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Residual velocity and kinetic energy of the ballistic simulations test on hardened medium carbon steel plate

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Abstract. Ballistics testing is the study of collision phenomena between projectiles and target material. Simulation with finite element is one alternative to ballistic testing that can provide detailed numerical data and specific. Validated simulations can be used as a reference for improving projectile resistant material in addition to the results of experiments test. These papers presents the effect of austenization temperature and quench media in the S45C steel plate on the residual velocity of the projectile and kinetic energy after being fired blunt projectile at a speed of 303.5 m/s with simulation base on finite element. Material data was obtained from the results of an experimental test of S45C steel plate thickness 8 mm which was austenization at 700, 800, 900°C which was quenched in water and oil media. Validation of simulations is carried out with past research. The simulation results show that the steel plate is austenization 900°C with treatment on the quench oil media can withstand the projectile better, with a projectile residual velocity of 234.46 m/s, with projectile kinetic energy of 1346.8 Joule.

1. Introduction

Military vehicles are special vehicles made and designed to be projectile or bullet or ballistic-resistant. The construction of this type of vehicle is made from projectile-resistant or ballistic-resistant steel plates. The thicker the steel plate used, the more resistant they are to projectiles, in exchange with increased vehicle weight. The heavy weight of the vehicle will reduce the efficiency and agility in maneuvers [1]. For that reason, much research has been done to produce thin yet strong steel plate through alloying or heat treatment [2]–[5]. Ballistic resistance is the capability of a target to take projectile impact energy. One of its indicators projectile's residual velocity after perforation through an object and kinetic energy absorbed by the target.

Ballistic resistance can be determined with a ballistic test, by firing certain level projectiles at a certain distance. This experiment requires considerable costs and complex instruments both in testing and data collection phase. Projectile and target's relative velocity, projectile and target shape, relative rigidity, target and projectile mass, contact surface, geometry and condition limit, and characteristics of projectile and target material are complex ballistic parameters [6]. A simulation using finite elements is proposed for efficiency and to obtain more detailed and complex data [7]. A simulation can save time and cost with better benefits [8]. A simulation with chosen and validated model obtains the results necessary for the analysis [9].

Projectile fired from firearms are an object with extreme velocity. In the testing, a projectile was fired against other object to test its resistance. In the simulation, model and boundary condition for the material used was made. In addition to density, the material model when it is elastic and plastic is defined with an equation. Elastic material is considered linear and affected by elasticity modulus and Poisson's ratio. Johnson-Cook [10] proposes plasticity equation for material subjected to impact at extreme velocity [11], [12].

A simulation using finite elements was done to calculate the energy absorption of the projectile fired against a plate. Kinetic energy absorption reached maximum value a moment after collision occurred and diminished when the plate sustained failure and perforation [13]. Less resistant metal plate with Lode-dependent modified Mohr-Coulomb (MMC) fracture criterion is predicted to have much lower ballistic limit velocity compared to Lode-independent modified Johnson-Cook (MJC) fracture criterion. In contrast, metal plates with high ductility in both fracture criteria would produce quite close ballistic limit velocity predictions [14]. In the simulation, ballistic resistance of layer configuration was less than monolithic plate. It is also concluded in the simulation that minimum ballistic limit is obtained independently from projectile's end shape and it increases significantly by layering the target to double its thickness [15]. Simulation and experiment results show that target resistance increases along with an increase in target obliquity [16].

To determine the ballistic resistance of a steel plate, a ballistic test is required. The lower the projectile's residual velocity and kinetic energy after it collides and passes through a target, the higher the ballistic capability of the target is. This study aims to determine and analyze the effect of austenitizing temperature and media quench applied to steel plates on the projectile's residual velocity and kinetic energy using finite element-based simulation.

2. Methods

Material models in the simulation are obtained from the experiment test. The material used is a medium carbon steel plate with 0.45% carbon content which is austenitized by using induction heating at 700, 800 and 900°C and quenched in water and oil media. The modeling process was carried out on a target of 500 mm in diameter and 8 mm in thickness with a blunt-nosed projectile with a diameter of 20 mm, a length of 80 mm and a mass of 0.197 kg. Projectile and target material conditions are deformable. The projectile was given initial velocity of 303.5 m/s. The geometry and meshing schemes can be seen in Figure 1. The meshing was done using body sizing and multizone method where the area of element collision is made smaller. In the collision area and outer area, a 0.5 mm and 16 mm mesh, respectively, are given, with a total of 58912 elements and 65575 nodes. Engineering data is presented in Table1, Table2 and Table 3. Simulation validation was treated to experiment result test and simulation done by Brøvik et al [11].

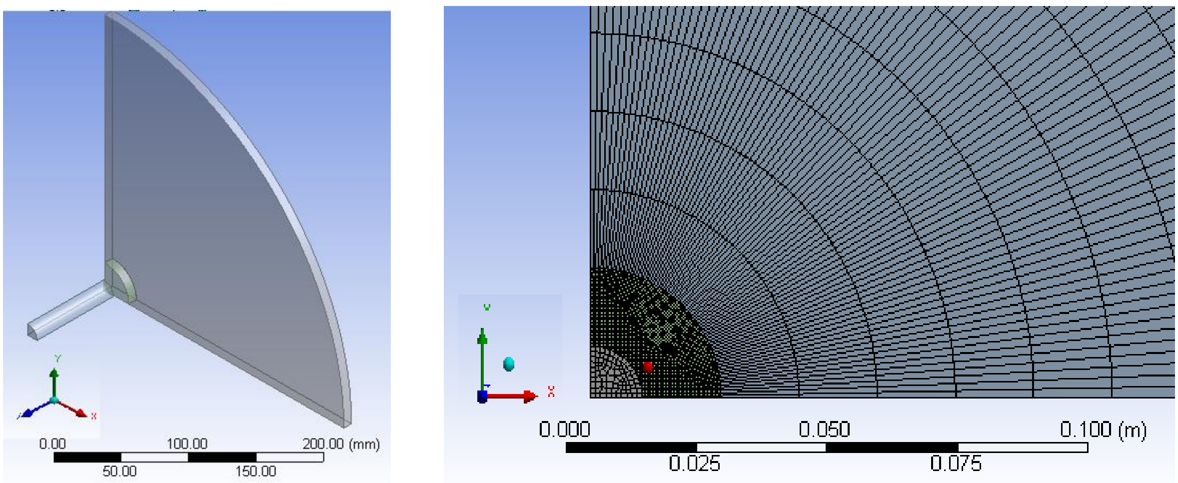

Figure 1. Modelling and meshing scheme

Table 1. Yield and maximum stress of test experiment results

No	Austenization and quench media	Yield stress (MPa)	Hardness (VHN)	Code
1	Raw Material	495	176.2	RM
2	700°C Water	596	188.25	W7
3	800°C Water	723	227.35	W8
4	900°C Water	636	335.05	W9
5	700°C Oil	621	209.5	O7
6	800°C Oil	637	232.45	O8
7	900°C Oil	813	281.55	O9

Table 2. Projectile material properties [11]

Description	Notation	Nominal
Modulus young	E (MPa)	200000
Poisson ratio	v	0.33
Density	ρ $(\mathrm{Kg/m^3})$	7850
Yield stress	A (MPa)	1900
Plastic Strain	$\varepsilon_r(\%)$	1

Table 3. Target material properties [11]

Description	Notation	Nominal
Modulus young	E (MPa)	200000
Poisson ratio	v	0.33
Density	ρ $(\mathrm{Kg/m^3})$	7850
Yield stress	A (MPa)	Exp. test
Strain Hardening	B (MPa)	807
constant	n	0.73
Viscous effect	C	0.012
Thermal Softening	m	0.94
Strain rate hardening	$p_{0,}r_0(S^{-1})$	5.10^{-4}
Specific Heat	*Cp* (J/Kg.K)	452
Melt temperature	*Tm* (K)	1800
Transition temperature	*To* (K)	293
Fracture strain constrain	*D1*	0.0705
	D2	1.732
	D3	-0.54
	D4	-0.0123
	D5	0
User Defined reference strain rate	*Po*	1

3. Results and Discussion

In the simulation results at each variation, the projectile was able to perforate and pierce the target. Projectile's residual velocity and plate fracture or plugging after perforating the target is seen in Figure 2.

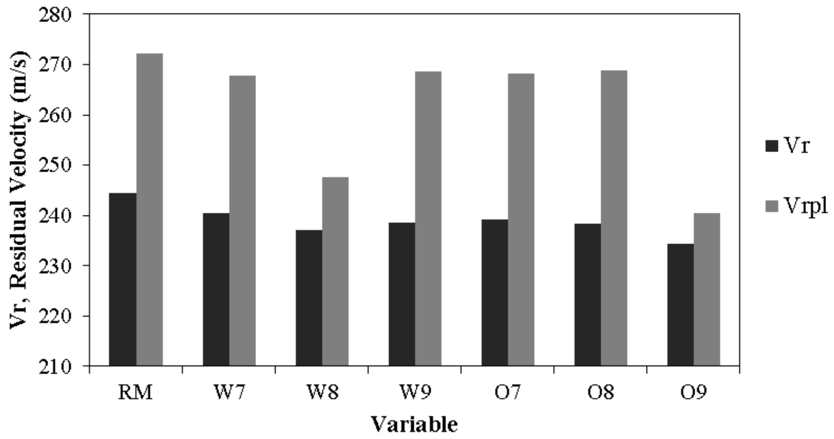

Figure 2. Projectile's residual velocity and plugging after perforation

The smallest projectile's residual velocity (v_r) value is on the steel plate with austenitizing heat treatment temperature of 900°C with oil quench medium with 234.46 m/s and plugging residual velocity (v_{rpl}) of 240.39 m/s. While the highest residual velocity value is on the steel plate without any treatment with projectile's residual velocity of 244.36 m/s and plugging residual velocity of 272.15 m/s. The simulation results show that the plate with low hardness, 176.2 VHN, has high residual velocity, which means low ballistic resistance. However, the plate with high hardness, 335.05 VHN, austenitized at 900°C and quenched in water, did not have the most optimal ballistics. This shows that hardness is not the only factor affecting the ballistic resistance. Elastic materials are easily deformed by projectiles, while hard materials are able to withstand ballistic velocity, but are vulnerable to failure due to shifting and cracking into holes due to projectile collision [17], [18]. Projectile's kinetic energy occurred after the collision with the target plate as shown in Figure 3.

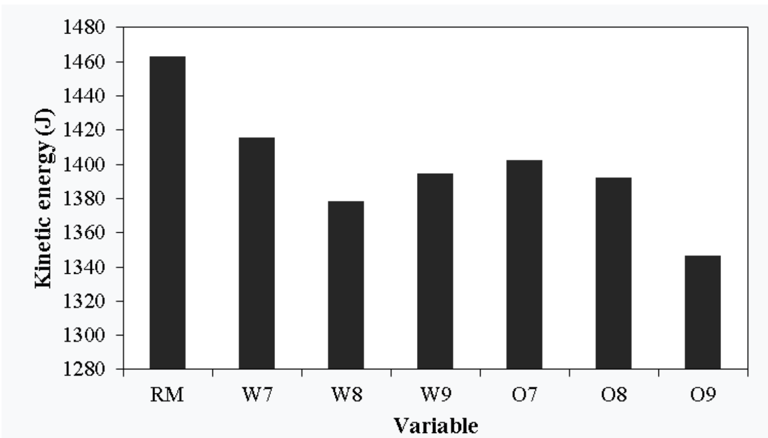

Figure 3. Projectile's kinetic energy after impact with target plate

Projectile's kinetic energy is directly proportional with the residual velocity. The lower the velocity is, the lower the kinetic energy on the projectile will be. The highest kinetic energy occurred on the plate with no treatment (raw material), while the lowest kinetic energy occurred on the plated treated with 900°C austenitization and quenched in oil. Blunt projectile penetration and perforation at austenitizing temperature of 900°C and oil quench media can be seen in Figure 4.

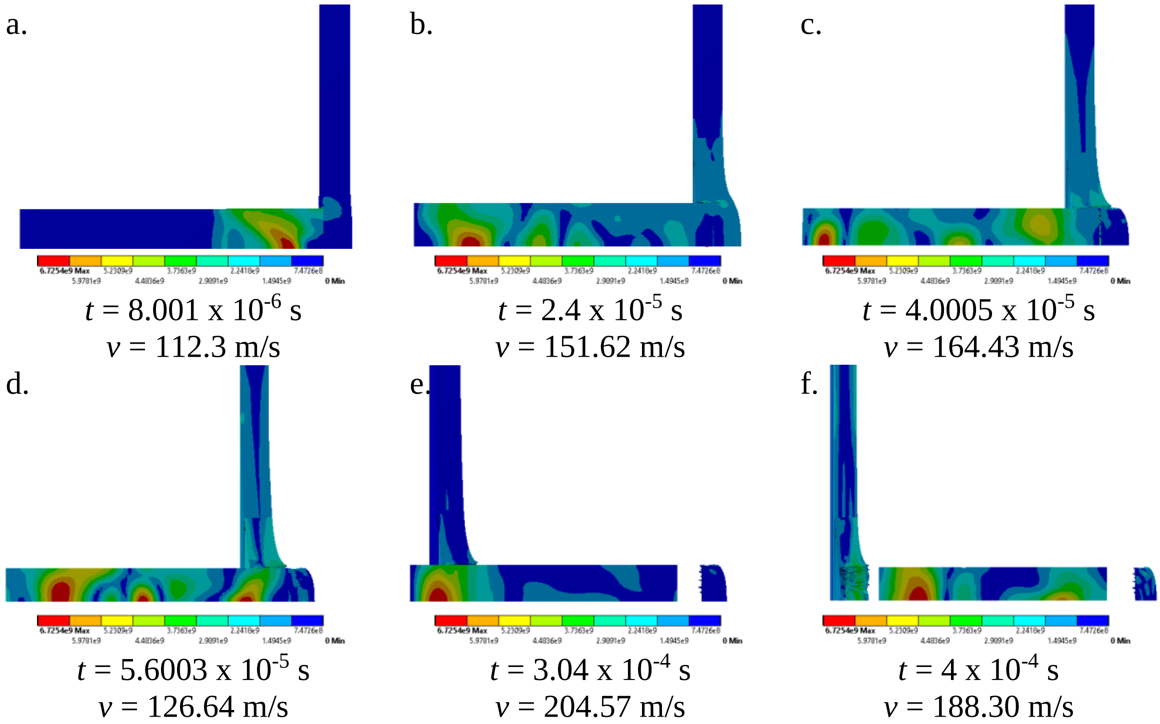

Figure 4. Perforation process of blunt projectile with austenitizing temperature of 900°C and oil quench media

As shown in Figure 4, at the beginning of the impact, projectile's velocity decreases rapidly and significantly to 112.3 m/s at 8.001 x 10-6 second due to the tension occurred at the beginning of the impact between the projectile and plate is at maximum value of 6.72 x 103 MPa. The velocity started to increase at 2.4 x 10-5 second when fracture occurred on the plate, but then in a short time it started to decrease again to 126.64 m/s, and started to increase again after the projectile passed through the plate. The tension concentration is indicated by discoloration. Red colour indicates higher tension than blue colour. Tension concentration occurred at the front end of the projectile and spread to the back of the projectile. While the tension concentration of the plate is observed on the penetration point.

The perforation shape on the plate after penetration process can be seen in Figure 5. The type of the fracture obtained is plugging where the residual plate after the fracture resembles the surface of projectile's end [19].

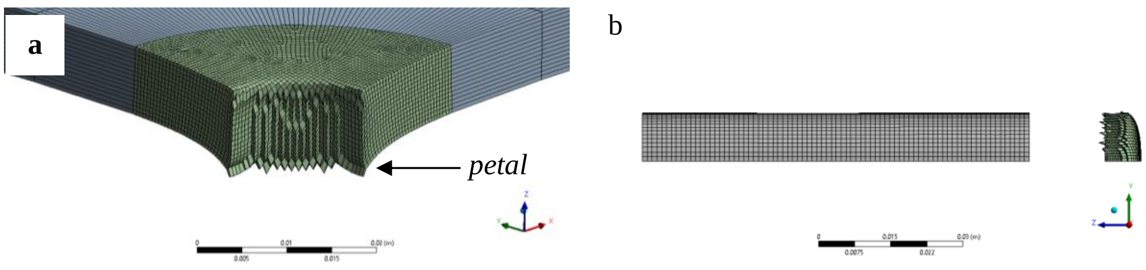

Figure 5. Perforation shape (a) Plate shape after perforation (b) Projectile and plug after perforation

Plugging fracture occurred on hard target material or with blunt projectile. Plugging fracture occurs when there is a shifting of parent material due to deformation. In this case, petal is also observed on the back side of the target. This indicates that the target material still possesses deformable characteristic.

4. Conclusions

Based on the result of the simulation on 8 mm hardened medium carbon steel plate fired with a blunt projectile at a velocity of 303.5 m/s, following conclusions can be drawn:

1. Medium carbon steel plate with quenching treatment cannot withstand the velocity of a projectile. Factors contributing to this failure may be plate thickness, plate material yield stress and projectile material.
2. The results of projectile's residual velocity and plug simulation show that the higher the yield stress value of a material is, the lower the projectile's velocity and plug. The lower the projectile's residual velocity is, the better the ballistic resistance of a plate will be. The lowest residual velocity is 234.46 m/s on medium carbon steel treated with a temperature of 900°C with oil quenching.
3. Projectile's kinetic energy will decrease along with the decrease in projectile's mass and velocity. The highest kinetic energy from the simulation is 1462.9 J on medium carbon steel plate without any treatment and the lowest kinetic energy is 1346.8 J on steel plate with treatment temperature of 900°C and oil quenching.

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