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A Numerical Study on Aluminum Plate Response under Low Velocity Impact

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ABSTRACT

In the present paper, a numerical study is performed to investigate the response of different plates aluminum alloys subjected to low velocity impact condition. In this regard, the square AA5083-H116 aluminum plates with dimensions 300×300 and 3 mm and 5 mm thick under low velocity impact are modelled, and a mesh convergence study is carried out to decide the appropriate number of elements. In this research, the influence of strain rate effects in low velocity impact response is examined by doing a comparative study using the isotropic elasto-plasticity and the Johnson-cook material models. The response to impact events of models including deflection history and maximum and permanent deflection is extracted and validated by available numerical and experimental data in literature. The results indicate that the strain rate has a significant influence on time histories and increases the accuracy of the predicted data. Then, using the developed modeling procedure, the behavior of three aluminum alloys under low velocity impact is investigated based on Johnson-Cook model. The results show that 7075-T6 and 6061-T6 alloys have the highest and lowest stiffness, respectively. Also, the lowest rate of absorbed energy to mass is observed in the 7075-T6 alloy.

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1. INTRODUCTION

In aerospace and marine industries, sports equipment, and lightweight vehicles, low density, strength, ductility and forming ability are some of the advantages of aluminum alloys. One of the properties required in industries is high energy absorption capacity per unit mass. Aerospace and marine structures for various reasons experience impact force and plastic deformations. Thus, investigating impact forces and understanding material behaviors for designing these structures is necessary. The focus of most researches is to predict the ballistic limit velocity, and little attention has been paid to low velocity impact. Low velocity impact is defined as an impact with a velocity within the range of 0 to 50 m/s, such as impacts occurring in collisions between cars, cargo, maintenance damage, dropped tools, etc.

Study of aluminum structures subjected to low velocity impacts needs investigation of structural dynamics and material behavior. To examine the dynamic behavior of structures to achieve a better understanding of the impact problem and to improve design reliability, different analytical models have been developed in which little attention has been paid to the actual behavior of materials. Experimental results indicate that metals show nonlinear strain hardening effects. Therefore, to achieve more accurate results, in most commercial finite element softwares, nonlinear material constitutive models such as the Johnson-Cook model is employed [1]. Over the years, due to being highly accurate and user-friendly, finite element softwares like LS-DYNA [2] and ANSYS [3] have somewhat replaced analytical methods in designing structures for analyzing dynamic loads.

However, many researchers have drawn their attention towards developing an analytical model to predict the low velocity impact response of structures [4-9].

Langseth and Larsen [10] numerically and analytically examined the behaviour of mild steel square plates subjected to circular blunt-ended load. The virtual energy method was used to develop an analytical model, which was then used to predict the maximum deflection of the plates under impact loadings. Moreover, some

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researchers examined perforation mechanism and ballistic velocity of perforator [11, 12]. Duffy [13] studied large deformation of metallic plates under blast loading. Grytten et al. [14] conducted an experimental and numerical investigation on low velocity perforation of aluminum plates. In their tests, square plates were mounted in a circular frame and penetrated by a cylindrical blunt-nosed projectile. The perforation process was analyzed using LS-DYNA code in order to study the effects of anisotropy, dynamic strain aging and thermal softening in low velocity impacts on the present aluminum alloy. Fagerholt et al. [15] numerically and experimentally studied the continuous out-of-plane deformation of AA5083-H116 plates subjected to low velocity impacts. Mohotti et al. [1] developed an analytical model to predict the out-of-plane deflection of aluminum plates subjected to low velocity impact. An energy-based analytical model was modified with the non-linear strain hardening effect of aluminum to predict the permanent plastic deformation at the center of the plates. In this work, experimental and numerical investigations were performed to verify the modified analytical model. Liu et al. [16] proposed an analytical failure criterion to characterize ship plated structures manufactured from aluminum and steel subjected to low impact velocities. The criterion considered the critical deflection, force and absorbed energy of plates laterally impacted by a hemispherical indenter, and assumed that failure occurred at the presence of necking. The proposed expressions was compared with numerical results validated with drop weight experiments conducted on small scaled rectangular aluminum and steel plates of the same bending stiffness.

Babaei [17] studied experimental responses of the clamped mild steel, copper and aluminum circular plates are presented subjected to blast loading. Also, the GMDH-type (Group Method of Data Handling) neural networks was used for modelling of the mid-point deflection thickness ratio of the circular plates using experimental results. Liu et al. [18] conducted a high velocity penetration experiment between an aluminum sphere and a square aluminum plate to provide data for depicting the penetration process and behavior of both projectile and target at multi-length scales. Veisi et al. [19] numerically studied the maximum deflection of aluminum circular plates under blast loading. Shock waves were produced by exploding a spherical charge at different distances. In order to decrease errors due to the nature of the conwep model, a VDLOAD user subroutine was developed for the Friedlander function. Koubaa et al. [20] conducted a numerical investigation to analyze the perforation process of target AA5754-O Aluminum plate subjected to normal impact at low to moderate velocities. A fully coupled elasto-visco-plastic-damage model was implemented into a user-defined material (VUMAT) subroutine for the commercial finite element code ABAQUS.

In this study, an attempt is made to create a numerical model based on commercial finite element code ABAQUS to predict the impact response of aluminum plates. A modeling procedure is developed for aluminum plates subjected to low velocity impact and a mesh convergence analysis is performed. The influence of considering strain rate on low velocity impact response of aluminum plates is evaluated by executing a study on isotropic elasto-plasticity (based on plasticity data) and Johnson-Cook models (based on analytical forms of the hardening law and rate dependence). Then, by using the development methodology, the response of three aluminum alloy plates (2024-T3, 6061-T6 and 7075-T6) subjected to low velocity impact is investigated. These materials have common applications in the aerospace industry, where they are subjected to impact loading through their service life.

2 MATERIAL MODELING

General dynamics of low velocity impact event can be described as follows: when the impactor strikes the plate, its kinetic energy is initially transferred to the plate as elastic and plastic strain energy. As the impactor's velocity reaches zero, all its kinetic energy has either been transformed to elastic and plastic strain energy, or dissipated through damage. Elastic strain energy makes impactor and plate move and deform in the opposite direction, which transforms elastic strain energy into kinetic energy. Finally, vibration of plate, dissipates the remaining energy.

Choosing the right material model is essential in order to accurately capture the behavior of structures under low velocity impact. The material model should be able to predict deformation-time history and damage accurately. Aluminum materials are very sensitive to strain rate, therefore strain rate effects on material behavior have to be considered. The Johnson-Cook plasticity model is a wieldy used model that indicates the non-linear behavior of metallic materials. In addition, this model takes into account strain hardening, strain rate hardening, and thermal softening effects, as given in Equation (1). Here, the constitutive relation of Johnson-Cook is chosen to describe the plastic behaviour of the investigated alloy.

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - T^m) \quad (1)$$

In the above equation, $\dot{\varepsilon}/\dot{\varepsilon}_0$ is the plastic strain rate for $\dot{\varepsilon}_0 = 1\,\text{s}^{-1}$, T is homologous temperature, ε is equivalent plastic strain, A, B, C, n, and m are material constants which are obtained experimentally [21].

It is noted that the effects of temperature is neglected in the present work.

In addition to Johnson-Cook plasticity model, the Johnson-Cook damage model can also be used if needed, which is defined as:

$$\varepsilon^f = (D_1 + D_2 e^{D_3 \sigma^*})\left(1 + \frac{D_4 \ln \dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - D_5 T) \quad (2)$$

$$\sigma^* = \frac{\sigma_m}{\bar{\sigma}} \quad (3)$$

In Equations (2) and (3), D_1 to D_5 are engineering constants that are derived experimentally, ε^f is the strain at fracture, σ_m average of three normal stresses, and $\bar{\sigma}$ Von Mises equivalent stress [21]. In the low velocity impact event, due to absence of damage, there is no need to use a damage model. However, if impact velocity comes close to ballistic limit, to achieve accurate results, it is necessary to use damage model.

3. IMPACT MODELLING PROCEDURE AND VERIFICATION

For simulation of the impact event, the commercial FE code of ABAQUS/Explicit is employed, which uses a central difference rule to integrate the equations of motion explicitly through the time [22].

In the present study, modelling procedure of low velocity impact of aluminum alloys plates is validated by comparing the numerical results with the experimental data reported by Mohotti et al. [1]. A square plate with dimensions of 300×300 mm^2 and thickness of 3 and 5 mm is considered for simulation, as shown in Figure 1. The plate is made of AA5083-H116 aluminum alloy belonging to the aluminum 5000 series and alloyed with magnesium as the major component. This material is extensively considered for structural elements because of the possibility of achieving comparatively high ductility and corrosion resistance [1].

The plates are subjected to transverse impact by a cylindrical impactor of 37 mm diameter at its center with initial velocities of 9.02 and 12.31 m/s. Weight of the impactor is 5 kg. The material properties of AA5083-H116 aluminum are listed in Table 1.

3. 1. Meshing, Boundary and Loading Conditions

To decrease the solution time, modeling is carried out by taking advantage of the geometric symmetry of the plate. Hence, only one-quarter of the plate is taken into account in the impact analysis. Consequently, appropriate symmetry boundary conditions are applied.

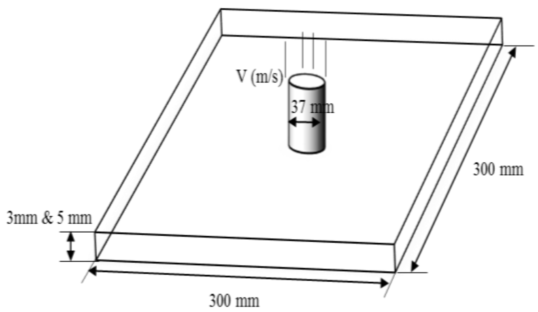


Figure 1. Schematic representation of the target plate and cylindrical impactor

TABLE 1. Material Property of AA5083-H116 Aluminum [1]

Parameter	Value
E (GPa)	70
v	0.33
ρ (kg/m^3)	2660
A (MPa)	215
B (MPa)	280
n	0.404
C	0.0085
Ref. strain rate (s^{-1})	0.001
D_1	0.178
D_2	0.389
D_3	-2.25
D_4	0.147
D_5	16.8

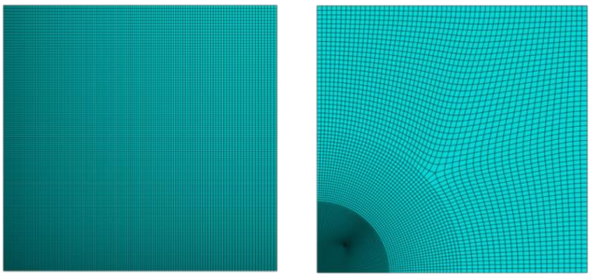
Corresponding to a perfect-clamping assumption, all displacement degrees of freedom are fixed at non-symmetric plate boundaries. The plates are meshed using C3D8R element which is an eight node linear brick element with reduced integration and hourglass control. According to impact simulation, there is excessive distortion in the elements, thus it is important to utilize hourglass control for deformable elements. When these elements experience much extensive??? distortion as a consequence of impact load, zero-energy hourglass modes can be a critical problem for reduced-integration elements.

It is possible to model the impactor either as a rigid, or a deformable body. Here, due to much larger stiffness beside negligible deformation of the impactor, the rigid body model is chosen. Additionally, the impactor is constrained to move only along the normal vector of the plate, and the initial velocity of the impactor is specified.

3. 2. Contact Modeling For contact modeling, there are many contact laws that can be applied in ABAQUS software. The hard contact law is chosen in the simulation process. In this method, the contact constraint is applied when the clearance between two surfaces becomes zero. There is no limit in the contact formulation on the magnitude of contact pressure that can be transmitted between the surfaces [22]. The surfaces separate when the contact pressure between them becomes zero or negative, and the constraint is removed. This behavior is called ‘‘hard” contact [22]. Moreover, the surface-to-surface contact is used to define contact interactions.

3. 3. Mesh Pattern and Sensitivity Analysis Obtaining accurate results requires a fine mesh at the impact zone. Using fine mesh for the plate increases solution time; therefore, an optimum pattern should be chosen to generate the fine mesh at the vicinity of the impact zone. Two types of mesh patterns are used in this modeling, the structured and unstructured mesh patterns, as shown in Figure 2. The comparison between the deflection-time curves of these two types of mesh patterns is presented in Figure 3. The thickness of these plates is 3 and 5 mm, respectively, and the size of their elements is 0.5×0.5 mm^2. In order to maintain an acceptable aspect ratio, plates are divided into 1-mm-deep elements through their thickness. Results show that unstructured mesh pattern (with 26733 and 44250 elements) are almost same as structured mesh pattern (with 67681 and 112500 elements) but with shorter solution time, due to less number of elements.

In order to obtain the optimum number of elements at the contact zone in unstructured mesh pattern, a mesh sensitivity analysis is performed for 3 mm thickness plate under an impact velocity of 9.02 m/s. Accordingly, the variation of the maximum deflection error versus the element size at impact zone in the unstructured mesh pattern is illustrated in Figure 4. The figure shows that variations of maximum deflection error become stable at 0.5×0.5 mm^2 element size. Therefore, this element size is chosen in the present study.



(a) (b)

Figure 2. Two different mesh patterns for one-quarter model a) structured mesh pattern, b) unstructured mesh pattern

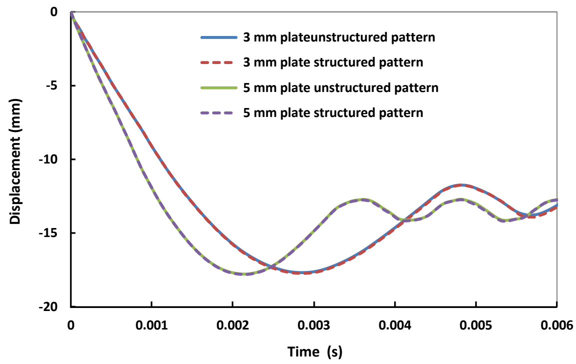


Figure 3. Effect of mesh pattern on deflection history for one-quarter model

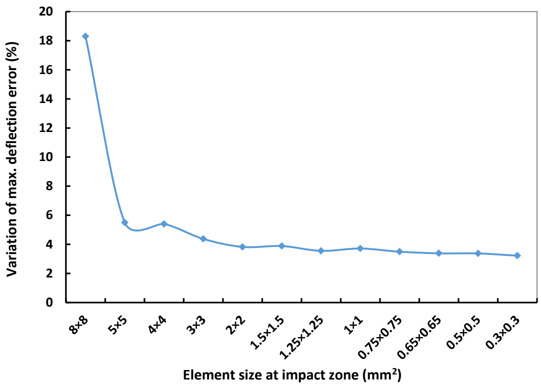


Figure 4. Mesh sensitivity analysis

4. VERIFICATION AND STUDY OF STRAIN RATE EFFECTS ON IMPACT RESPONSE

To ensure that an impact model is reliable, it needs to be validated. Thus, a comparative study between present numerical results and the numerical and experimental results presented by Mohotti et al. [1] is carried out. In order to investigate the effects of strain rate in low velocity impact response, two different material behaviors, including isotropic elasto-plasticity and Johnson-Cook method is used to model the plate. As presented in Table 2, for isotropic elasto-plasticity model, some of the nominal values obtained from the stress-strain curve are utilized [14]. The comparison between the deflection histories for plate thicknesses of 3 mm and 5 mm is performed to investigate the discrepancy of the present simulation results from experimental ones, as shown in Figures 5 and 6.

TABLE 2. AA5083-H116 Aluminum Stress-Strain Curve Nominal Values for Two Different Thicknesses [14]

Thickness (mm)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
3	249	344	13.1
5	261	360	14.0

In these figures, it is shown that the present numerical results in terms of deflection versus time history have a good agreement with experimental data and numerical predictions based on Johnson-Cook material model in literature. Also, there is a fluctuation at unloading section for both plates which is due to the absence of damping in the model and springback of the plate. The predicted numerical values compared with available experimental data are listed in Table 3. For the permanent deflection, the average deflection during oscillations is determined. The results show that for 3 mm thickness plate, maximum discrepancy in maximum deflection for isotropic elasto-plasticity and Johnson-Cook models are 5.41% and 3.37%, respectively. However, the predicted numerical maximum deflection results by Mohotti et al. show more accurate response compared with the experimental results. Nevertheless, for 5 mm plate thickness, compared to other models, the Johnson-Cook model predicts the most accurate maximum deflection which has only about 1% error. Also, the Johnson-Cook model show that the permanent deflection maximum discrepancy is less than 1%. Consequently, it is apparent that the Johnson-Cook model results are more accurate than other numerical results for 3 mm and 5 mm thickness plates. It should be noted that isotropic elasto-plasticity model has a maximum error in all predictions.

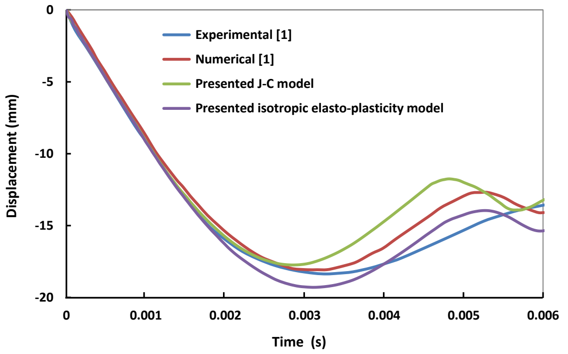


Figure 5. The Comparison of deflection-time history for 3 mm thick plate under impact velocity of 9.02 m/s

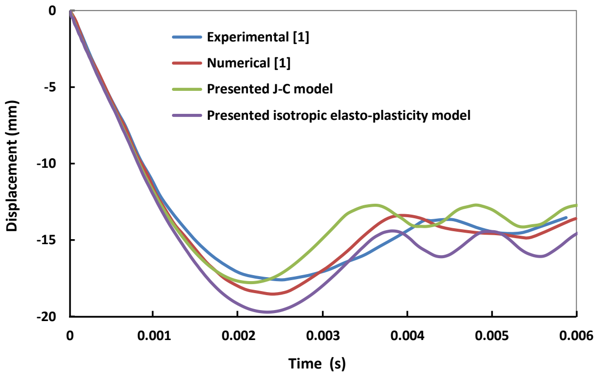


Figure 6. The Comparison of deflection-time history for 5 mm thick plate under impact velocity of 12.31 m/s

TABLE 3. Comparison of Obtained Numerical Results with Available Data [1]

Plate thickness	Model	Max. deflection		Permanent deflection	
		Value (mm)	Error (%)	Value (mm)	Error (%)
3 mm	Experimental [1]	18.3	---	12.8	---
	Numerical [1]	18	1.64	14	9.37
	Presented J-C model	17.683	3.37	12.765	0.27
	Presented elasto-plasticity	19.29	5.41	14.66	14.53
5 mm	Experimental [1]	17.6	---	13.5	---
	Numerical [1]	18.5	5.11	13.6	0.75
	Presented J-C model	17.78	1.02	13.41	0.66
	Presented elasto-plasticity	19.71	11.98	15.24	12.88

Figure 7 shows a comparison between the deflected shape of the plate after impact obtained from numerical simulations and experimental test for the 5 mm plate impacted at 12.31 m/s. As shown, the prediction of deflection shape of the plate for both numerical models (Figures 7b and 7c) are in good agreement with experimental tests. In general, elasto-plasticity model and Johnson-Cook model predicted almost similar deflection shapes.

A comparison of Von-mises stress field at maximum deflection, residual stress after impact and equivalent plastic strain for both of isotropic elasto-plasticity and Johnson-Cook models in 3 mm and 5 mm plates are shown in Figures 8, 9 and 10, respectively.

From all these figures, it can be seen that for thicker plate, despite the greater impact load, maximum stress and strain values decrease; however, stress and strain field increase in both material models.

(a)

(b)

(c)

Figure 7. Deflected shape of the plate after impact; comparison of a) experimental result, b) isotropic elasto-plasticity model prediction (6 ms), c) Johnson-Cook model prediction (6 ms) for the 5 mm thick plate under impact velocity of 12.31 m/s

In addition, as it gets farther from center of the impact zone the stress and strain values have a lower drop rate. It can be noticed that the predicted fields of parameters are almost the same in both models. Since Johnson-Cook model is dependent on strain rate and loading condition, the plate's stiffness is higher, and therefore, stress and strain values predicted by isotropic elasto-plasticity model is slightly more than those predicted by the Johnson-Cook model.

5. LOW VELOCITY IMPACT SIMULATION OF DIFFERENT ALUMINUM ALLOYS

In this section, according to validations of the modeling process in the previous section, the response to low velocity impact of three types of aluminum alloys including aluminum 2024-T3, 7075-T6, and 6061-T6 is examined. Note that these materials have many industrial applications, particularly in the aerospace industry. Material properties of each type are represented in Table 4. Dimensions of the plates are 60×60 mm^2 with thickness of 0.5 mm. The unstructured mesh pattern with element of type C3D8R is chosen for the plates which had a size of 0.5×0.5×0.5 mm^3 at impact zone. Fixed boundary conditions are set for plate edges. The plates are subjected to transverse impact by a rigid spherical 37 mm impactor with initial velocities of 2.01 m/s and 5 kg mass. Simultaneously, the impactor is constrained to move only along the normal vector of the plate.

Here, due to lower accuracy of isotropic elasto-plasticity material model, only Johnson-Cook material model is considered in the numerical modelling.

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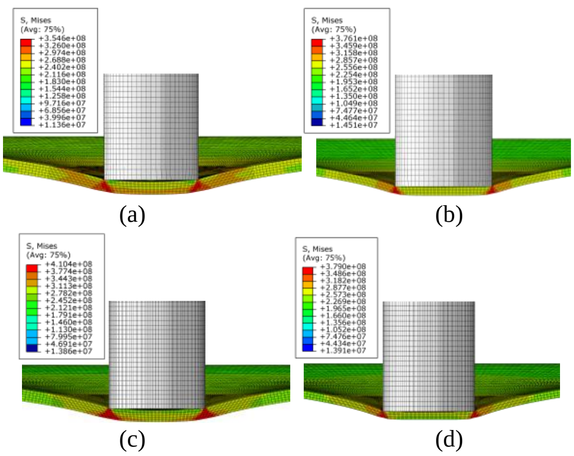

Figure 8. Von-Mises Stress at maximum deflection for a) Johnson-Cook model for 5 mm thick plate impacted at 12.31 m/s, b) Johnson-Cook model for 3 mm thick plate impacted at 9.02 m/s, c) isotropic elasto-plasticity model for 5 mm thick plate impacted at 12.31 m/s, d) isotropic elasto-plasticity model for 3 mm thick plate impacted at 9.02 m/s

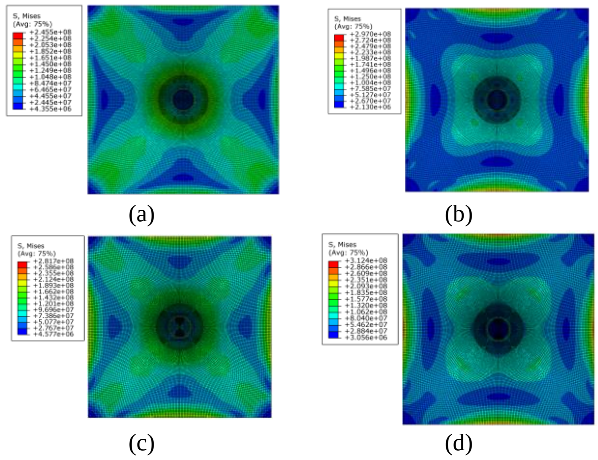

Figure 9. Residual stress after impact (6 ms) a) Johnson-Cook model for 5 mm thick plate impacted at 12.31 m/s, b) Johnson-Cook model for 3 mm thick plate impacted at 9.02 m/s, c) isotropic elasto-plasticity model for 5 mm thick plate impacted at 12.31 m/s, d) isotropic elasto-plasticity model for 3 mm thick plate impacted at 9.02 m/s

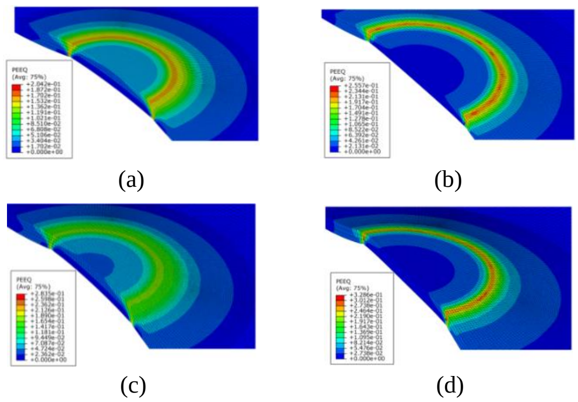

Figure 10. Equivalent plastic strain for a) Johnson-Cook model for 5 mm thick plate impacted at 12.31 m/s, b) Johnson-Cook model for 3 mm thick plate impacted at 9.02 m/s, c) isotropic elasto-plasticity model for 5 mm thick plate impacted at 12.31 m/s, d) isotropic elasto-plasticity model for 3 mm thick plate impacted at 9.02 m/s

TABLE 4. Material Properties for Aluminum Alloys

Parameter	Al 2024-T3 [23, 24]	Al 7075-T6 [25-27]	Al 6061-T6 [28]
E (GPa)	73.8	67.5	70
ν	0.33	0.33	0.33
A (MPa)	368.98	473	270
B (MPa)	683.97	210	154.3
n	0.73	0.3813	0.2215
m	1.7	1	0.1301
$\dot{\varepsilon}_0$ (s^{-1})	1	0.001	597.2
C	0.0083	0.033	0.1301
ρ (kg/m^3)	2700	2805	2700

Impact force-deflection curve results for three aluminum alloys are plotted in Figure 11. As illustrated in this figure, after about 2 mm deflection, 6061-T6 alloy shows loss stiffness, and later, after 4 mm deflection stiffnesses of two other alloys change. Since, 7075-T6 has the highest impact force and the lowest maximum and permanent deflections, it is stiffer than other alloys. Also, 2024-T3 alloy shows more stiffness than 6061-T6. Figure 12 illustrates absorbed energy versus time. It can be noticed that 6061-T6 alloy absorbs more energy than others alloys. The comparison between results is shown in Table 5. As represented in the table, 7075-T6 alloy has the lowest absorbed energy, maximum deflection and maximum absorbed energy to mass ratio.; moreover, it has the highest maximum impact force. Figure 13 shows a comparison of stress distribution at maximum deflection for different aluminum plates. It can be noticed that 2024-T3 aluminum plate has the highest von Mises stress at maximum deflection, while 6061-T6 aluminum plate has the lowest value.

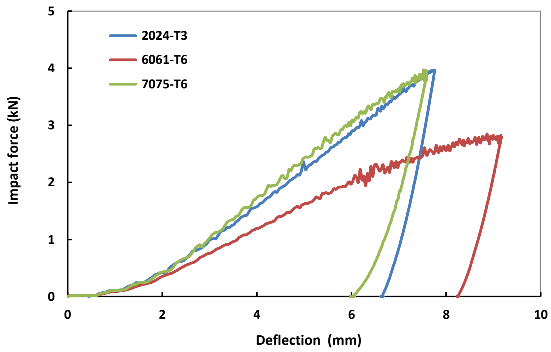

Figure 11. Impact force-deflection curves for three aluminum alloys with 0.5mm thick plate and impact velocity of 2.01 m/s

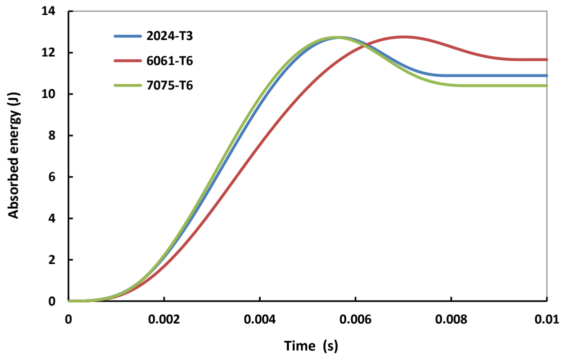

Figure 12. Absorbed energy versus time for three aluminum alloys with 0.5mm thick plate and impact velocity of 2.01 m/s.

TABLE 5. Comparison of predicted Results for Three Aluminum Alloys

Aluminum alloys	2024-T3	6061-T6	7075-T6
Absorbed energy (J)	10.88	11.6646	10.4068
Max. impact force (N)	3970	2448.38	3971.7
Max. deflection (mm)	7.75	9.16	7.585
Mass (kg)	0.001215	0.001215	0.001262
Ratio of absorbed energy to mass (J/kg)	8954.73	9600.49	8246.27

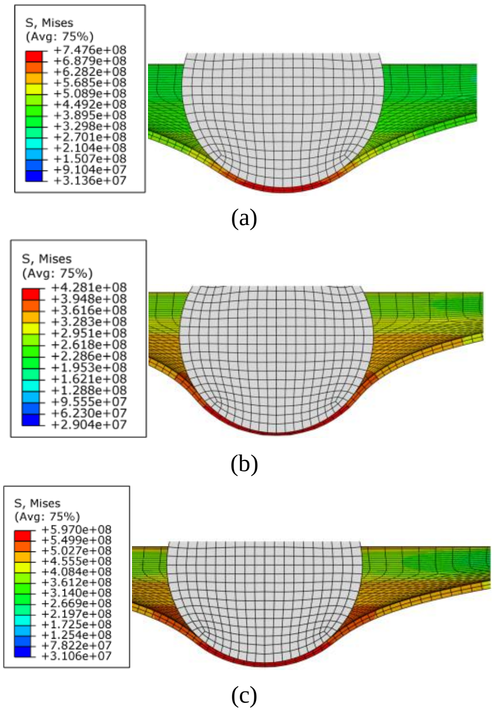

Figure 13. Von-Mises Stress at maximum deflection for 0.5 mm thick aluminum plate impacted at 2.01 m/s a) 2024-T3, b) 6061-T6, c) 7075-T6.

6. CONCLUSION

In this paper, a numerical study on AA5083-H116 aluminum plates under low velocity impact has been carried out. The modeling aspects, such as element type, boundary conditions, solution method, impactor modeling and mesh pattern, are discussed in detail. Then, a mesh sensitivity analysis is done to carry out an appropriate simulation. To validate the modelling process, a comparative study is performed between results obtained from Johnson-Cook and isotropic elasto-plasticity models with experimental data and numerical prediction in literature. The results show that in term of deflection-time history, the two material models have good agreement with experimental results. However, Johnson-Cook model which indicates the non-linear behavior and includes analytical forms of the hardening law and rate dependence givs the most accurate results. Unlike the conclusion made by Grytten et al. [14], it demonstrates that strain rate effects have great influence on the accuracy of predicted deflection-time curve and maximum and permanent deflections. Therefore, low velocity impact cannot be predicted accurately using simple models such as isotropic elasto-plasticity model. Although, spring-back effects is noticed in the numerical deflection time histories, presented numerical predictions of deflection time history are in considerably good agreement with experimental results. Therefore, the numerical modelling approach presented in the paper is accurate and reliable for analyzing the low velocity impact of plates. Finally, using the developed procedure, the low velocity impact response of three different aluminum alloys (2024-T3, 6061-T6 and 7075-T6) are investigated. Comparison of results shows that 7075-T6 and 6061-T6 have the highest and lowest stiffnesses, respectively. Moreover, The aluminum 7075-T6 alloy has the lowest absorbed energy, maximum deflection and absorbed energy to mass ratio, and the highest maximum impact force.

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A Numerical Study on Aluminum Plate Response under Low Velocity Impact

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چکیده

در مقاله حاضر به بررسی عددی پاسخ ورق‌های آلومینیومی با آلیاژهای مختلف تحت شرایط ضربه کم‌سرعت پرداخته شده است. در این راستا، ورق مربعی آلومینیومی AA5083-H116 با ابعاد $۳۰۰\times۳۰۰\ mm^2$ و ضخامت‌های ۳ و ۵ میلی‌متر تحت ضربه کم‌سرعت مدل سازی شده و مطالعه هم‌گرایی شبکه بندی برای رسیدن به تعداد مناسب المان صورت گرفته است. در این تحقیق، اثرات نرخ کرنش در پاسخ ضربه‌ی کم‌سرعت با انجام مطالعه مقایسه‌ای با استفاده از مدل ایزوتروپیک الاستو–پلاست و مدل مواد جانسون–کوک بررسی شده است. پاسخ به رخداد ضربه مدل‌ها شامل تاریخچه تغییر مکان، مقادیر حداکثر تغییر مکان و تغییر مکان دائم استخراج شده و با نتایج عددی و تجربی موجود صحت سنجی شده است. نتایج نشان داد که نرخ کرنش تاثیر قابل توجهی بر روی تاریخچه‌ی تغییر شکل داشته و دقت نتایج پیش بینی شده را افزایش می‌دهد. سپس با استفاده از مدل توسعه یافته، رفتار سه آلیاژ آلومینیوم تحت ضربه کم‌سرعت بر اساس مدل جانسون–کوک مورد بررسی قرار گرفت. نتایج حاصله بیشترین و کمترین میزان سفتی را به ترتیب برای آلیاژهای 7075-T6 و 6061-T6 **نشان داده است.** همچنین کمترین نسبت جذب انرژی به جرم در آلیاژ 7075-T6 مشاهده شده است.

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