



Finite Element Analysis of Impact-Velocity Effects on the Erosion Behavior of GH4720Li Superalloy-Based Cr_3C_2 Coatings

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Received: 15/10/2025

Revised: 15/11/2025

Accepted: 02/01/2026

Abstract: This study examines the effect of impact velocity on the erosion behavior of GH4720Li superalloy with and without Cr_3C_2 -NiCr coating using Finite Element Analysis. Silica particles (0.7 mm) were modeled at velocities of 25–125 m/s under normal impact. Results show that increasing velocity raises the maximum Von Mises stress before reaching a dynamic equilibrium. Coated specimens exhibited nearly twice the stress values of uncoated ones, indicating better load distribution and initial damage resistance. At low velocities (25–50 m/s), the coating reduced plastic deformation by absorbing impact energy. However, at higher velocities (≥ 75 m/s), the coating transferred more energy to the substrate, causing greater plastic strain than in uncoated material. These findings demonstrate that cermet coatings improve erosion resistance at low-to-moderate velocities but have limited performance under high-velocity impacts

Keywords: coating; erosion; velocity; FEM; superalloy



SDGs Problem Solving

Research and problem-solving in this study support the SDGs Chapter #9 by advancing durable engineering materials that reduce erosion, extend component lifespan, and lower maintenance needs. Such innovations promote sustainable industrialization, efficient resource use, and resilient infrastructure.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

Solid particle erosion is a material degradation phenomenon that occurs when discrete particles strike a surface at velocities that may exceed several hundred meters per second, resulting in substantial surface damage and performance deterioration (Hamed, Tabakoff and Wenglarz, 2006; Deng, 2025). This mechanism is of particular concern in numerous engineering applications such as offshore structures, aerospace systems, and mining operations, where critical components such as valves, pumps, pipelines, and gas turbines are routinely exposed to erosive and aggressive environments (Wood, 1999; Tarodiya and Levy, 2021). When solid particles such as sand impact the material surface at sufficiently high velocities, progressive surface degradation can occur through repeated impacts. Over time, this process compromises structural integrity and operational safety, reduces component service life, and significantly increases maintenance costs, with gas turbine systems being especially vulnerable to such erosive wear (Deng, 2025).

GH4720Li is a material commonly used in disc turbines, with the main advantages of high yield strength and fatigue resistance (Yaer et al., 2019). Turbine discs, which function as critical elements in aero-engines, frequently operate under erosive conditions, and their ability to withstand erosion has a direct influence on overall engine reliability (Freimanis et al., 2002; Silayev and Danilenko, 2015). To mitigate erosion on material surfaces, coating technologies have been increasingly applied. Due to their excellent properties such as superior resistance to oxidation and wear, high durability, and improved mechanical characteristics, cermet coatings are becoming increasingly popular. In particular, Cr₃C₂-based coatings, produced through thermal spray processes, have demonstrated considerable potential in protecting components that operate in severe erosive environments (Alvaredo, Mari and Gordo, 2013; Rajabi, Ghazali and Daud, 2015; Mahade et al., 2021).

Using silica sand particles with a size of 700 µm, Yaer et al., investigated the erosion behavior of three superalloy materials: GH4720Li, GH738, and GH4169 (Yaer et al., 2019). The particles were tested at velocities of 25 m/s and 55 m/s with impact angles ranging from 30° to 90°. GH4720Li exhibited the best erosion resistance at 55 m/s and a 30° impact angle, although GH4169 performed better at higher velocities due to its greater tensile strength and hardness. A numerical simulation consistent with the experimental results confirmed the accuracy of the finite element model used to evaluate erosion wear.

Using multiple solid particle impacts, Zhang and Dong conducted a comprehensive study on how cermet coatings applied to nickel-based superalloy substrates respond to erosive conditions (Zhang and Dong, 2015). In this study, Finite Element Analysis (FEA) was employed to simulate the effects of coating thickness, particle velocity, and particle size on erosion behavior. Their findings indicated that thicker coatings (greater than 100 µm) significantly enhance erosion resistance. However, radial and lateral cracks were observed as a result of increased particle velocity, which elevated stress at the interface between the coating and the substrate. The researchers concluded that the proposed model can accurately predict erosion-induced damage, consistent with experimental observations, thereby contributing to improved coating performance in real-world applications.

Based on previous studies, the erosive wear behavior of GH4720Li superalloy has been analyzed at three different impact angles using finite element analysis (FEA). However, the influence of erodent

velocity, one of the most critical factors in assessing a material's wear resistance, has not yet been investigated. Moreover, the effect of Cr_3C_2 -NiCr coatings on GH4720Li superalloys which can increase the wear resistance of material also remains unexplored. Therefore, this study integrates both aspects by employing a single-particle FEA erosion model to provide a more comprehensive understanding of the erosion behavior of Cr_3C_2 -NiCr-coated GH4720Li under varying impact velocity conditions.

2. METHODOLOGY

In this study, the overall research and simulation procedures are structured into several sequential stages, as illustrated in Figure 1. The process starts with a literature review aimed at analyzing previous studies and relevant theoretical concepts to establish a foundational basis for the study. Following this, the pre-processing stage involves preparing the simulation setup, which includes creating the geometry model, generating the mesh, defining boundary conditions, and determining the material properties used in the analysis.

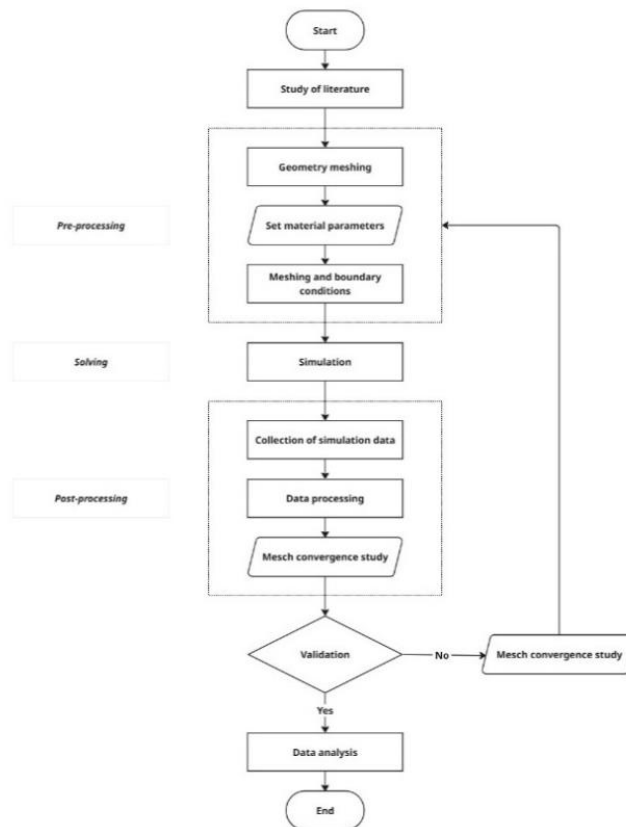


Figure 1. Research flowchart

Once these preparations are completed, the simulation proceeds to the solving phase, which utilizes the Finite Element Method. In the post-processing phase, the simulation data are gathered and analyzed. A mesh convergence study is performed to verify the accuracy and stability of the simulation model. The validation stage then evaluates whether the simulation outcomes are consistent with experimental data or theoretical predictions. If the computational results are found to be invalid, the process returns to the pre-processing stage for model refinement until the data

meet the required accuracy. The overall procedure concludes with the analysis phase, ensuring a systematic workflow from initial preparation to the final interpretation of results.

2.1. Material

In this study, the Cowper Symonds strain rate material model is employed. GH4720Li is selected as the specimen, while silica sand (SiO₂) is used as the erodent particle in the simulation (see Table 1). Equations (1) and (2) are applied to calculate the yield stress (σ_y) and the plastic hardening modulus (E_p) within the framework of the Cowper Symonds model (Hernandez *et al.*, 2013).

$$\sigma_y = [1 + (\varepsilon/\dot{C})^{\frac{1}{P}}](\sigma_0 + \beta E_p \varepsilon_p^{eff}) \quad (1)$$

$$E_p = \frac{E_{tan}E}{E - E_{tan}} \quad (2)$$

Table 1. Material properties (Aba-Perea *et al.*, 2016, 2019; Janka, 2018; Jonda, Łatka and Pakieła, 2020; Pan *et al.*, 2021; Sharma *et al.*, 2022; Zhang *et al.*, 2022; He *et al.*, 2025)

Materials	Density (kg/mm ³)	Poisson's Ratio	Young's Modulus (GPa)
Cr ₃ C ₂ -NiCr	6.7 x 10 ⁻⁶	0.25	280
GH4720Li	8.2 x 10 ⁻⁶	0.30	220
SiO ₂	2.65 x 10 ⁻⁶	0.19	74.8

2.2. Simulation Geometry

This study employs a three-dimensional Finite Element Analysis (FEA) model to compare the erosion behavior of GH4720Li under five different impact velocity conditions. A 0.7 mm silica particle is used as the erodent in the simulation, referring to the experimental research Yaer *et al.* (Yaer *et al.*, 2019). While the eroded target material has dimensions of 1 × 1 × 0.6 mm. As this study uses ceramic layers, which are brittle materials, a 90-degree angle was used to observe maximum erosion (Deng, 2025). Referring to previous studies that used particle velocities of 25 m/s (Purba *et al.*, 2025) and 200 m/s (Purba *et al.*, 2023). In this study the impact velocities evaluated in the simulation are 25, 50, 75, 100, and 125 m/s. The simulation geometry is illustrated in Figure 2.

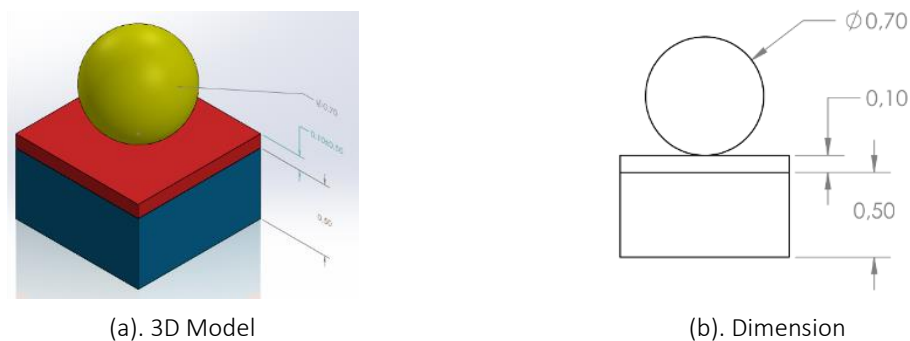


Figure 2. Simulation geometry

2.3. Mesh Convergence Study

To ensure that the simulation results are not affected by the number of mesh elements used, a standard method known as the Mesh Convergence Study was applied (Patil and Jeyakarthyayan, 2018). The simulation employed four different mesh densities: 62,500; 256,000; 500,000 and 1.5 ×

10^6 elements, according to our previous study (Purba *et al.*, 2025). The evaluation was carried out by comparing the maximum von Mises stress in the eroded material. The analysis results indicated that the variation in maximum stress values across the model decreased as the number of mesh elements increased. Therefore, a mesh density of 1×10^6 elements was selected for the simulation, as it produced a stress difference of only 0.73% while requiring less computational time compared to finer mesh configurations. Table 2 as shown mesh convergence results.

Table 2. Mesh convergence results

Mesh Density	Maximum Stress (GPa)	Error (%)
62500	1.1183710098	-
256000	1.2531775236	10.76
500000	1.2954077721	3.26
10^6	1.3098628521	1.1
1.5×10^6	1.3194630146	0.73

3. RESULTS AND DISCUSSION

3.1. Validation

To ensure the accuracy of the data in this study, simulation validation is essential. Therefore, the simulation results were compared with data from a previous study (Yaer *et al.*, 2019). The target material GH4720Li was used for validation, with a particle impact velocity of 25 m/s and an impact angle of 90 degrees. A comparison of effective stress beneath the target material surface was conducted along the x, y, and z axes. The simulation data were found to be consistent with the findings of the previous study, as shown in Figure 3. However, some discrepancies were observed, particularly at distances closer to the impact point (25 – 80 μm). These differences may be attributed to slight variations in the material parameters used in the simulation.

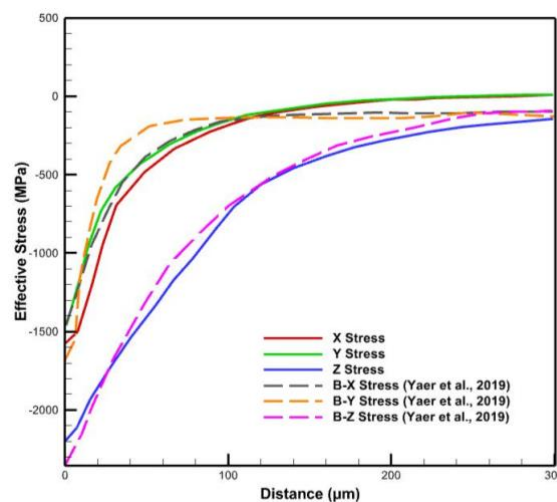


Figure 3. Simulation validation result

The graph illustrates the fluctuation of effective residual stress components (X, Y, and Z directions) relative to distance from the surface, measured in micrometers (μm). The vertical axis denotes effective stress in megapascals (MPa), whereas the horizontal axis indicates depth from the surface.

Solid lines represent the current results for X, Y, and Z stresses, while dashed lines denote reference data from Yaer et al., facilitating direct comparison and validation (Yaer et al., 2019).

At the surface (distance approaching 0 μm), all stress components display significant compressive stresses, attaining their peak negative magnitudes. This robust compressive stress state is characteristic of surface-modified or mechanically treated materials, wherein intense plastic deformation and thermal gradients produce considerable residual stresses. Of the three components, the Z-direction stress exhibits the greatest compressive magnitude near the surface, suggesting that through-thickness effects or normal loading conditions predominate the residual stress distribution at shallow depths.

As the distance from the surface increases, the intensity of compressive stress in all directions progressively diminishes. The X and Y stresses recover more swiftly, nearing zero values at a shallower depth than the Z stress. This indicates that in-plane stresses are more concentrated near the surface, whereas the Z-direction stress extends further into the material. Beyond approximately 200–300 μm , all stress components approach a low-stress or nearly neutral state, indicating that the effect of surface treatment decreases with depth, and the material reverts to its bulk stress condition.

The comparison with the findings of Yaer et al., demonstrates favorable qualitative concordance regarding stress trends and depth-dependent behavior (Yaer et al., 2019). Minor discrepancies in magnitude and recovery rate may be ascribed to variations in material properties, processing parameters, or modeling assumptions. The graph illustrates a uniform residual stress relaxation pattern with depth and corroborates that the current findings are consistent with earlier research, thereby affirming the validity of the stress analysis and the foundational methodology.

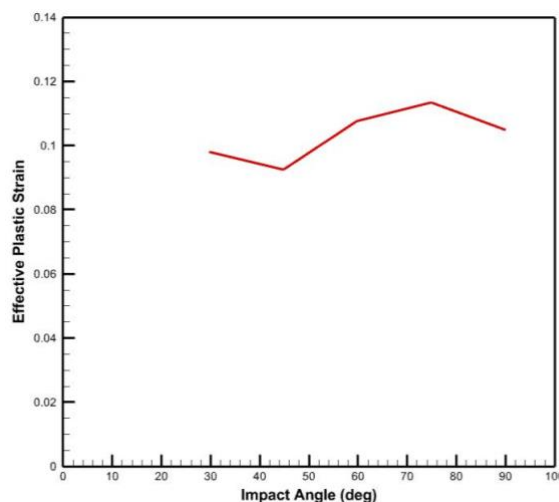


Figure 4. Effective plastic strain at various angles

The effective plastic strain resulting from erosive particle impacts on the material is illustrated in Figure 4 highlighting the regions of permanent deformation. This strain occurs when the material exceeds its elastic limit, leading to deformation that compromises the material's resistance in subsequent impact cycles. The strain magnitude varies depending on the impact angle and the hardness of the cermet coating. At the point of direct impact, angles approaching 90 degrees

typically produce higher plastic strain; however, lower angles tend to generate shallower and more evenly distributed strain due to the broader dispersion of impact energy across the surface.

Nonetheless, [Figure 4](#) the graph indicates that certain factors reduce the strain at a 90-degree impact angle. At this angle, a significant portion of the impact energy is absorbed as elastic deformation, which is transmitted into the deeper layers of the substrate, thereby reducing surface plastic deformation. In addition, material detachment (peel-out) and the hardness of the cermet layer allow energy to be distributed without significantly increasing surface plastic strain. As shown in the graph, the combination of energy distribution and material properties leads to a notable reduction in plastic strain, despite the direct nature of the 90-degree impact

3.2. Effective Stress Distribution

In previous study by Xiao et al., Von Mises stress was expressed as a combination of three principal stresses, so it can be used as an assessment of the mechanical condition of iron and steel materials ([Xiao, Shimizu and Kusumoto, 2017](#)). [Figure 5](#) illustrates the distribution of effective stress, which accounts for the combined stress components within the material under varying impact velocities and surface treatments (coatings), and identifies regions where permanent deformation may occur, potentially leading to damage. Areas exhibiting high effective stress indicate zones subjected to significant mechanical loading.

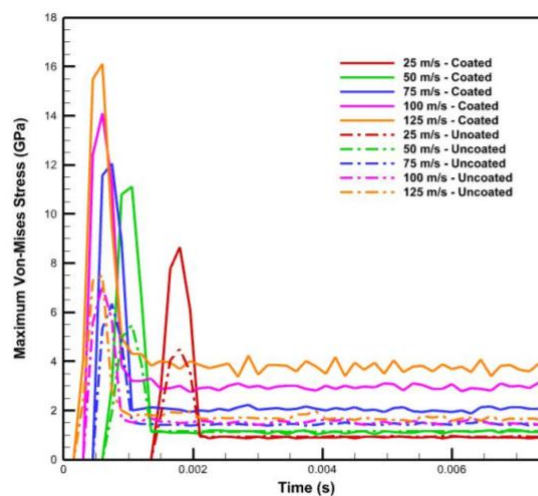


Figure 5. Effective stress (v-m)

The graph depicts the fluctuation of maximum von Mises stress (GPa) over time (s) for coated and uncoated materials exposed to varying impact velocities between 25 m/s and 125 m/s. During the initial phase of impact (about 0.001 s), all instances demonstrate a rapid increase in stress, reflecting the material's fast reaction to high-rate loading. The peak becomes more apparent at elevated velocities, indicating that an increase in impact velocity substantially enhances the initial stress concentration within the material.

The stress peaks for uncoated specimens are often higher and more abrupt, especially at velocities of 75 m/s, 100 m/s, and 125 m/s. The pronounced first peaks indicate significant localized deformation and an increased probability of damage start. After the peak, the stress diminishes

swiftly and thereafter stabilizes at a reduced although still variable level, indicative of stress wave propagation and partial stress relaxation inside the material.

Conversely, coated specimens exhibit somewhat reduced peak stresses and a more gradual transition to steady-state behavior. Coated samples at elevated velocities still endure significant initial pressures, although the intensity is reduced compared to uncoated samples. This signifies that the coating layer efficiently redistributes the applied load and alleviates stress concentration upon impact. Over time, the coated materials exhibit somewhat elevated stable stress levels compared to certain uncoated instances, attributable to energy absorption and load distribution by the coating–substrate system.

At lower velocities (25 m/s and 50 m/s), both coated and uncoated materials demonstrate decreased stress levels; however, the coated specimens consistently display more stable responses with less severe variations. This action underscores the coating's protective function in attenuating stress waves and improving structural integrity. At the initial stage of testing, a sharp increase in Von Mises stress was observed under all velocity conditions (25 m/s, 50 m/s, 75 m/s, 100 m/s, and 125 m/s). This spike reflects the material's immediate response to dynamic loading caused by high-velocity impacts. As shown in Figure 5 after reaching its peak, the stress rapidly decreases and stabilizes at a lower level over time, indicating that the material has passed through the initial deformation phase and entered a dynamically balanced state. The maximum stress observed is directly correlated with impact velocity, where higher velocities result in greater maximum stress due to the increased kinetic energy carried by the eroding particles.

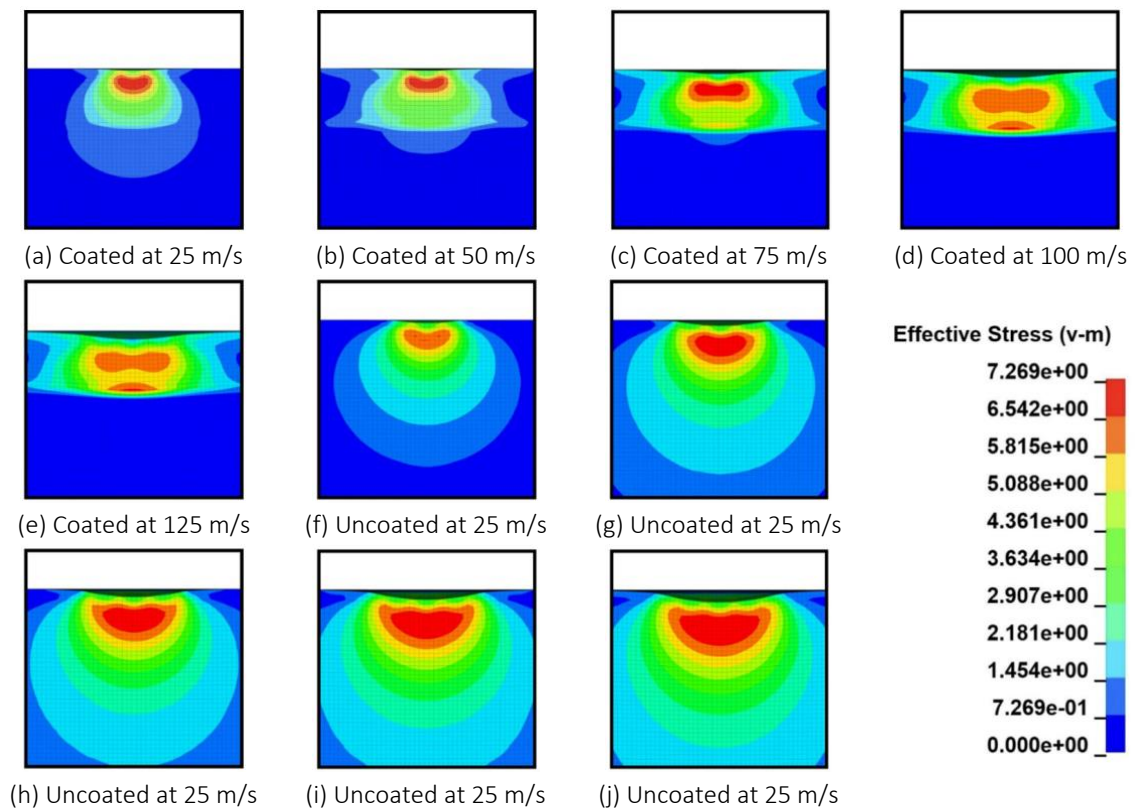


Figure 6. Cross sectional of effective stress

A notable distinction was found between GH4720Li with and without a Cr_3C_2 -NiCr coating. At all velocity levels, the uncoated material exhibited lower Von Mises stress compared to the coated counterpart. For instance, at an impact velocity of 125 m/s, the coated material reached a peak stress of approximately 16 GPa, whereas the uncoated material only reached 8 GPa. This indicates that the protective coating significantly reduces internal stress by absorbing a portion of the impact energy and distributing it more evenly, as illustrated in Figure 6e. Such behavior reduces the likelihood of plastic deformation leading to early damage or failure of the substrate.

3.3. Effective Plastic Strain

A previous study by Xiao et al., found that plastic strain is directly correlated with the erosion behavior of the material (Xiao, Shimizu and Kusumoto, 2017). Figure 7 presents the distribution of maximum effective plastic strain in GH4720Li, both with and without Cr_3C_2 -NiCr coating, at various impact velocities. The Figure 8 illustrates how rapidly the material undergoes plastic deformation following exposure to impact energy.

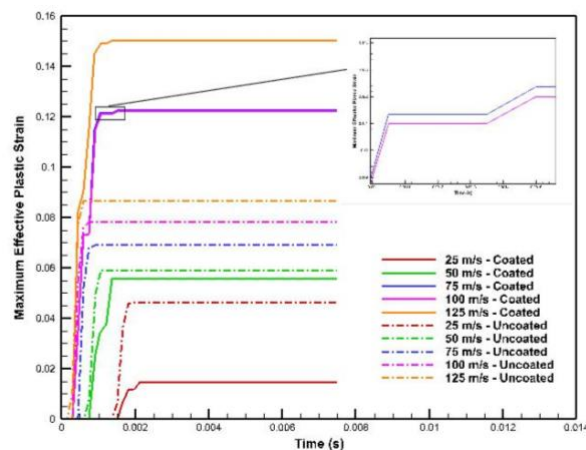


Figure 7. Effective plastic strain

The effect of impact velocity on the maximum plastic strain in GH4720Li shows a distinct contrast between the uncoated and coated conditions. Simulation results indicate that at lower velocities, such as 25 m/s and 50 m/s, the uncoated material exhibits higher maximum plastic strain than the coated material. This implies that the Cr_3C_2 -NiCr coating effectively mitigates plastic deformation by absorbing or redistributing the impact energy before it reaches the GH4720Li substrate. The coating consists of a ductile NiCr metallic matrix and hard Cr_3C_2 ceramic particles, which together form a more distributed deformation zone and reduce stress concentration at the substrate surface.

However, an opposite trend emerges as the impact velocity increases (≥ 75 m/s). At higher velocities, the coated material demonstrates higher plastic strain values than the uncoated counterpart. This suggests that the protective layer is unable to sufficiently absorb the increased impact energy, resulting in greater impact energy transmission to the substrate. The strong bond between the coating and substrate facilitates more efficient force transfer. Consequently, stress concentration and plastic strain in the region beneath the coating increase, transforming the coating into an impact energy transfer medium that amplifies plastic deformation at high velocities. This phenomenon is clearly visible in Figure 8c, Figure 8d and Figure 8e, where the contour plots indicate more

pronounced deformation between the coating and substrate layers. Therefore, the level of plastic strain generated at different impact velocities serves as an indicator of how much of the incoming impact energy is transformed into internal deformation within both the coating and the substrate.

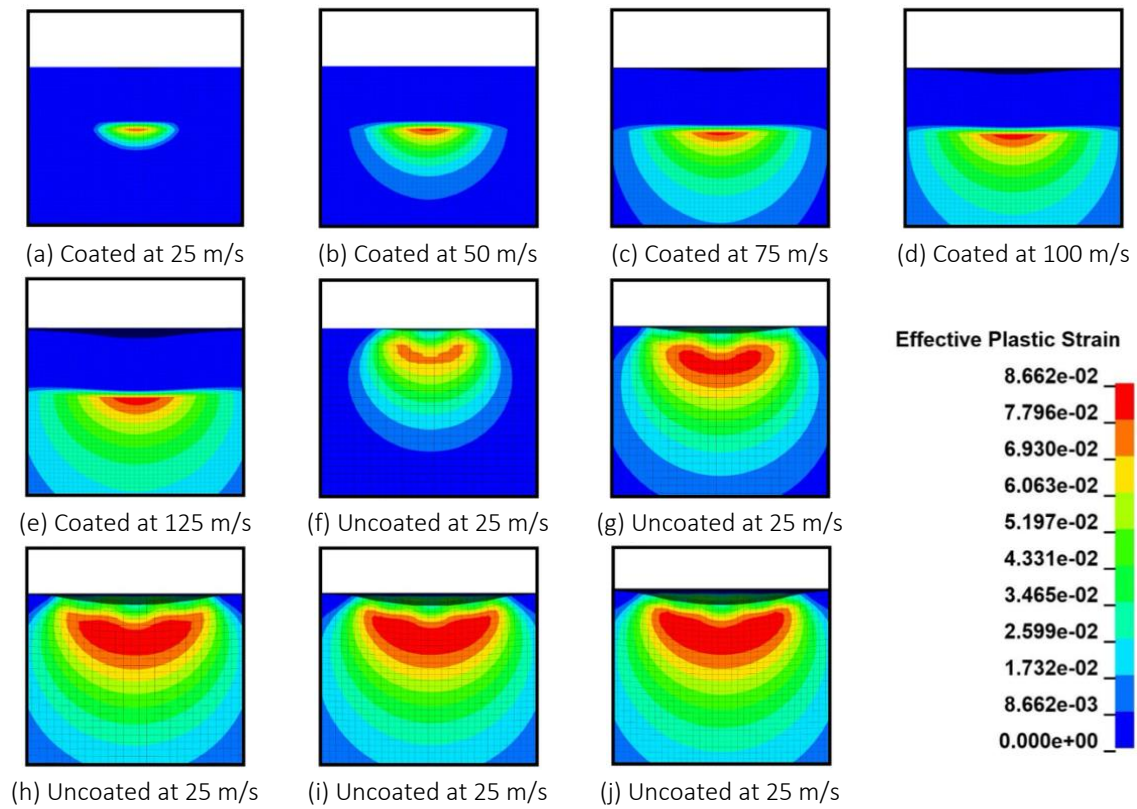


Figure 8. Cross sectional of effective plastic strain

4. CONCLUSION

As the impact velocity increases, the maximum stress also rises. Immediately following the impact, a peak in stress occurs, after which the stress decreases and stabilizes into a dynamic equilibrium state. At higher velocities, the Cr_3C_2 -NiCr-coated material exhibits Von Mises stress values nearly twice those of the uncoated material. This indicates the coating's ability to mitigate initial damage and effectively distribute the impact load.

The cermet coating (Cr_3C_2 -NiCr) significantly enhances erosion resistance. At lower velocities (25 – 50 m/s), the coating absorbs and redistributes impact energy before it reaches the GH4720Li substrate. However, at higher velocities (≥ 75 m/s), the coating transfers a greater portion of the impact energy to the substrate, leading to greater plastic deformation compared to the uncoated material.

The maximum plastic strain occurs at the direct impact surface. While uncoated materials exhibit greater plastic deformation at low velocities, coated materials display higher plastic strain at high velocities, as the protective layer becomes less effective in dissipating the impact energy. This observation suggests that the performance of cermet coatings has limitations in absorbing impact energy under high-velocity impact conditions.

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