An Investigation of AA7075-T651 Plate Perforation Using Different Projectile Nose Shapes

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1 Abstract

In this study, the ballistic resistance of monolithic and double-layered plates made of AA7075-T651 are evaluated using the non-linear finite element code LS-DYNA®. Plate simulations are carried out using 20 mm diameter, 197g mass hardened steel projectiles with blunt and ogival nose shapes. Penetration simulations of 20 mm monolithic plates made of AA7075-T651 are performed with both Lagrange and ALE methods and the results are compared with literature experimental studies. Simulations are performed with both 2D axisymmetric and 3D solid elements and Modified Johnson Cook constitutive equation is utilized. Moreover, Cockcroft-Latham fracture criterion is used for material behavior of metallic plates. In addition to the material model validation studies, different types of hourglass and element formulations are evaluated and the results are compared under the effects of blunt and ogival projectile nose shapes.

Keywords: ballistic simulation, modified johnson-cook, cockcroft-latham, lagrange, ALE, monolithic plates, double-layered plates,

2 Introduction

Ballistic simulations with finite element method is widely used for evaluation of ballistic performance of armour plates. In order to get acceptable results, correct material properties and modelling techniques must be used. In this study the ballistic resistance of monolithic plates are evaluated using the non-linear finite element code LS-DYNA®.. AA7075-T651 material which is frequently used for armour plate is considered. Material properties and ballistic experiment results are taken from the comprehensive study that conducted by Børvik et al [1]. In addition, Modified Johnson Cook constituve equation and Cockcroft-Latham fracture criterian is utilized to simulate material behaviour. Plate simulations are carried out using 20mm diameter, 197g mas hardened steel projectiles with blunt and ogival nose shapes. Ballistic simulations are performed with both Lagrange and ALE methods and the residual velocities are compared with experiment results. The focus of the present work is to comparison of modelling techniques and parameters such as mesh size, element type and hourglass and their effects on projectile residual velocity. Moreover, optimization study for material parameters is performed in order to validate simulations with test results. Finally, double-layered plates are investigated against ogival and blunt projectiles and the residual velocities are compared with monolithic plates.

3 Ballistic Experiment

Ballistic tests which were carried by Børvik et al [1] using hardened steel projectiles (20 mm diameter, 197g mass,52 HRC) with blunt and ogival nose shapes. 20 mm thick AA7075-T651 plates were tested. Dimension of plates were 600 x 600 mm² and plates were clamped in 500 mm diameter circular frame. There were twelve impact tests were conducted with different initial velocities that varied between 180m/s and 350 m/s and two of them are considered which are shown in Table 1. Figure 1 illustrates the projectile dimensions and experiment capture.

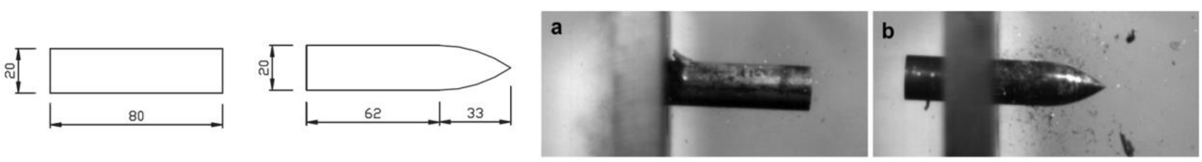

Fig.1: Blunt and Ogival Projectile Dimensions and Experiment Capture [1]

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Experiment No	Projectile Type	Impact Velocity (m/s)	Residual Velocity (m/s)
1	Blunt	320	250
2	Ogival	337	260

Table 1: Experiment results for blunt and ogival projectiles [1]

4 Material Properties

`*MAT_MODIFIED_JOHNSON_COOK (MJC)` material model and Cockcroft-Latham fracture criterion is used for material behaviour of aluminium target plate. Material characterization of AA7075-T651 were conducted by Børvik et al [1]. They carried out quasi-static tensile tests which were oriented 0°,45° and 90° with respect to the rolling direction of the plates and they presented MJC parameters that shown in Table 2.

Projectile is modelled as an elastic-plastic von Mises material with bilinear isotropic hardening without fracture using **`*MAT_PLASTIC_KINEMATIC`** in LS-DYNA®. Material constants for the projectile are given in Table 3 which are taken from [2].

Parameter	Set1 (0° direction)	Set 2 (45° direction)	Set 3 (90° direction)
E (Young's Modulus) [GPa]	70	70	70
v (Poisson's ratio)	0.3	0.3	0.3
ρ (Density) (kg/m³)	2700	2700	2700
A (Yield strength) [MPa]	**520**	**426**	**478**
B (Strain hardening parameter) [MPa]	**477**	**339**	**414**
n (Strain hardening parameter)	**0.52**	**0.31**	**0.38**
ε (Strain rate) [1/s]	5e-4	5e-4	5e-4
C (Strain rate sensitivity parameter)	0.001	0.001	0.001
Tr (Room Temperature) [K]	293	293	293
Tm (Melt Temperature) [K]	893	893	893
Tc (Critical Temperature Parameter) [K]	800	800	800
m (Thermal softening parameter)	1	1	1
Cp (Specific heat capacity) [J/kg/K]	910	910	910
X (Taylor-Quinney coefficient)	0.9	0.9	0.9
α (Thermal expansion coefficient) [1/K]	2.3e-5	2.3e-5	2.3e-5
Wcr (Cockcroft-Latham parameter) [MPa]	**106**	**292**	**164**

Table 2: AA7075-T651 Material Properties [1]

Parameter	Value
E (Young's Modulus) [GPa]	204
v (Poisson's ratio)	0.33
ρ (Density) (kg/m³)	7850
A (Yield strength) [MPa]	1900
Et (Tangent Modulus) [MPa]	15000

Table 3: Projectile Material Properties [2]

5 Modelling with Lagrange

Finite element models for blunt and ogival projectiles and 20 mm thick target plates (circular with 500 mm diameter) are modelled with both 2D axisymmetric and 3D solid elements. Target plates are fully constrained around the outer diameter. The LS-DYNA® SMP 7.1.2 solver is used for all simulations. 320 m/s initial velocity for blunt projectile and 337 m/s for ogival projectile is considered using initial velocity definition in LS-DYNA®.

Interaction between projectile and target is modeled using **`*2D_AUTOMATIC_SINGLE_SURFACE`** for axisymmetric models and **`*ERODING_SINGLE_SURFACE`** contact definition for solid models without

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friction. Moreover, area weighted element formulation (ELFORM14) is used for axisymmetric models and ELFORM1, 2,-1 and -2 are utilized for comparative study of solid models. Material properties for target aluminum plate and projectile is shown in Table 2 and 3. MJC parameters "SET1" is used for all comparative studies.

In the first part, mesh sensitivity study is performed and residual velocities are presented. Different mesh configurations are considered both for projectile and target plate. In the next step, different types of hourglass and element formulations are discussed for 3D solid elements. In addition to blunt projectile simulations, the mesh sensitivity study is performed also for the simulations with ogival projectile. According to simulations, significant difference is observed between test and simulation results for the ogival projectile. Therefore, material optimization study is carried out to find optimum material parameters using Ls-Opt. After the all sensitivity and optimization studies, double-layered plates are investigated for blunt and ogival projectiles and residual velocities are compared with monolithic plates.

5.1.1 Mesh Sensitivity

Mesh sensitivity studies are carried out using different mesh configurations that compared in Table 4 and 5. Firstly, mesh size (h) of projectile is kept constant and different mesh sizes are utilized for aluminum plate that varied between 2 mm and 0.125 mm. For the axisymmetric models the mesh consisted of 4-node elements with one integration point (ELFORM14) and for the solid models 8-noded constant-stress solid elements with one integration point (ELFORM 1) were applied. Stiffness based hourglass control were used for all calculations. Examples of solid and axisymmetric element models are illustrated in Figure 2.

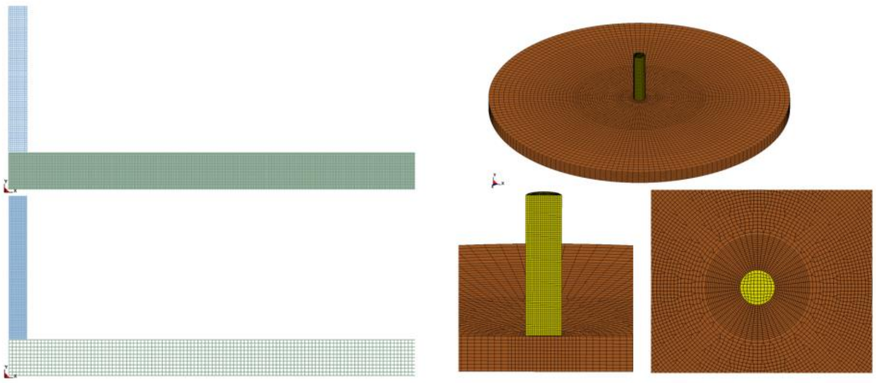

Fig.2: Blunt projectile solid and axisymmetric mesh

Model (Blunt Projectile)	Initial Velocity [m/s]	Projectile Element Size (h) [mm]	Plate Element Size (h) [mm]	Element Type	Residual Velocity [m/s]
B_AX_PL_2mm	320	0.5	2	Axisym.	200
B_AX_PL_1mm	320	0.5	1	Axisym.	228
B_AX_PL_0.5mm	320	0.5	0.5	Axisym.	235
B_AX_PL_0.25mm	320	0.5	0.25	Axisym.	241
B_AX_PL_0.125mm	320	0.5	0.125	Axisym.	240
B_SLD_PL_2mm	320	1	2	Solid	216
B_SLD_PL_1mm	320	1	1	Solid	227
B_SLD_PL_0.5mm	320	1	0.5	Solid	242
EXPERIMENT	320				**250**

Table 4: Target plate mesh sensitivity results

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Model (Blunt Projectile)	Initial Velocity [m/s]	Projectile Element Size (h) [mm]	Plate Element Size (h) [mm]	Element Type	Residual Velocity [m/s]
B_AX_PR_1mm	320	1	0.5	Axisym.	237
B_AX_PR_0.5mm	320	0.5	0.5	Axisym.	235
B_AX_PR_0.25mm	320	0.25	0.5	Axisym.	236
B_SLD_PR_2mm	320	2	1	Solid	228
B_SLD_PR_1mm	320	1	1	Solid	227
B_SLD_PR_0.5mm	320	0.5	1	Solid	228
EXPERIMENT	320				**250**

Table 5: Blunt projectile mesh sensitivity results

Totally 14 runs were performed to investigate residual velocity variations for different mesh configurations. All the residual velocity results are shown in Table 4 and 5. According to the results, it is observed that, mesh size (h) of plate has a significant effect on residual velocity. Especially for 2 mm and 1 mm mesh size of plates, there are significant differences for residual velocities between test and simulation results. Furthermore 0.5, 0.25 and 0.125 mm mesh configurations of plates have more compatible and closer results with experiment. On the other hand, mesh size variation of the projectile does not have significant effect on the residual velocities.

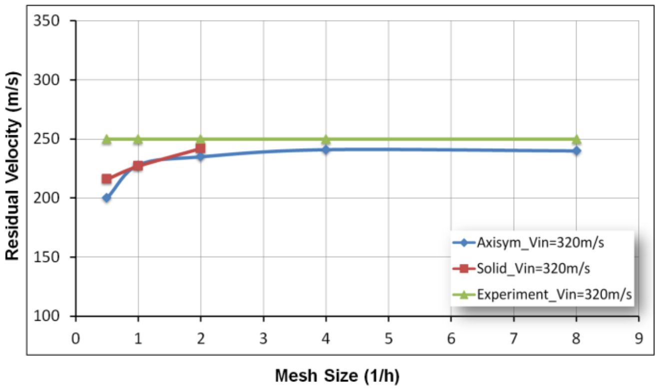

Fig.3: Blunt Projectile Mesh Sensitivity Plots (h=mesh size)

As illustrated in Figure 3, residual velocities are in the asymptotic regime and become closer to the experiment results with the 0.5 mm mesh size. Figure 4 and Figure 5 shows the deformed (T=0.07 ms) mesh configurations.

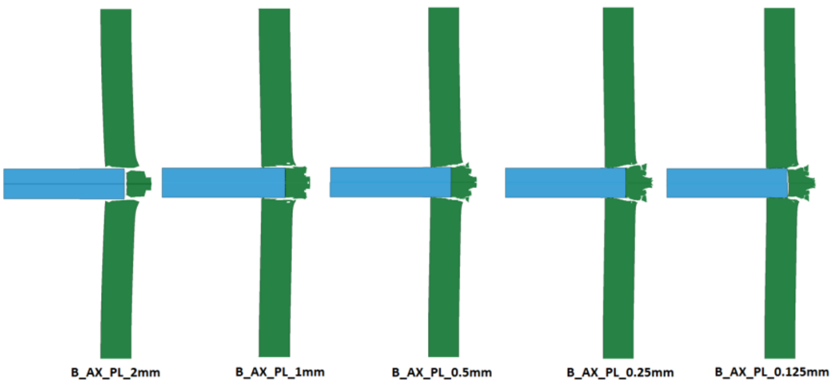

Fig.4: Blunt projectile deformed mesh configurations (T=0.07ms)

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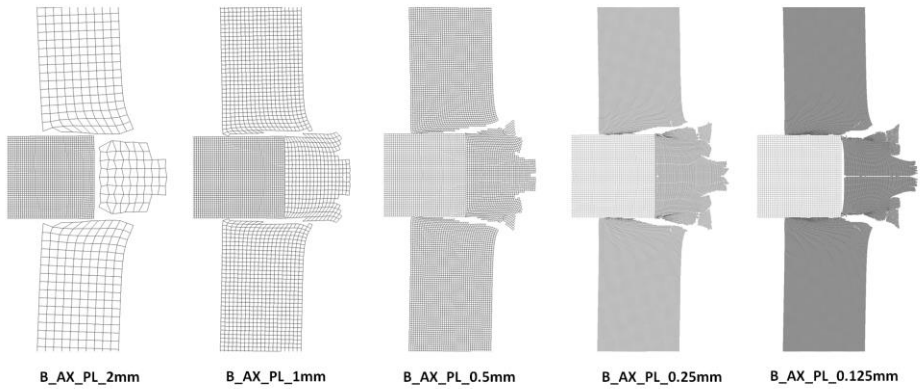

Fig.5: Blunt projectile deformed mesh configurations (T=0.07ms)

5.1.2 Hourglass

As mentioned before, 8-node constant stress solid elements (ELFORM 1) are used for the initial mesh sensitivity studies. ELFORM 1 has one integration point and it needs to control the zero energy modes called "Hourglassing". Hourglass comparison study is carried out for viscous and stiffness based hourglass types and solid elements (with ELFORM 1 formulation). 1mm mesh size is used for both projectile and target plate. Firstly, hourglass coefficient (QH) is kept constant and different types of hourglass controls are utilized. Secondly, stiffness form hourglass type 4 is used and various hourglass coefficients are considered.

Residual velocity results for different hourglass types are presented in Table 6. As mentioned in LS-DYNA® User's Manual [4] viscous hourglass control is recommended for problems with high velocities, stiffness control is often preferable for lower velocities. As shown in Table 6 there isn't significant difference obtained in residual velocities but the residual velocities of stiffness form (IHQ4 and 5) control are more compatible with experiment results.

Model (Blunt Projectile)	IHQ	QH	Residual Velocity [m/s]
IHQ_2	2	0.05	219
IHQ_3	3	0.05	217
IHQ_4	4	0.05	227
IHQ_5	5	0.05	227
EXPERIMENT			**250**

Table 6: Blunt Projectile Hourglass Type Comparison

Model (Blunt Projectile)	IHQ	QH	Residual Velocity [m/s]
IHQ_4-QH_0.01	4	0.01	220
IHQ_4-QH_0.05	4	0.05	227
IHQ_4-QH_0.09	4	0.09	229
IHQ_4-QH_0.15	4	0.15	231
EXPERIMENT			**250**

Table 7: Blunt Projectile Hourglass Coefficient Comparison

Table 7 compares the different hourglass coefficient results with the constant stiffness hourglass control (IHQ 4). It is shown that even the residual velocities have similar magnitudes with each other, during the increase of the hourglass coefficient, residual velocity is increased.

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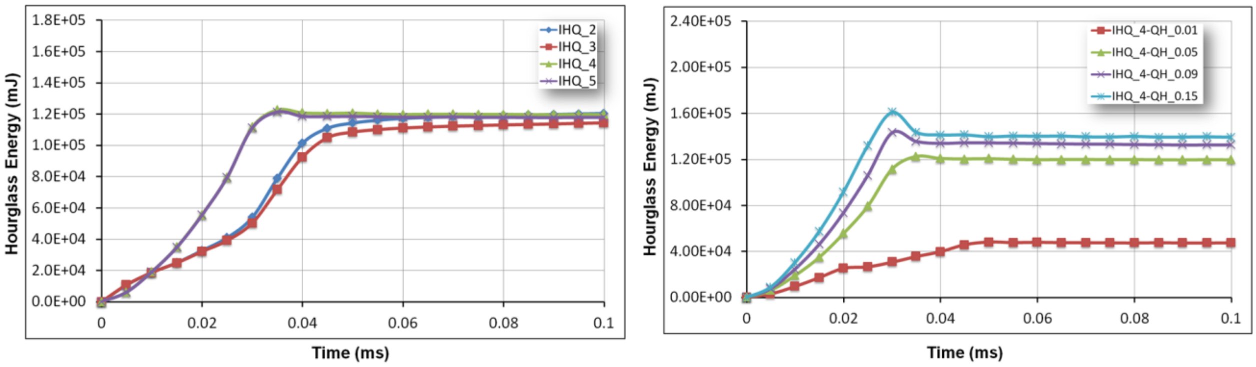

Fig.6: Blunt Projectile Hourglass Energy Comparison

Figure 6 shows hourglass energy plots with the effect of hourglass types and hourglass coefficients. The maximum hourglass energy levels are very closer for the viscous and stiffness form hourglass types. Regarding to the results depend on the hourglass coefficient, minimum hourglass energy is observed with the minimum hourglass coefficient. Moreover all hourglass energy levels are dramatically lower with the comparison of total energy.

5.1.3 Element Type

For the comparative study of element types, four element formulations are considered. Table 8 presents the element types, mesh size and residual velocities of comparison. The deformed (T=0.07ms) mesh configurations for the solid element formulations are illustrated in Figure 7.

Model (Blunt Projectile)	Element Type	Projectile Element Size (h) [mm]	Plate Element Size (h) [mm]	Residual Velocity [m/s]
ELFORM_1_2mm	ELFORM 1	1	2	216
ELFORM_1_1mm	ELFORM 1	1	1	227
ELFORM_1_0.5mm	ELFORM 1	1	0.5	242
ELFORM_2_2mm	ELFORM 2	1	2	204
ELFORM_2_1mm	ELFORM 2	1	1	227
ELFORM_2_0.5mm	ELFORM 2	1	0.5	242
ELFORM_-1_2mm	ELFORM -1	1	2	205
ELFORM_-1_1mm	ELFORM -1	1	1	228
ELFORM_-1_0.5mm	ELFORM -1	1	0.5	241
ELFORM_-2_2mm	ELFORM -2	1	2	206
ELFORM_-2_1mm	ELFORM -2	1	1	230
ELFORM_-2_0.5mm	ELFORM -2	1	0.5	243
EXPERIMENT				**250**

Table 8: Blunt Projectile Solid Element Type Comparison

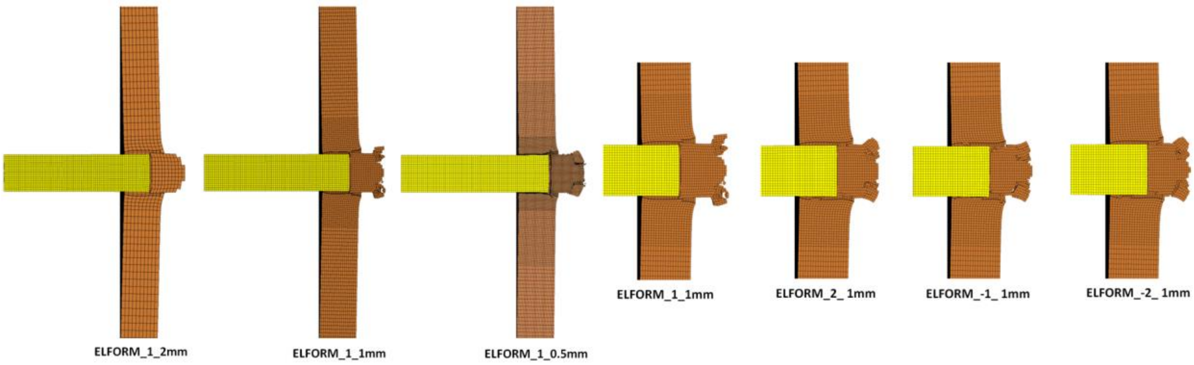

Fig.7: Blunt Projectile Solid Elements Deformed Mesh Configurations (T=0.07ms)

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Regarding to the residual velocity plots that shown in Figure 8, all the element formulations have similar results and velocities are in asymptotic regime. Main conclusion of the comparison is ELFORM 2,-1 and -2 don't need hourglass stabilization and there is no hourglass energy obtained. On the other hand ELFORM 1 formulations have slightly small hourglass energy that shown in Figure 6 but the cpu time is dramatically lower than the other element formulations.

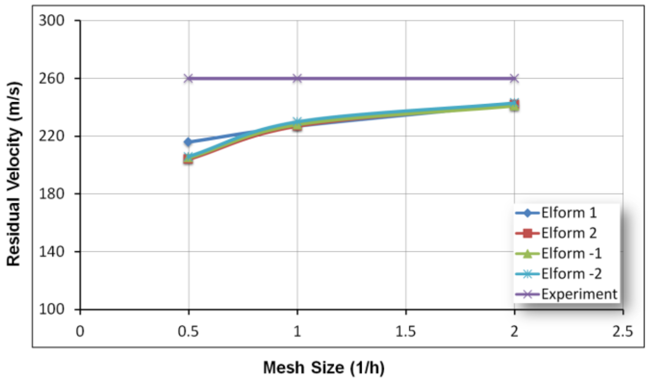

Fig.8: Residual velocity comparison for solid element formulations (h=mesh size)

5.2 Ogival Projectile

5.2.1 Mesh Sensitivity

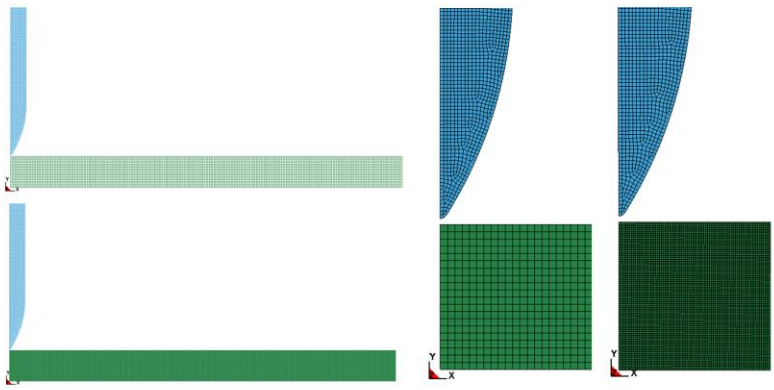

Fig.9: Ogival Projectile Mesh

Mesh sensitivity studies for ogival projectile are carried out for axisymmetric models with 4-noded elements that have one integration point (ELFORM 14) and stiffness based hourglass control is used for all calculations. Residual velocity results and mesh configurations are compared in Table 9.

Model (Ogival Projectile)	**Initial Velocity [m/s]**	**Projectile Element Size (h) [mm]**	**Plate Element Size (h) [mm]**	**Element Type**	**Residual Velocity [m/s]**
OG_AX_PL_1mm	337	0.5	1	Axisym.	189
OG_AX_PL_0.5mm	337	0.5	0.5	Axisym.	193
OG_AX_PL_0.25mm	337	0.5	0.25	Axisym.	195
EXPERIMENT	337				**260**

Table 9: Ogival projectile mesh sensitivity results

According to the residual velocity results, there are significant differences between simulation and experiment results are observed. For the initial velocity of 337 m/s, residual velocity of projectile is calculated nearly 200 m/s.

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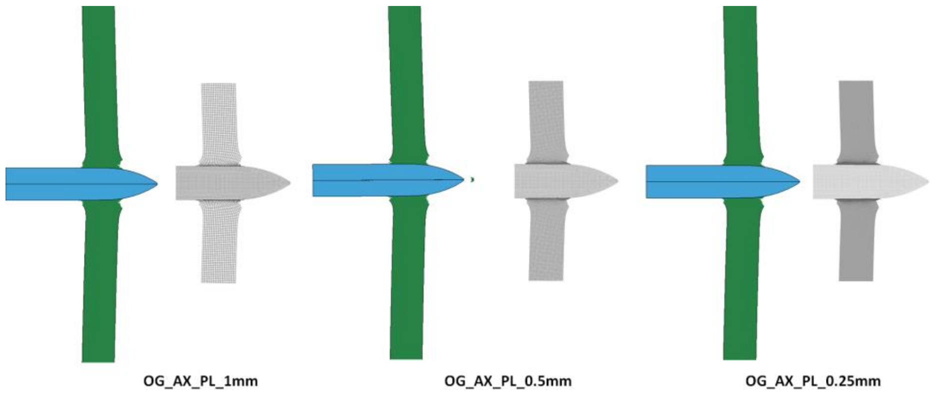

Fig.10: Ogival projectile deformed mesh configurations (T=0.07ms)

5.3 Material Parameter Optimization

As mentioned in Section 3, material characterization of AA7075-T651 were conducted by Børvik et al [1]. They carried out quasi-static tensile tests which were oriented 0°, 45° and 90° due to the rolling direction of the plate and they presented different material parameters depending on the rolling directions [1]. As shown in Table 2, A, B, n and Wcr material parameters show relatively large variations. Regarding to the simulation results, although residual velocities of blunt projectile has quite compatible with experiment result, blunt projectile velocities are significantly different with test result. Due to the fact that material parameters have major effect on the simulation results the optimization study is performed to obtain optimum MJC parameters for compatible residual velocities.

5.3.1 Parameter optimization -1 for Blunt and Ogival Projectile

Depend on the material properties that shown in Table 2, optimization variables are considered below (Table 10). Finite element simulations of blunt and ogival projectiles are used simultaneously in the optimization study. The objective is to find optimum material parameters with the residual velocity constraints that shown in Table 11.

Parameter	Initial	Minimum	Maximum
A (Yield strength) [MPa]	520	426	520
B (Strain hardening parameter) [MPa]	477	339	477
n (Strain hardening parameter)	0.52	0.31	0.52
Wcr (Cockcroft-Latham parameter) [MPa]	106	106	292

Table 10: Material optimization-1 parameters

Response	Minimum	Maximum
Ogival Projectile Residual Velocity	240 m/s	260 m/s
Blunt Projectile Residual Velocity	250 m/s	270 m/s

Table 11: Residual velocity constraints

For the simulations of blunt and ogival projectiles 2D axisymmetric elements (ELFORM 14) are used with the 0.5 mm mesh size both for projectile and the target plates. There are four material variables and “”space filling” design of experiment method is selected with the “radial basis function” metamodel type. Totally 46 calculations were performed both for blunt and ogival projectile.

5.3.2 Optimization-1 Results

Figure 11 and Figure 12 illustrate the influence of the material variables on the projectile velocity for blunt and ogival projectiles. As shown in figures for the blunt projectile, Cockcroft-Latham parameter (Wcr) has the biggest effect on residual velocity. However for the ogival projectile it is observed that the yield strength (A) has the biggest influence. On the other hand strain hardening parameter (n) does not have significant influence on the results.

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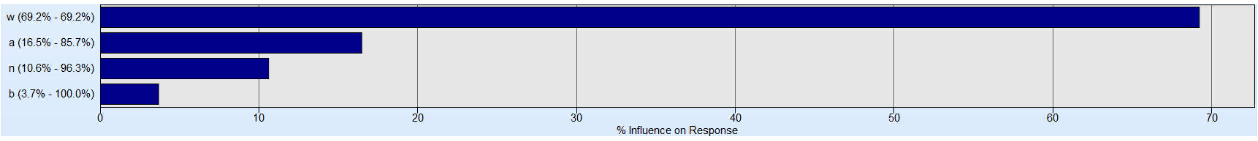

Fig.11: Blunt projectile optimization-1 sensitivity results

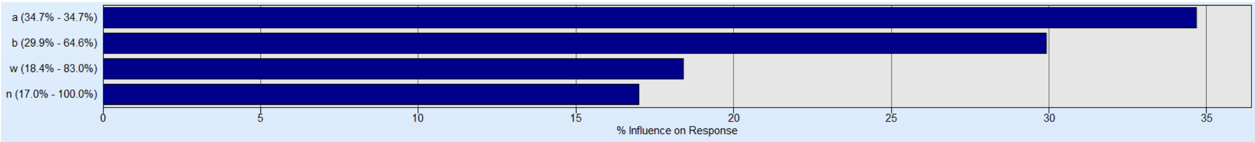

Fig.12: Ogival projectile optimization-1 sensitivity results

Table 12 shows the optimum material parameters for the variables and the final residual velocities after optimization. As mentioned before, although Cockcroft-Latham parameter (Wcr) has the biggest effect on residual velocity for blunt projectile, it has less influence on the ogival projectile results. Nevertheless, yield strength parameter (A) and strain hardening parameter (B) have relatively great influence on the residual velocities. As a result of the optimization study, it is observed that only A and B parameters are changed and settled to minimum values as shown in Table 12. According to the optimization results, residual velocities of blunt and ogival projectiles are increased and especially blunt projectile velocity is observed somewhat compatible with test results, Moreover, ogival projectile velocity is became closer to expected magnitudes but there is still a difference between test and simulation results.

Optimization	**Projectile**	**$V_{initial}$ [m/s]**	**A [MPa]**	**B [MPa]**	**n**	**Wcr [MPa]**	**$V_{residual}$ [m/s]**	**Experiment $V_{residual}$ [m/s]**
Before Optimization	Blunt	320	520	477	0.52	106	235	250
	Ogival	337					193	260
Optimization-1 Results	Blunt	320	426	339	0.52	106	243	250
	Ogival	337					221	260

Table 12: Material optimization-1 results

*5.3.3 Parameter optimization-2 using *MAT_ADD_EROSION for Blunt and Ogival Projectile*

According to the first optimization results, ogival projectile residual velocity is still not compatible with experiment results. Due to the difference of the velocity magnitudes between experiment and simulation results an additional optimization study is performed. As mentioned before, material parameters have the major influence on the failure behaviour and it is observed that the variance of the parameters that shown in Table 2 is not enough to simulate entire material behaviour for the considered impact velocity. For the next material parameter optimization, ***MAT_ADD_EROSION** keyword with a maximum shear strain criterion (EPSSH) is decided to use. As mentioned by Schwer [6], The ***MAT_ADD_EROSION** option provides a way of including failure in constitutive modes although the option can also be applied to constitutive models with other failure/erosion criterion [4]. In this study, initially EPSSH=1.0 or a shear strain of 100% is applied. Table 13 presents the variations of the parameters.

Parameter	**Initial**	**Minimum**	**Maximum**
A (Yield strength) [MPa]	520	426	520
B (Strain hardening parameter) [MPa]	477	339	477
n (Strain hardening parameter)	0.52	0.31	0.52
Wcr (Cockcroft-Latham parameter) [MPa]	106	106	292
EPSSH (Shear strain at failure)	1	0.5	1.5

Table 13: Material optimization-2 parameters with EPSSH

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5.3.4 Optimization-2 Results

According to the results of the second optimization study, it is concluded that Cockcroft-Latham parameter (Wcr) has the biggest effect for the blunt projectile as indicated at first optimization study and the EPSSH parameter has the minimum influence on the residual velocity (Figure 13). In contrast to blunt projectile results, the biggest influence is found out from EPSSH parameter (Figure 14).

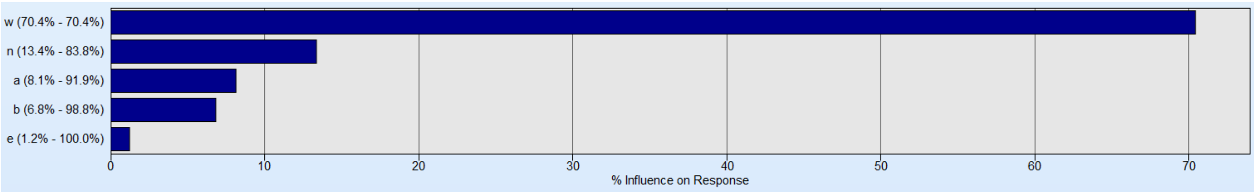

Fig.13: Blunt projectile optimization-2 sensitivity results

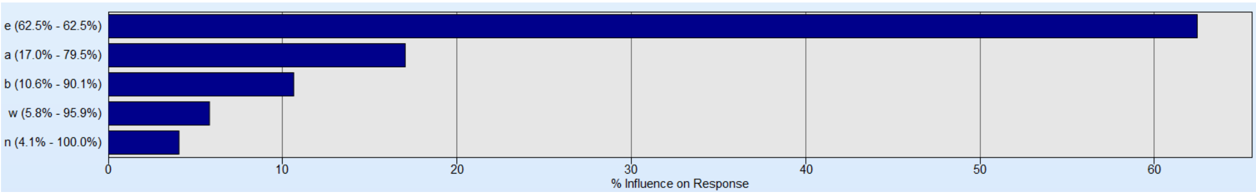

Fig.14: Ogival projectile optimization-2 sensitivity results

Table 14 shows the optimum parameters of the target plate and the final residual velocities. Implementing the additional EPSSH parameter, velocity results both for ogival and blunt projectile are observed quite acceptable with expected results.

Optimization	Projectile	$V_{initial}$ [m/s]	A [MPa]	B [MPa]	n	Wcr [MPa]	EPSSH	$V_{residual}$ [m/s]	$V_{residual}$ [m/s] Experiment
Before Optimization	Blunt	320	520	477	0.52	106	------	235	250
	Ogival	337						193	260
Optimization-2 Results	Blunt	320	454	349	0.49	107	0.52	241	250
	Ogival	337						253	260

Table 14: Material Optimization-2 Results

5.4 Double Plate Results

Ballistic resistance of double layered plates is investigated with the total thickness of 20 mm of AA7075-T651 (10mm x2) for the blunt and ogival projectiles. Nevertheless, residual velocities of double layered plates are compared with the results of the monolithic plates. For the simulations of blunt and ogival projectiles 2D axisymmetric elements (ELFORM 14) are used with the 0.5 mm mesh size for projectile and 0.25 mm mesh size for aluminum plates that illustrated in Figure 15 All the simulations are carried out with the original material properties for the aluminum target plate that shown in Table 2.

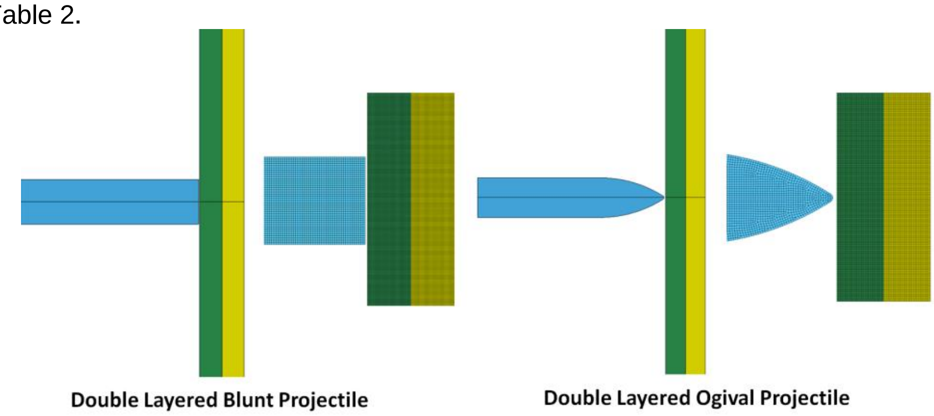

Fig.15: Double-layered models for blunt and ogival projectile

Model	Projectile Type	Plate Type	Initial Velocity [m/s]	Residual Velocity [m/s]
BL_DB_V1	Blunt	Double	320	214
BL_MN_V1	Blunt	Mono	320	241
BL_Experiment_V1	Blunt	Mono	320	250
OG_DB_V1	Ogival	Double	337	237
OG_MN_V1	Ogival	Mono	337	195
OG_Experiment_V1	Ogival	Mono	337	260

Table 15: Double-layered results for blunt and ogival projectile

As shown in Table 15, residual velocity of the blunt projectile with the double layered configuration is lower than the monolithic plate configuration because of the deformation modes. During the impact of the blunt projectile to the thick monolithic plate failure is caused by the plugging due to the strong shear localisation. In case of the impact on double layered plates, global bending and shear localisation occurred simultaneously and double layered plates can absorb the impact energy more successfully. This situation is also mentioned by Dey et al [5]. In contrast to blunt projectile, residual velocity at double-layered plates are higher than the monolithic plates due to the hole enlargement deformation mode for the impacts of ogival projectile. The reason that in case of the ogival projectile impact on the double layered plates, tensile and shear stresses cannot be transferred between the plates and the ballistic resistance is weakened [5]. Figure 16 illustrates the deformed shape of the double layered plates (T=0.07ms)

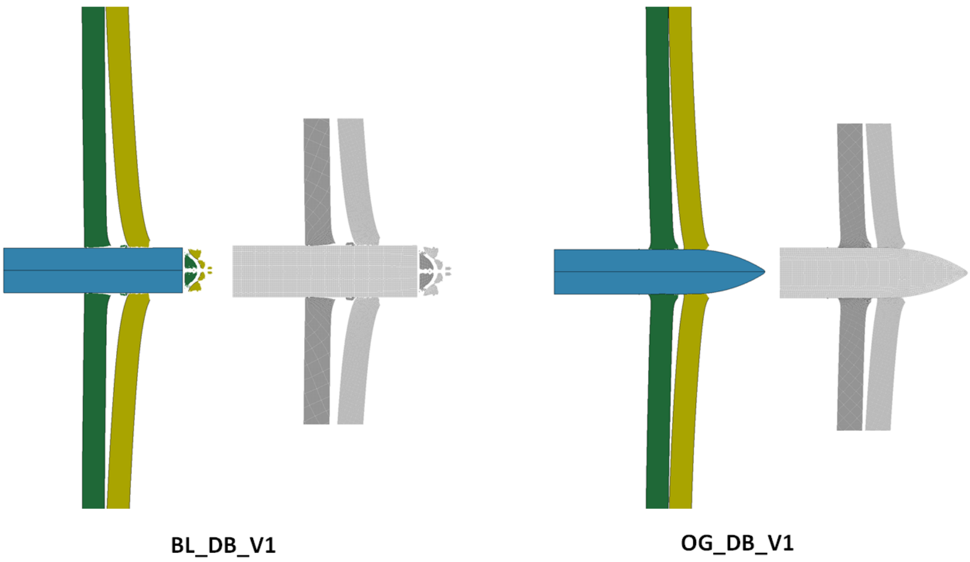

Fig.16: Double-layered deformed shape for blunt and ogival projectile (T=0.07ms)

6 ALE Method Assessment

After several trials with the Lagrange models, an assessment is also made with the ALE method. For ALE method, in addition to the projectile and the target plate mesh, an extra background mesh and material is also required. The background is modelled with **`*MAT_VACUUM`** having the density of air. The rest of the materials are the same as in the Lagrange model. For the solution, Intel® MPI version of LS-DYNA® R7.1.2 is used. A comparison is also made between the results of SMP and MPP versions. Only 2D axisymmetric model is used in the ALE method simulations. Moreover, all the simulations are performed with the original material data only. The prepared models are shown below for the blunt and ogival projectiles.

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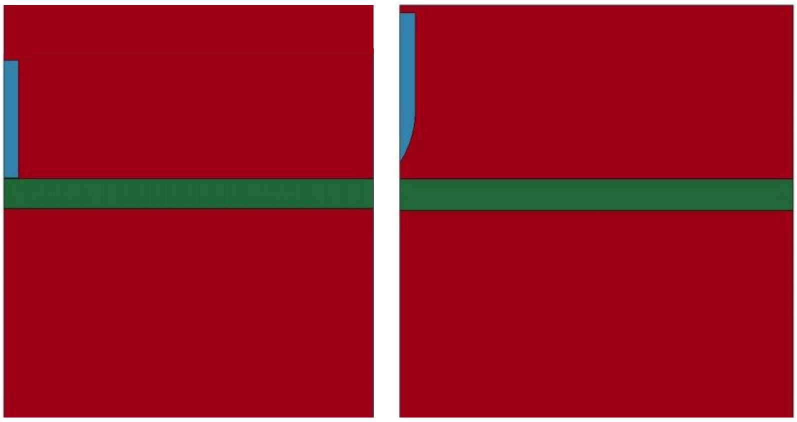
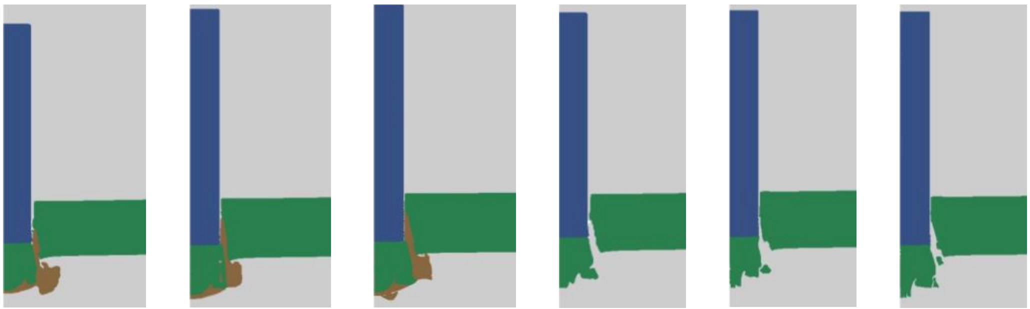


Fig.17: 2D Axisymmetric models (a) blunt projectile (b) ogival projectile

Three different mesh size models are prepared for both blunt and ogival projectile. The exit velocities and velocity histories of the projectiles are compared with each other. The velocities are extracted with ***DATABASE_TRACER** keyword from the projectile multi-material group. Also the results are compared with the y rigid body velocity values taken from the ***DATABASE_MATSUM** keyword.

6.1 Blunt Projectile

The deformation results for 3 different mesh sizes are shown in the figure below. The results are obtained with both SMP and MPP version of LS-DYNA®.



(a) (b) (c) (d) (e) (f)

Fig.18: Target plate deformations @0.07ms (a) 0.5mm (b) 0.25mm (c) 0.125mm (SMP solution) (d) 0.5mm (e) 0.25mm (f) 0.125mm (MPP Solution)

The failed elements are modelled with ***ALE_FAIL_SWITCH_MMG** keyword [4], which created problem in the MPP version of LS-DYNA®. Therefore, in the MPP solution, this keyword is removed.

As it can be seen from figure above, the target plate deformations are not obtained exactly the same with SMP and MPP versions of LS-DYNA®. Along with the target plate deformations, the projectile velocity histories are also compared. The results are shown below.

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Fig.19: Velocity histories for blunt projectile (SMP vs. MPP).

As it can be seen above, at first glance, the exit velocity of the projectile is found different at each mesh size, output type and solver. Therefore, a velocity band can be drawn for upper and lower limits. By looking at the histories between 0.15 and 0.2 milliseconds, a detailed analysis can be made. It is observed that as the mesh size decreases, the exit velocity difference between SMP and MPP solver increases. Moreover, as the mesh size decreases, the exit velocity becomes higher. One other observation is that the results taken from the matsum file (rigid body velocity) behave like moving average filter applied tracer point results.

An additional comparison is performed for different advection methods defined in **`*CONTROL_ALE`** keyword with the parameter METH. Two different methods, 2 and 3, are investigated. Only MPP version is used for this comparison. The velocity histories are shown below.

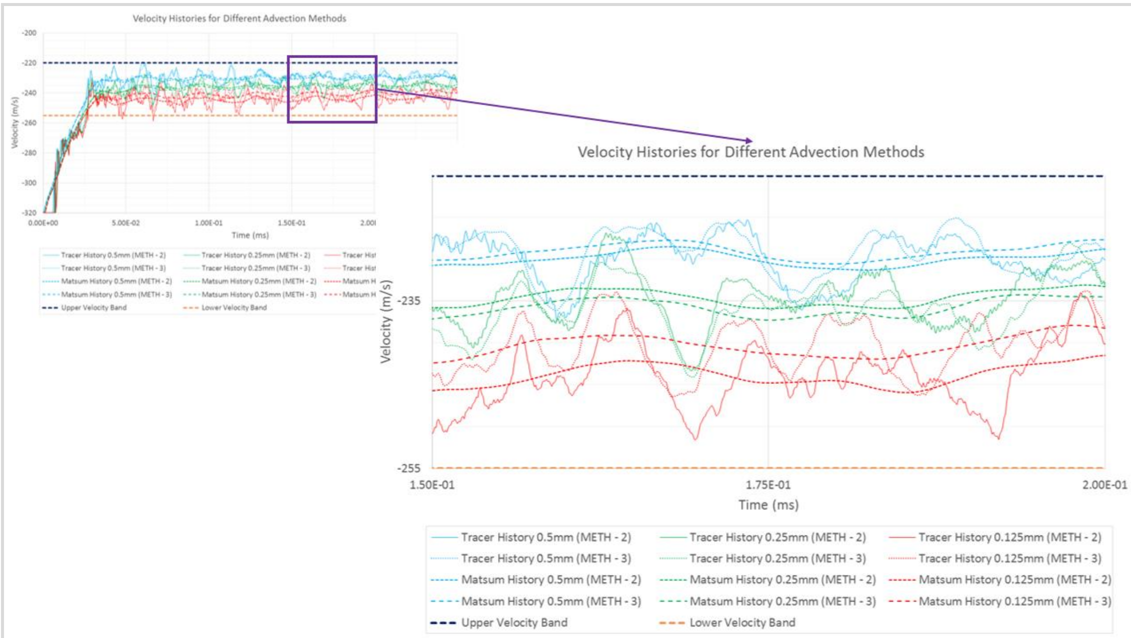

Fig.20: Velocity histories for blunt projectile (different advection methods).

It is observed that as the mesh size decreases, the gap between the advection methods increases, but not in significant amount. The exit velocity summary for the blunt projectile is given in table below. Only average values are used.

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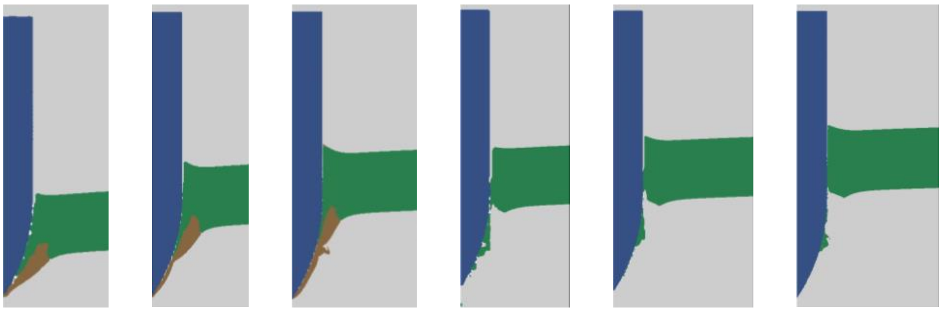
Mesh Size	SMP (METH – 2)	MPP (METH – 2)	MPP (METH – 3)
0.5mm	229	230	230
0.25mm	232	235	237
0.125mm	236	244	241
Experiment	**250**	**250**	**250**

Table 16: Summary of exit velocity for blunt projectile.

6.2 Ogival Projectile

As in the blunt projectile simulations, the deformation results for 3 different mesh sizes are shown in the figure below. The results are obtained with both SMP and MPP version of LS-DYNA®.



(a) (b) (c) (d) (e) (f)

Fig.21: Target plate deformations @0.3ms (a) 0.5mm (b) 0.25mm (c) 0.125mm (SMP solution) (d) 0.5mm (e) 0.25mm (f) 0.125mm (MPP Solution).

As it can be seen from the figure above, the projectile is found to be not perforating the target plate with the SMP version in contrast with the test results. The deformation obtained with MPP version is completely different than SMP version. As in blunt projectile simulations, **`*ALE_FAIL_SWITCH_MMG`** keyword is removed due to encountered problems in MPP version. Velocity histories are shown below.

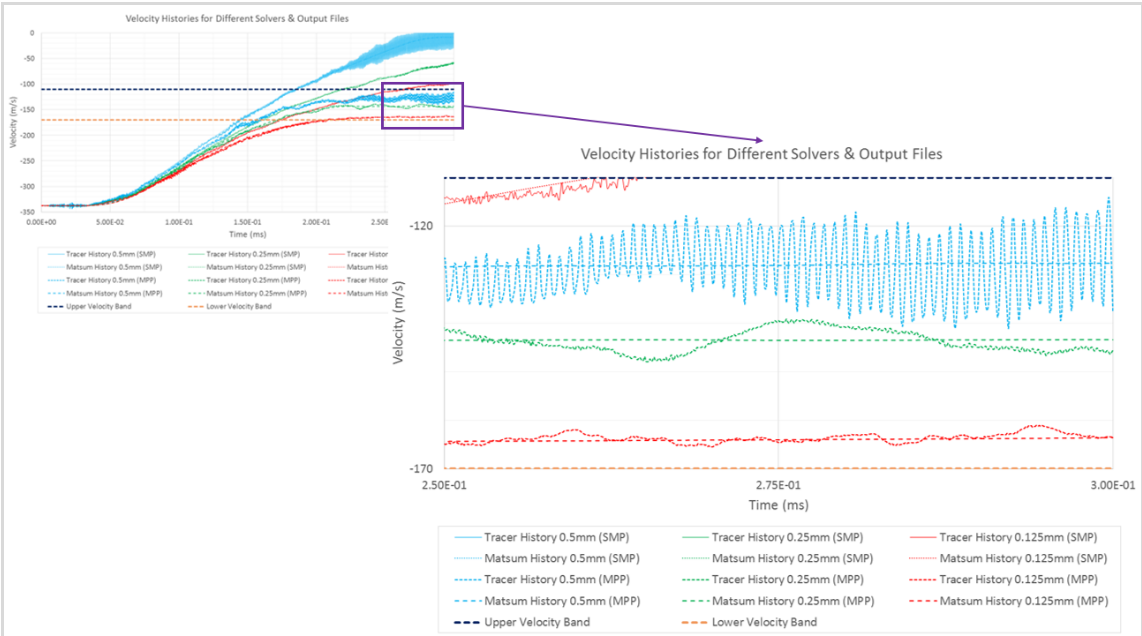


Fig.22: Velocity histories for ogival projectile.

It is observed that with the SMP solver, the projectile velocity approaches to zero, which is contradictory with the test results. Therefore, only the results of MPP version is considered. The closer look between the times 0.25-0.3 milliseconds will give more detailed information about the results. The figure above implies that as the mesh size decreases, the exit velocity of the projectile increases as in the case of blunt projectile. However, the amount of increment is more significant in the ogival

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projectile. This is the results for advection method 2. There is also a comparison between method 2 and 3, but only with the MPP version. The results are shown below.

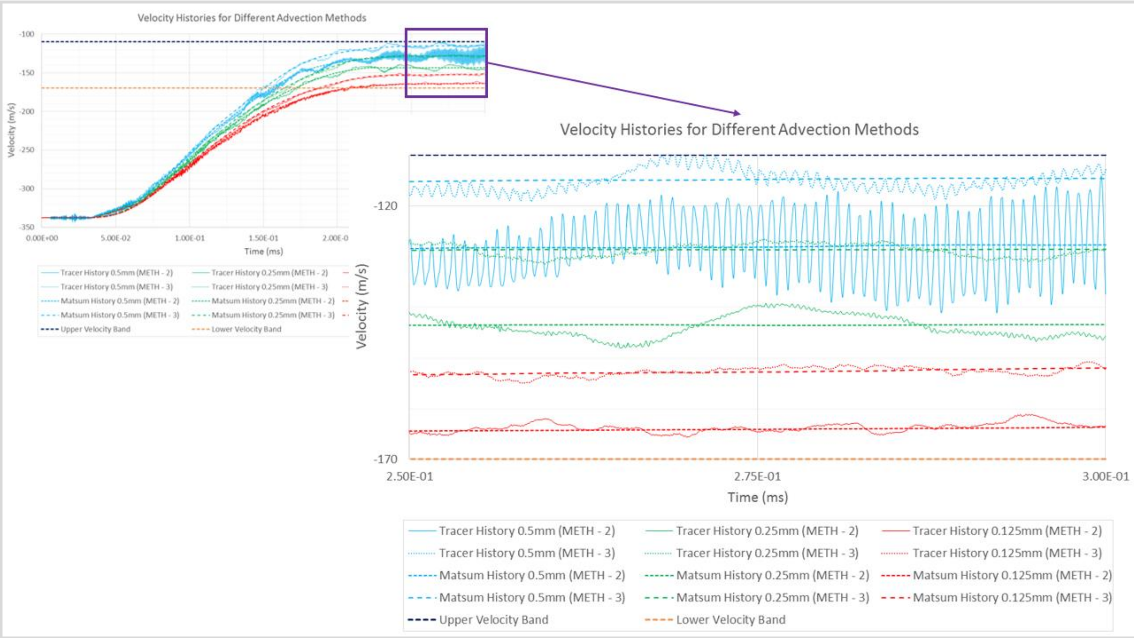


Fig.23: Velocity histories for blunt projectile (different advection methods).

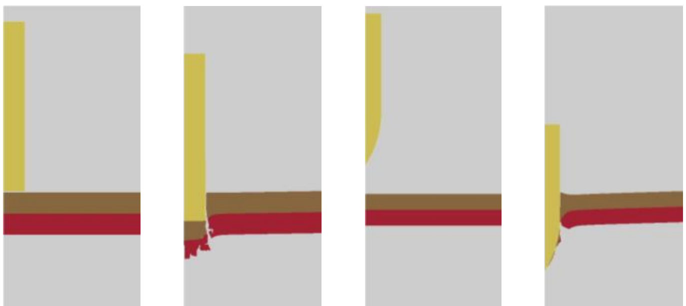
As in the case of blunt projectile, method 3 gives lower exit velocities than the method 2. The summary of all results for the ogival projectile is given below.

Mesh Size	SMP (METH – 2)	MPP (METH – 2)	MPP (METH – 3)
0.5mm	-	128	115
0.25mm	-	143	129
0.125mm	-	164	153
Experiment	**260**	**260**	**260**

Table 17: Summary of exit velocity for ogival projectile.

6.3 Double Plate Results

The double plate configuration is composed of 2 10mm aluminum plates as in the case of Lagrange solution. The mesh size is 0.25mm for both blunt and ogival projectile simulations. The perforation results are shown in figure below.



(a) (b) (c) (d)

Fig.24: Target plate deformations (a) Blunt @0.0ms (b) Blunt @0.06ms(c) Ogival @0.0ms(d) Ogival @0.3ms.

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The solution is done by the MPP version of LS-DYNA®, therefore the ***ALE_FAIL_SWITCH_MMG** keyword could not be used. The failed elements cannot be seen in the visualization. The velocity histories regarding the tracer and rigid body output are shown in figure below.

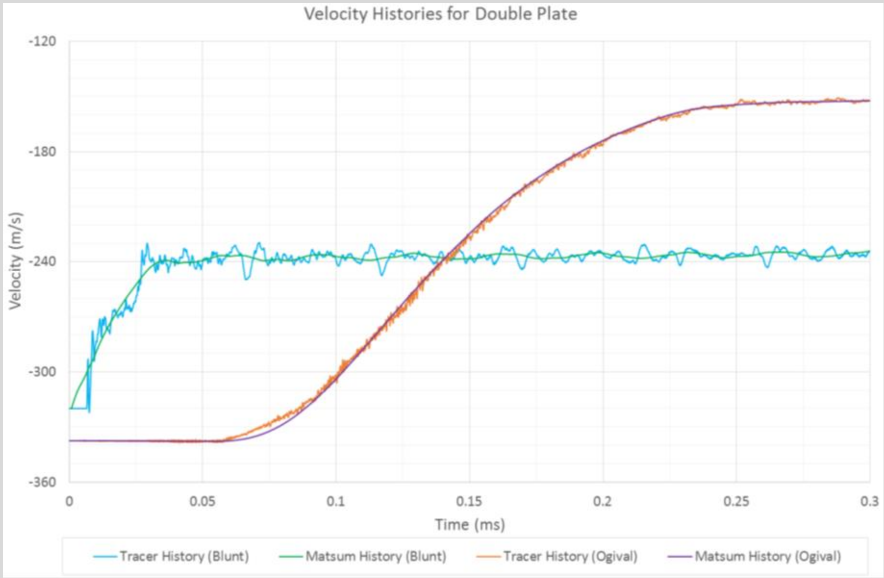

Fig.25: Velocity histories for all projecties and output types.

The final exit velocity for the blunt projectile is obtained as 236 m/s, while for the ogival projectile it is obtained as 152m/s. The ogival projectile result is completely different than the Lagrange solution. Moreover, the deformation behavior obtained in ALE method is completely differs from the ones obtained in Lagrange method.

7 Summary and Future Works

This study is consisted of perforation studies for AA7075-T651 plates with blunt and ogival nose shape projectiles. Simulations are carried out using 2D axisymmetric and 3D solid elements with Lagrange and ALE methods. There are several comparative studies are performed for different mesh configurations, hourglass and element types. Furthermore due to the lack of validation of the simulation and experiment results, material optimizations is performed to get more compatible residual velocities with experiments. Additionally double layered plates are considered and simulation results are compared with monolithic plates.

According to the simulation results, it is observed that residual velocities of perforation studies are quite dependent on mesh configurations. Mesh sensitivity studies are very important to determine optimum mesh configurations for penetration and perforation studies. Moreover 2D axisymmetric elements give consequent results compared with the 3D elements. In present work there isn't any significant effects of hourglass types and solid element formulations on residual velocities are obtained.

Material parameter optimization studies are carried out to determine optimum material parameters and investigate the influence of the parameters on residual velocities. In addition, MAT_ADD_EROSION keyword is considered and the maximum shear strain criterian (EPSSH) is utilized. As mentioned before, Cockcroft-Latham parameter (Wcr) has the major effect for blunt projectile impact and the EPSSH parameter has the biggest influence for the ogival projectile impacts among the considered parameters.

Finally double layered plates are investigated and simulations are performed with the same boundary conditions of monolithic plates. To distinguish between monolithic and layered plates, double layered plates have relatively high ballistic resistance than monolithic plates in case of the blunt projectile penetration. However, for the ogival projectile perforation case monolithic plates show great ballistic performance. This finding supports previous research as mentioned by Dey et al [5].

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As a result of the study, it is concluded that mesh dependency, material parameters and material model types are quite important to simulate the target plate behaviour correctly for penetration and perforation studies. Due to the importance of the material parameters and mesh dependency for the ballistic problems, detailed material characterization for different material types and internal ballistic experiments will be carried out to improve ballistic simulation capabilities.

8 Literature

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