to metal mass, velocities peak at approximately 1200 m/s, underscoring the dynamic energy release during fragmentation. Conversely, velocities vary across other fragments, with velocities ranging from approximately 200 m/s to a minimum, with the fuze exhibiting an axial velocity of around 180 m/s, reflecting the diverse kinetic outcomes across different components of the projectile.

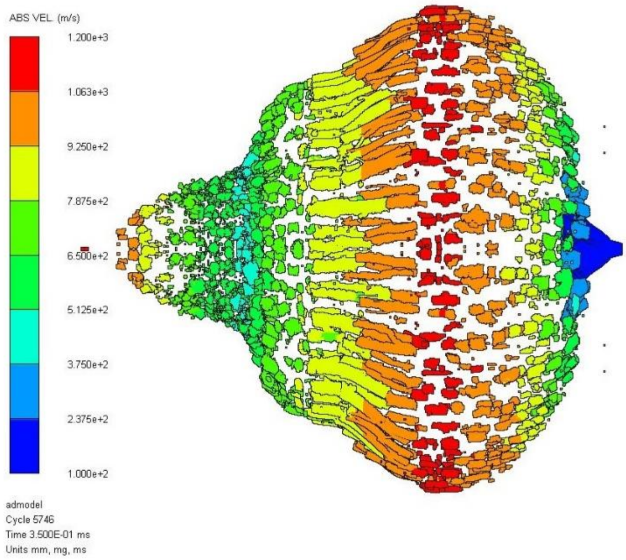

Figure 7. Absolute velocity distribution along axis of symmetry in 250 µs

In Figure 8, it can be observed that the absolute velocities of fragments do not vary significantly when considering PS 2 decreasing to the value of PS 0.5. It can be concluded that convergence with velocity values is achieved already at PS 2.

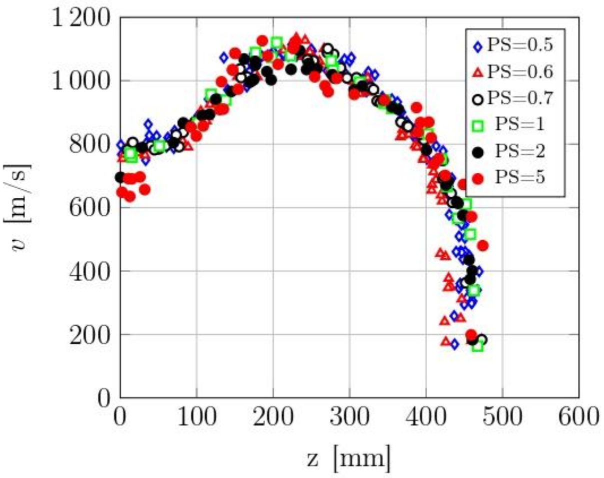

Figure 8. Absolute velocity of each fragment at 350 µs along the axis of symmetry for different particle sizes (PS)

On the other hand, when PS is greater than 2 or exactly PS 5, scattered velocity distribution values can be seen, with some zones showing both lower and higher velocities of fragments compared with other obtained results. In all cases, the maximum velocity does not exceed 1200 m/s. Besides comparing the velocity results influenced by PS, the total number of fragments was also monitored. From Figure 9, it can be concluded that decreasing the PS has a significant impact on changing the total number of fragments. Each simulation was compared with the experimental data, and it was found that numerical results converged at PS 0.7.

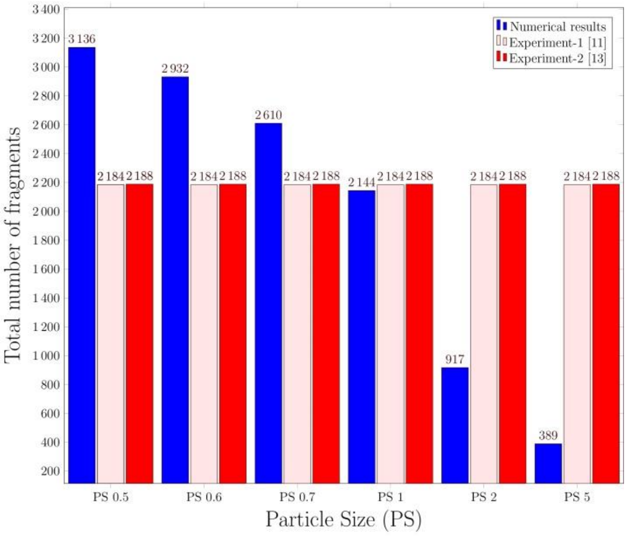

Figure 9. Comparison of the total number of fragments obtained by numerical simulation for various particle sizes (PS) with available experimental data.

Below value of PS 0.7, we have an increasing number of fragments compared with previous numerical results for 12.33%. It must be mentioned that additionally decreasing PS will strongly increase computation time, and the simulation will require more computational resources. For lower values of PS 0.7 it is notable that total number of fragments increases significantly. For example, for PS 0.5 compared to both available experimental results, the difference in achieving results is 30.4%. It can be concluded that a greater number of fragments obtained through simulation represents the number of fragments that could not be found after the experiment (pit test), due to very small dimensions and mass.

4. CONCLUSION

Based on the research conducted and the numerical results obtained in this paper, focusing on the particle size (PS) influence and the capabilities of the Smoothed Particle Hydrodynamics (SPH) solver in ANSYS Autodyn software, the following conclusions can be drawn:

- The natural fragmentation process was analyzed using the Johnson-Cook strength model and the Johnson-Cook failure model to study the behavior of projectile cases under high strain rate deformation;
- The research reveals that considered PS values exhibit minimal changes in absolute fragment velocities, while the total number of fragments varies significantly. Below a PS 0.7 threshold, further simulation may not be necessary due to time constraints, as the outcomes show negligible deviation. A final conclusion can be drawn after characterizing the mass distribution for each simulation.
- Based on the results, it can be concluded that convergence cannot be followed based on a single parameter, as stated in some research papers. It is necessary to consider multiple parameters, analyze them, and then draw a conclusion.
- Findings include the observation that the complete fragmentation process was done at approximately 200 µs. The distribution of velocities among different fragment zones is calculated, with maximum velocities at approximately 1200 m/s in zones with a higher explosive-to-metal mass ratio. This comprehensive examination provides valuable insights into optimizing projectile design and enhancing understanding of fragmentation dynamics in ballistic applications;
- To effectively validate a numerical model for optimizing existing projectiles and designing new ones, it is crucial to accurately determine both the material properties of the projectile casing and the characteristics of the explosive material.

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