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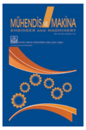

A NUMERICAL STUDY ON HYPER VELOCITY IMPACT BEHAVIOR OF METALLIC PLATES

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Keywords

Hyper velocity impact,
oblique impact,
numerical analysis

Abstract

Hyper velocity impact is a well-known problem due to micro meteoroid coincidence with space structures. Hence, hyper velocity impact behavior of materials is an interesting topic for researchers. Despite this fact, experimental studies require heavy costs to install hyper velocity impact systems. For this reason, numerical efforts come into prominence to understand hyper velocity impact events in a cost-effective way. In this work, a numerical model was built to simulate hyper velocity impacts on metallic plates. The model was validated by using the experimental results of a previous paper. Two different factors were investigated in impact conditions. The first one was target plate material and the other one was impact angle. Aluminum alloy Al 6061-T6 and A36 steel were used as the plate material due to their applications in space structure components. Impact angle was varied as 30°, 60° and 90° in the simulations. According to the results, plate material leads to a variation in fragmentation especially in normal impacts. Impact angle effect is observed in damage size on plates. Impact hole on target plates turn from circular to elliptical form by reducing impact angle.

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METALİK PLAKALARIN HİPER HIZLI ÇARPMA DAVRANIŞI ÜZERİNE SAYISAL BİR ÇALIŞMA

Anahtar kelimeler

Hiper hızlı çarpma, eğik çarpma, sayısal analiz

Öz

Hiper hızlı çarpma, mikro meteoroidlerin uzay yapılarına çarpmasından dolayı iyi bilinen bir sorundur. Bu nedenle, malzemelerin hiper hızlı çarpma davranışı araştırmacılar için ilginç bir konudur. Bu gerçeğe rağmen, deneysel çalışmalar, hiper hızlı çarpma sistemleri kurmak için yüksek maliyetler gerektirir. Bundan dolayı sayısal yöntemler, hiper hızlı çarpma olaylarını anlamak için maliyet açısından etkin bir şekilde ön plana çıkmaktadır. Bu çalışmada, metal plakalar üzerindeki hiper hızlı çarpmaları simüle etmek için sayısal bir model oluşturulmuştur. Model, önceki bir makalenin deneysel sonuçları kullanılarak doğrulanmıştır. Çarpma koşullarında iki farklı faktör incelenmiştir. Birincisi hedef plaka malzemesi, diğeri ise çarpma açısıdır. Uzay yapı uygulamalarından dolayı plaka malzemesi olarak alüminyum alaşımı Al 6061-T6 ve A36 çeliği kullanılmıştır. Simülasyonlarda çarpma açısı 30°, 60° ve 90° olarak değiştirilmiştir. Sonuçlara göre, levha malzemesi özellikle dik çarpmalarda farklı bir parçalanmaya yol açmaktadır. Çarpma açısı etkisi ise plakalardaki hasar boyutunda görülmektedir. Hedef plakalardaki çarpma deliği, çarpma açısı azaldığında daireselden eliptik forma dönüşmektedir.

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1. Introduction

Hyper velocity impact is a challenging phenomenon for astronautical and aerospace engineers designing space systems since space debris are freely traveling with extreme speeds around spacecraft and satellites. For this reason, structures serving in space are covered by protective materials. In literature, some works have been carried out on hyper velocity impacts of various metallic plates. In experimental investigations, gas gun systems have been efficiently used for decades due to their advantages in replication of space debris impacts at hyper velocity conditions. One of the advantages is characterizing structures at shock conditions that is producing similar environments with those of micro meteoroid impacts with structures in space (Chhabildas, Davison, and Horie 2005). At this condition, both impacting and impacted materials introduce severe local deformations due to excessive pressure generation in the event. Sufficiently thick structures exhibit excessive plastic deformations such as plugging, spalling or petalling. On the other hand, bending, stretching or perforation are common failure modes in relatively thin structures (Rosenberg and Dekel 2012). Figure 1 shows an image of a failed aluminum plate impacted by a polymer piece at hyper velocity. As shown in figure, a small piece at hyper velocity produces devastating results in materials. If spacecraft or satellites are faced with this kind of events, space missions may end up with catastrophic losses. Researchers make great efforts to lower damages on space structures and thereby controlling a set of factors such as material properties, impact velocity, geometrical design etc. in hyper impact events (O'Toole et al. 2015).

Figure 1. Deformation on a 50 mm Thick Aluminum Plate Due to an Impact by a 10 g Lexan Slug at 7 km/s (Christiansen and Calhoun 2017)

Although experimental investigations provide better understanding of hyper velocity impact phenomenon for researchers, most of studies in literature have been completed by analytical or numerical efforts due to heavy burden of cost in experimental systems (Gürgen 2018a, 2018b, 2019, 2020; Sheikhi et al. 2021; Silnikov et al. 2018; Slimane et al. 2021; Xu et al. 2021; Zhang et al. 2018). Merzhievskii and Titov (1976) proposed an analytical solution to hyper velocity impact problems. They investigated failure of steel plates subjected to particle impacts at velocities from 3 to 9 km/s. Moritoh et al. (2003) studied hyper velocity impact damage of stainless steel plates impacted by a polymer projectile travelling at 9 km/s. A hydrocode simulation method was used in this research to investigate spalling during collision. Silnikov et al. (2018) built a numerical model to simulate protective capabilities of spacecraft shielding elements at hyper velocity impact conditions. In their work, a spacecraft alloy, Al 6061-T6 was impacted by a projectile made from Al 1100 travelling at around 4 km/s. The role of projectile geometry was investigated by using three different designs such as sphere, cylinder and cube. According to the results, spalling mode and failure on the plate are heavily depended on projectile geometry. Fortov et al. (2006) proposed a numerical model based on a three-dimensional gas dynamic code. Similar to Silnikov et al. (2018), they changed projectile geometry to understand the impact damage and spalling during collision. A sphere, a rod and a disc were modeled as projectile in the impacting system. In addition, impact velocities were increased up to 5 km/s. From the results, projectile shape is an important factor on impact damage on plate. Moreover, diameter of perforation hole is related to elasto-plastic properties and strength level of plate material. Allende et al. (2020) conducted a numerical work to decide on the ballistic limit of impacting system. They simulated a micro meteoroid collision case in their study. A spherical projectile made from an aluminum alloy was used in a velocity range of 3 to 8 km/s. Based on this study, a damage prediction tool was developed from the simulation results. Another tool was developed on material design that allows change of material parameters in their numerical model and thereby providing response of impacted plate made from different materials.

Because of large deformations and fragmentations in hyper velocity impact problems, traditional grid methods in numerical works cannot accurately simulate the impacting systems (Wen, Chen, and Lu 2021). For this reason, meshless methods are more accurate for problems including excessive deformations such as hyper velocity impact, explosion, plastic forming, crack growth etc. (Gu 2005). Smoothed Particle Hydrodynamics (SPH) is one of meshless methods that comes to the fore among the other meshless computations especially for hyper velocity impact problems. SPH uses Lagrangian approach while having a set of interpolation nodes to discretize the body. These nodes possess single values in the calculated body while working based on governing equations. Pressure and velocity gradients are predicted according to the variable convolutions (Wen et al. 2021). In the present work, a hyper velocity impact problem is modeled by using SPH method. Two different materials, aluminum alloy Al 6061-T6 and A36 steel were used as target plate while delivering a spherical projectile made from aluminum alloy Al 6061-T6. Impact velocity was set at 6.15 km/s based on an early experimental study (Piekutowski 1997). Considering the real cases in space applications, oblique impact conditions were also investigated in this work. According to the results, hyper velocity impact is a crucial phenomenon for space structures because severe deformations are encountered in collisions.

2. Numerical Modeling and Validation

The numerical model was built by using SPH method in Ls-Dyna. SPH is a meshless Lagrangian method that provides easy solutions for sophisticated problems. This method enables calculating problems in large and irregular area of interest due to the meshless nature of computation. The system is defined with a set of nodes that are allowed to move under loading. Each node represents an interpolation point and thereby enabling calculation of all nodes with a regular interpolation function, namely smoothing length (Lacome 2006). SPH method is a very efficient way to solve especially large deformation problems as such in hyper velocity impact cases.

Experimental results of a previous work by Piekutowski (1997) were used in the validation of numerical model. The impact system was designed similar to the experimental work in this reference work. Hence, a target plate made from aluminum alloy Al 6061-T6 was impacted by a 16 mm diameter spherical ball made from the same alloy. The target plate was 0.8 mm in thickness and 60 mm in diameter. Impact velocity was 6.15 km/s at normal direction of target plate. Grüneisen equation of state (EOS) was selected in the numerical model. EOS describes the dynamic behavior of materials and therefore, it is essential to define the material by an EOS. Elasto-plastic material model was selected to define the materials in the problem. Based on early works (Ma, Zhang, and Qiu 2009; Wilkins 1999), material properties and Grüneisen EOS parameters for Al 6061-T6 are given in Table 1. In addition to the fundamental mechanical properties, Grüneisen EOS includes some other material parameters such as velocity constant (C), velocity slope constant (S) and Grüneisen constant (γ).

Table 1. Material Properties and Grüneisen EOS Parameters for Al 6061-T6

Density (g/cm^3)	Elastic Modulus (GPa)	Shear Modulus (GPa)	Yield Strength (MPa)	C (m/s)	S	γ
2.785	70	26	276	5300	1.34	2.00

Figure 2 shows the numerical and experimental views of the impact system at 8 μs. From these images, the deformation modes and spalling behaviors are quite close to each other. To numerically validate our model, a velocity parameter (V_axial/V_o) was calculated based on the description given in the reference work (Piekutowski 1997). V_axial defines the axial velocity of spalling pieces in projectile after perforation of target plate whereas V_o gives the initial velocity of projectile prior to the collision. Validation of our model was carried out by comparing the velocity parameter (V_axial/V_o) for Node-1 and Node-2 given in Figure 3. Node-1 is the forefront spalling piece while Node-2 shows the point at the center of the projectile. The comparison between the experimental reference work (Piekutowski 1997) and our model is given in Table 2. From the calculated data, the variations between the results are in a quite narrow band, which means that the numerical model could be accepted to investigate the hyper velocity impact system.

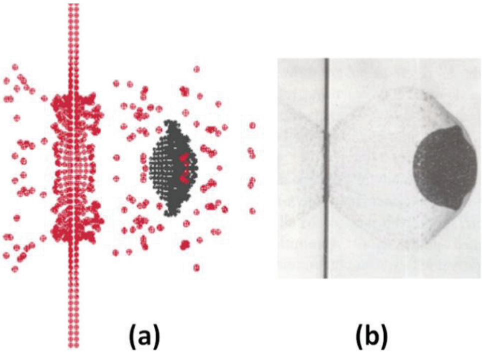

Figure 2. (a) Numerical and (b) Experimental (Piekutowski 1997) View of Impact

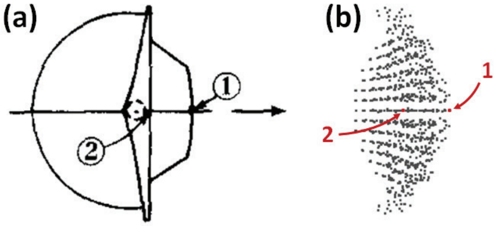

Figure 3. Velocity Measurement Nodes in (a) Experimental Reference Work (Piekutowski 1997) and (b) Numerical Study

Table 2. Comparison of Velocity Parameters

	Experimental (Piekutowski 1997)	Numerical	%error
Node-1	0.994	0.922	7.24
Node-2	0.968	0.934	3.51

3. Design of Hyper Velocity Impacts

Upon validating the numerical model, a set of numerical cases was designed to investigate the role of target plate material and impact angle. Aluminum alloy Al 6061-T6 and A36 steel were used as target plate materials in this study. Al 6061-T6 is a precipitation hardened aluminum alloy, in which magnesium and silicon are the main alloying components. This alloy is used for general purpose in many sectors due to its several advantages such as advanced mechanical properties, fairly good weldability and lightweight. These advantages make this alloy a good candidate for structural applications in space systems. On the other hand, A36 steel is a kind of structural steels having good mechanical properties and readily weldable behavior. In space structures, A36 steel is used in pressure vessel components (Jeyakumar and Christopher 2013). Geometries, dimensions and impact velocity were kept constant as is the case with the numerical validation state based on the reference work (Piekutowski 1997). For A36 steel, material properties and Grüneisen EOS parameters were taken from literature (O'Toole et al. 2015) as given in Table 3. To investigate obliquity in impacts, impact angle was varied as 30°, 60° and 90°. Table 4 gives the full set of impact cases used in this work.

Table 3. Material Properties and Grüneisen EOS Parameters for A36

Density (g/cm^3)	Elastic Modulus (GPa)	Shear Modulus (GPa)	Yield Strength (MPa)	C (m/s)	S	γ
7.895	200	78	250	4569	1.49	2.17

Table 4. Full set of İmpact Cases

Case	Plate material	Impact angle
1	Al 6061-T6	90°
2	Al 6061-T6	60°
3	Al 6061-T6	30°
4	A36	90°
5	A36	60°
6	A36	30°

4. Results and Discussion

Figure 4 shows the impact states for Case-1 including Al 6061-T6 target plate impacted at 90°. As shown in the images, the collision produces a full penetration, in other words perforation on the target plate. A heavy spalling is observed due to severe fragmentation as common in thin plates subjected to hyper velocity impacts. The spall emission takes place in a cone shape. Despite heavy spalling in target plate, projectile pieces travel in bulk form by creating a disc-shape debris cloud due to shock waves. On the other hand, fragmentation of projectile is clearly observed in oblique impacts as shown in Figure 5. At the impact angle of 30°, some part of projectile fragments ricochets off the target surface while the larger portion shows a spall emission at the back surface of target plate after perforation. By increasing obliquity in impacts, perforation on target plate turns to elliptical hole from circular deformation (Burchell and Mackay 1998). Figure 6 shows the front view of target plates after impacts for Case-1 to 3. From the images, it is clear that impact at normal direction results in a hole-growth type deformation on target plate. However, oblique impacts produce elliptical holes while ellipticity increases by reducing impact angle.

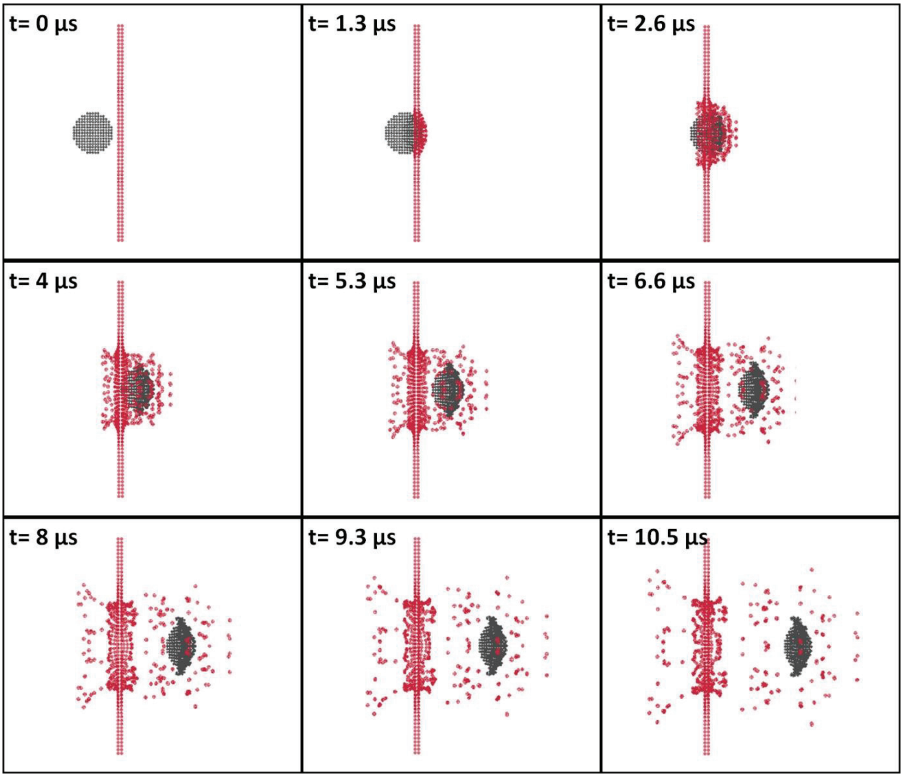

Figure 4. Impact States in Case-1

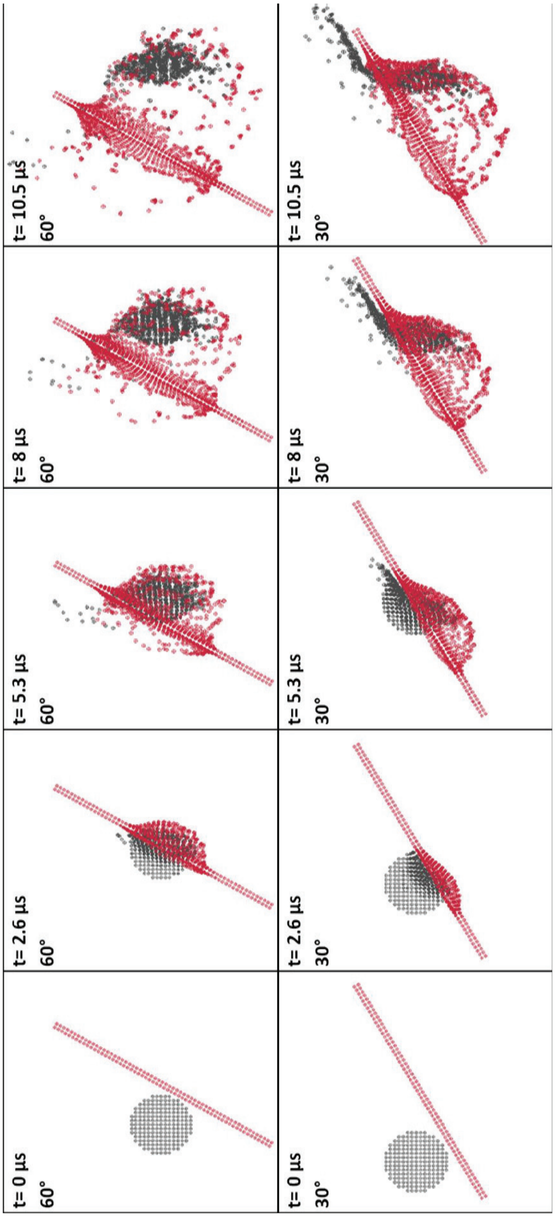

Figure 5. Impact States in Case-2 and Case-3

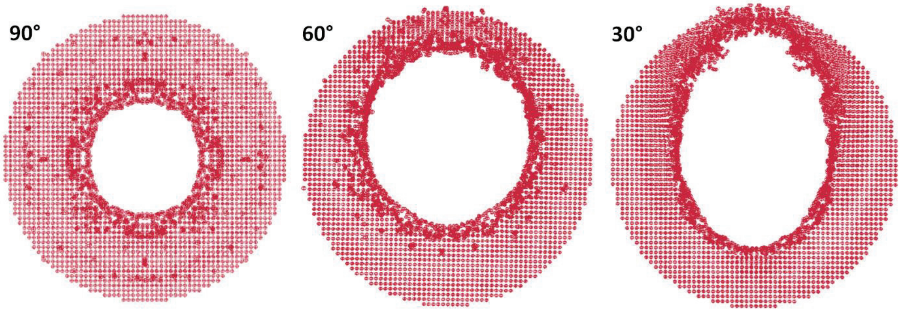

Figure 6. Front View of Target Plates After Impacts for Case-1 to 3

Figure 7 shows the impact states at 10.5 μs for A36 steel plates. Similar to Al 6061-T6 plate, A36 steel plate exhibits heavy spalling during perforation. Deformation on A36 steel plate turns from circular hole-growth to elliptical hole by increasing obliquity in impacts. Despite similar deformation modes with Al 6061-T6 plate, damage sizes are quite lower on A36 steel plate. Figure 8 shows the horizontal (d1) and vertical (d2) diameters of perforation holes on Al 6061-T6 and A36 steel plates. From this chart, obviously seen that perforation hole is a complete circle for both plate materials while A36 steel plate has a smaller hole in comparison to Al 6061-T6 one. By increasing obliquity in impacts, ellipticity develops in the perforation hole. Similar to normal impacts, perforation holes on A36 steel plate exhibit smaller sizes than those on Al 6061-T6 plates. This could be associated with the mechanical properties of plate materials.

Another output is residual velocities after impacts. Since projectiles are broken into several pieces during impacts, it is not possible to track the residual velocity of the projectile body as such in rigid body cases. Hence, velocities are given in a fringe plot for each node in the impact system as shown in Figure 9. In normal direction impacts, maximum velocities are observed on the spalling pieces that are ejected from the back side of target plates at the vicinity of impact point (Piekutowski 1997). On the other hand, maximum velocity fragments are seen at the impact side that are broken pieces of projectiles bouncing off target surfaces in oblique impacts. It is also important to mention that projectile fragments are in a bulk form having quite close velocities to each other in the normal impacts. However, projectile fragments lose their cluster form and thereby introducing a heavy spall emission in oblique impacts. Scattering of pieces leads to a reduction in residual velocities that is pronounced by increasing inclination angle in the impact system. Another issue is target material that yields a variation in deformation mode especially in normal impacts. Clearly seen that projectile fragments are much closer to each other after normal impact on Al 6061-T6 plate in comparison to A36 steel plate. This can be attributed to the strength of materials that A36 steel overcomes the aluminum alloy. It is also possible to state that the projectile spallation is heavier in the A36 steel impacts since the mechanical properties of A36 steel are higher than Al 6061-T6.

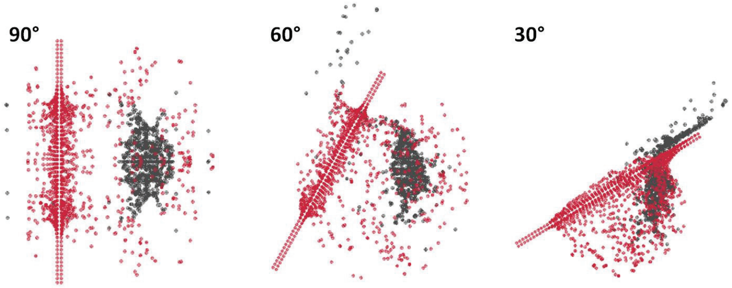

Figure 7. Impact States at 10.5 μs for Case-4 to 6

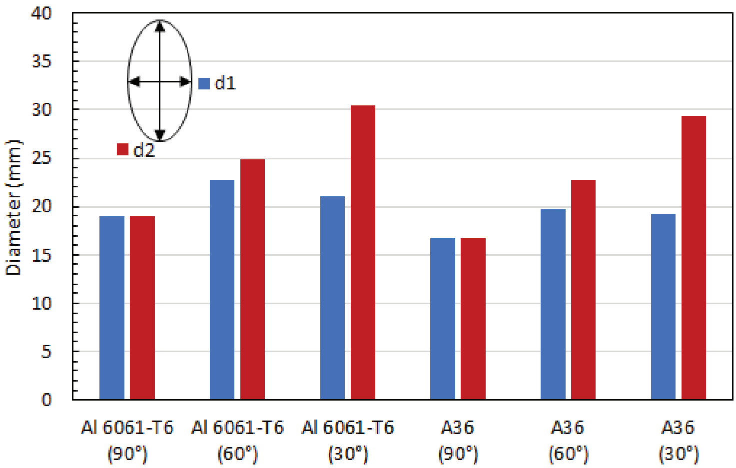

Figure 8. Horizontal (d1) and Vertical (d2) Diameters of Perforation Holes on Al 6061-T6 and A36 Steel Plates

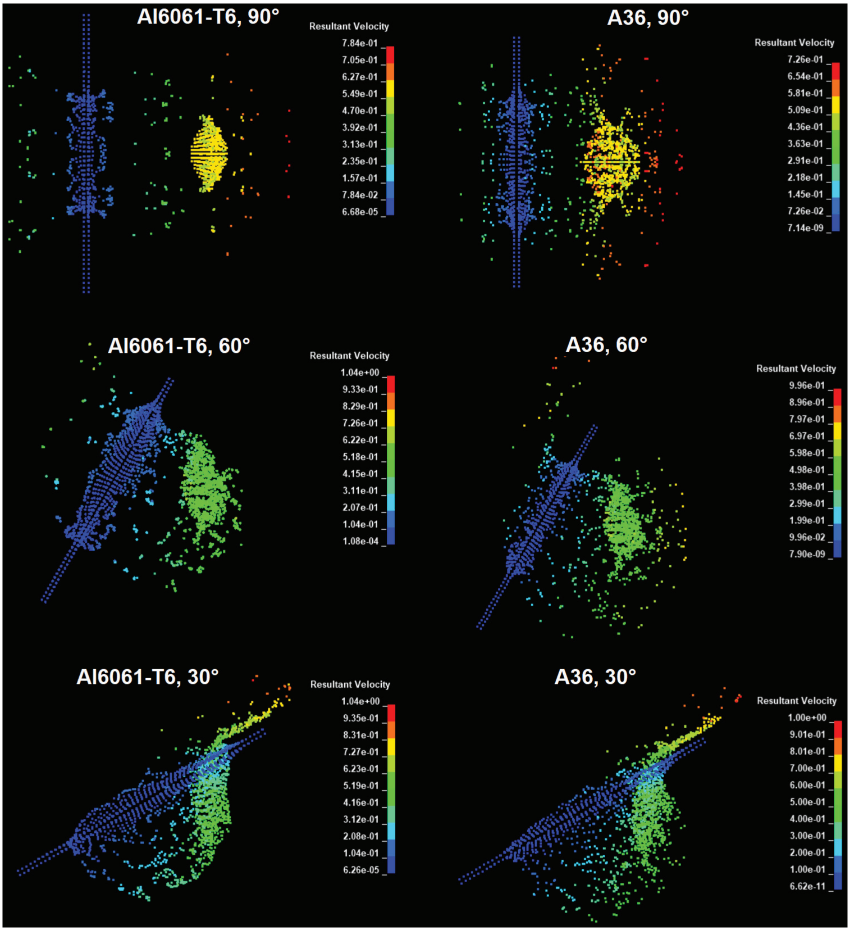

Figure 9. Velocity Gradients After Impacts

5. Conclusions

In the present work, a numerical model was built to investigate hyper velocity impact systems. Due to its efficiency in large deformation problems, SPH method was used in the modeling. The model was verified by an experimental result published in a previous work (Piekutowski 1997). In the design of simulations, target plate material and impact angle were varied to observe their effects in the impacts. Aluminum alloy Al 6061-T6 and A36 steel were used as plate material due to their applications in space structures. In addition, impact angle was changed from 90° to 30° by inclining target plate in simulations. According to the results, A36 steel provides slightly higher resistance to hyper impact conditions in comparison to Al 6061-T6. Considering the perforation holes, target plates made of Al 6061-T6 show larger damage than those of A36 steel. Moreover, projectile exhibits higher spalling effect after being impacted on A36 steel plate. Regarding the impact angle, it is possible to state that spalling effect grows stronger by increasing inclination in plates due to the increase in projectile spalling in addition to plate spalls. Furthermore, damage on plates gets larger in oblique impacts because projectile sweeps up a longer collision path due to inclination.

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