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Abstract. Ballistic limit is a speed limit where projectile with a certain shape, angle of attack and size is not able to perforate a target with certain properties and thickness. This paper aims is to determine and analyze the ballistic limit of commercial medium carbon steel plate which has been hardened by induction heating by using finite element based simulation. A plate with a thickness of 8 mm was shot by a deformable blunt projectile with a diameter of 20 mm, a length of 80 mm and a mass of 0.197 kg with an angle of attack of 90° against the plate. Simulation results show that projectile with a speed of 225 m s^{-1} is still able to penetrate the plate in the form of plugging. The plate can withstand the projectile rate at a maximum speed of 215 m^{-1}. At this speed, the plate is damaged but the projectile does not penetrate. The plate still has ductility properties, as during the simulation there were deflection and bulge in the back side.

Keywords: ballistic limit, medium carbon steel commercial, armor, hardened, simulation

1. Introduction

In the field of defence and security, military vehicles are designed to be resistant to ballistic impact. Military vehicles are designed and made using ballistic resistance material or armor. Armor can be made from commercial medium carbon steel by employing the quench heat treatment. The quench heat treatment can increase ballistic resistance of commercial medium carbon steel, even though quench steel with a thickness of 8 mm by simulation can still be projected through [1]. Commercial medium carbon steel which is austenized in 900°C and quench in oil produce better ballistic resistance compared to water media at different temperature [2].

To find out the armor's resilience at a certain volume, ballistic limit is sought. Ballistic limit or ballistic limit velocity is the minimum velocity at which a particular projectile is expected to consistently, completely penetrates the armor of given thickness and physical properties at a specified angle of obliquity [3]. Whereas Børvik [4] defines ballistic limit as the ability of the projectile for full penetration without residual energy. Ballistic limit is also defined as the lowest speed a projectile (need) to be able to penetrate a target at a certain volume [5]. Ballistic limit can also be defined as the speed required by projectile with certain properties to penetrate armor with certain properties as well. In other words, the projectile cannot penetrate the armor, if the velocity of the projectile is lower than the ballistic limit. Ballistic limit velocity depends on weapon properties, projectile and attack angle, and also from the target armor character. Ballistic resistance is influenced by the ability to absorb energy by the target material. The greater the moment of inertia of the area cross section, the bigger it is the ability to absorb energy [6] and energy absorption can be simulated by the finite element method [7]. Ballistic limit velocity is an important parameter to be known in ballistic material resistance studies.

Ballistic limit testing and measurement has been carried out on various types and forms of projectile and armor. The shape of the projectile affects the failure mode and the failure strain level [8]. Steel plate - Kevlar hybrid layer has superior ballistic resistance compared to monolithic steel plate of the same thickness, while being able to reduce weight by 26% [9]. The same thing is reported that monolithic target has lower ballistic limit velocity than layered target [10]. Monolithic titanium plate has superior ballistic limit compared to aluminum and Kevlar plate, whereas aluminum sandwich plate without honeycomb has ballistic limit velocity of 22.58% better than solid monolithic aluminum [11]. Ballistic limit velocity of MRHA steel 2.5 mm thicker than AISI 1045 and 4130, and possibly compatible with AerMet 100 steel and the penetration form is dominated by ductile hole growth and plugging modes [12]. The hardness of the plate affects the form of the plate failure, soft plate and ductile failure are caused by projectile that is able to pierce or penetrate the plate. While a hard plate failure is caused by a plate fracture [13].

Ballistic limit depends from the angle of attack on the target of woven and laminated high-strength fabric [14]. Ballistic resistance increases with increased target obliquity, critical angle of projectile ricochet with increased target thickness and the ballistic limit obtained is used to calibrate the Recht-Ipson empirical model [15]. Monolithic high strength steel plate has higher ballistic limit than steel plate and Al7075-T6 layered, but with regard to weight reduction the triple layered configuration, namely steel-Al-steel, produces good ballistic performance. [16]

Heat treatment has been carried out on an 8 mm commercial medium carbon steel plate with various austenization temperatures, quench media and tempering temperatures. Results of previous studies [1,2] with simulation showing austenization of 900°C and quench oil media producing better ballistic endurance. Thus, this paper aims to determine and analyze ballistic limit of S45C commercial medium carbon steel plate which had been justified by using an induction machine at 900°C and was quenched in oil media using finite simulation. The projectile used was steel that had been hardened with a blunt end in the angle of attack 90° towards the target plate.

2. Methods

The S45C commercial medium carbon steel plate which chemical composition is in accordance with Table 1 with length, width and thickness of 150 x 100 x 8 mm was austenized at 900°C using induction heating on one of its surfaces for 3 seconds. After the temperature and time were met, the plate was quenched in oil media as much as 15 liters. The yield stress, hardness and impact of material energy were respectively 813 MPa, 281.55 VHN and 0.58 J mm^{-2}. Experimentally quench steel plate was made (for) micro-vickers hardness and tensile test specimens. Tensile test specimens were according to ASTM E8/E8M. Experiment test results data were used as a reference in conducting ballistic testing simulations. Finite element based simulations were validated with the previous research [17]. Simulations were performed on a plate based on experimental test data using a blunt deformable projectile of 20 mm in diameter, 80 mm in length and a mass of 0.197 kg with an angle of attack of 90° against the target plate. Plasticity material models used the Johnson-Cook equations [18,19] with the properties and boundary conditions for the target plate as shown in Table 2 while [the properties and boundary conditions] for the projectiles are as shown in Table 3. 0.5 mm fine meshing as shown in **Figure 1**. Projectile initial velocity variations were performed to obtain ballistic limit velocity.

Table 1. Chemical composition (% wt.)

Material	**Chemical Compositions**
Medium carbon steel	0.4667 %C; 0.5584 %Mn; 0.0556 %Cr; 0.0411 %Ni; 0.2441 %Si; 0.0002 %Nb; 0.0163 %Al; 0.001 %V; 0.0106 %S; 0.0013 %Mo; 0.0016 %W; 0.0195 %P; 0.0577 %Cu; 0.0044 %Ti; 0.0078 %N; 0.0002 %B; 0.0064 %Sb; 0.0003 %Ca; 0.0009 %Mg; 0.0004 %Zn; 0.0108 %Co; Fe bal.

Table 2. Target material properties [17]

Description	**Notation**	**Nominal**
Modulus young	E (MPa)	200000
Poisson ratio	v	0.33
Density	$\rho\ (\mathrm{kg\ m^{-3}})$	7850
Yield stress	A (MPa)	813
Strain Hardening	B (MPa)	807
constant	n	0.73
Viscous effect	C	0.012
Thermal Softening	m	0.94
Constanta		
Strain rate hardening	$p_0, r_0\ (S^{-1})$	5.10^{-4}
Specific Heat	Cp (J Kg^{-1} K^{-1})	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

Table 3. Projectile material properties [17]

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

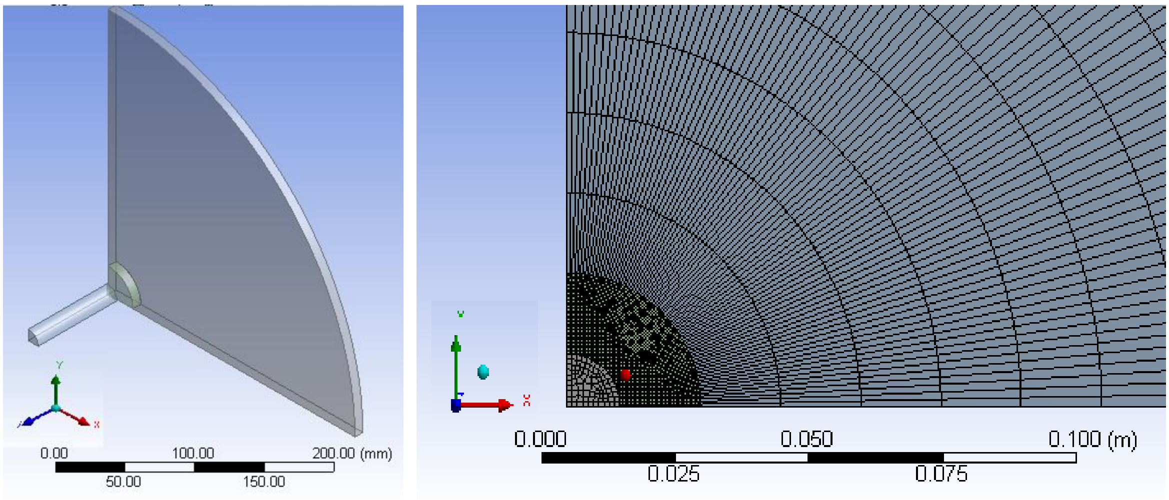

Figure 1. Modelling and meshing

3. Result and discussion

The test results using finite element based simulations are presented in **Table 4**. The initial velocity of the projectile is gradually decreased. The projectile residual velocity is the projectile velocity measured after passing through the plate. Meanwhile, the residual velocity of the flakes plate is the fracture velocity of the plate that was broken due to the projectile impact.

Table 4. Simulation of finite element base results on various projectile initial velocities

No	Initial velocity (m s^{-1})	Projectile mass (kg)	Residual velocity (m s^{-1})	
			Projectile	Plate flakes
1	303.5	0.049	214.72	272.15
2	250	0.049	133.24	203.61
3	225	0.049	71.014	120.25
4	215	0.049	0	0
5	200	0.049	0	0

In this simulation the initial velocity of 303.5 m s^{-1} was given to the projectile, the projectile was able to penetrate the plate with a thickness of 8 mm. At this speed, the resulting projectile residual velocity after penetrating the plate was 214.72 ms^{-1} while the plate flakes were 272.15 ms^{-1}. Until the initial velocity of 225 ms^{-1}, the projectile could still penetrate the target plate with residual velocity was as low as 71.014 ms^{-1} for the projectile and 120.25 ms^{-1} for the plate flakes. The average projectile residual velocity was lower than the plate flakes residual velocity. This was because the pro small flakes with lighter flake mass of each. At the initial velocity of 215 ms^{-1} and 200 ms^{-1}, the projectile was unable to penetrate the target plate.

Equivalent stress, time and the projectile velocity at an initial velocity of 215 ms^{-1} is shown by simulation in **Figure 2**. The colour contours show the change in equivalents stress. The blue colour shows the equivalents stress is lower, while red colour indicates a higher equivalent stress.

Figure 2a shows an initial velocity of 215 ms^{-1}, there is no contact between the projectile and the plate. Shortly after the impact occurred between the projectile and the plate (**Figure 2b**), that is at 6.0 x 10^{-6} seconds the projectile velocity dropped to 114.37 ms^{-1}. The speed dropped by almost 100%, the largest maximum stress occurred at the tip of the projectile which was around 5095.4 MPa. At 1.2 x 10^{-5} seconds, the projectile velocity dropped to 43.9 m s^{-1} (**Figure 2c**). The stress concentration travelled to the back of the projectile. Maximum stress had not yet occurred on the plate, this was due to the volume of the plate which is much larger compared to the projectile. The maximum stress moved on the plate until the end of the projectile successfully pierces the surface of the plate at 1.8 x 10^{-4} seconds (**Figure 2d**). In this case the maximum stress on the projectile was lower than the maximum stress that occurred on the plate. The plate was deformed due to projectile impacts. The plate managed to hold and reduce the projectile speed to 23.31 m s^{-1}. At the 0.06 x 10^{-4} seconds the maximum stress concentration continued on the plate until it reached 1392.8 MPa, resulting in damage to the surface of the plate (**Figure 2e**). Velocity could be reduced to reach 13.36 ms^{-1}. Finally the projectile could stop at 3.18 x 10^{-4} seconds after piercing the plate surface and finally the projectile bounced in the opposite direction (**Figure 2f**).

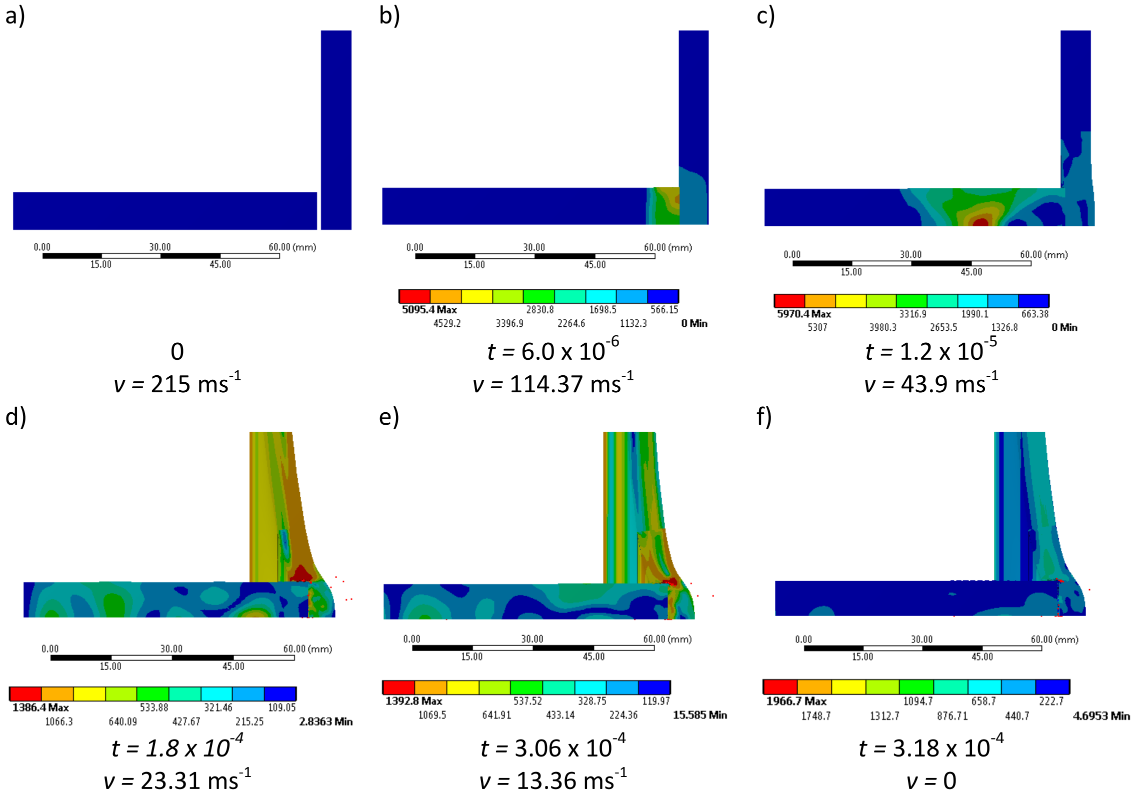

Figure 2. Equivalent stress, time and the projectile velocity at an initial velocity of 215 m s^{-1}

Deflection and projectile position at 3.18 x 10^{-4} seconds are as shown in **Figure 3**. **Figure 3a** shows the deflection from its original state after being hit by a projectile impact. **Figure 3b** shows more of an impaled projectile due to the blunt tip of the projectile.

The plate was deflected after a ballistic impact by the projectile (**Figure 3a**), this shows (that) the plate still has ductility. Ductility is needed to absorb the projectile impact. A very hard plate would not have deflection, the plate (would) immediately broken and form a hole with a form of plugging failure [13]. Projectile material made of hardened steel tends not to change shape (**Figure 3b**). This was due to the maximum stress that occurred in the projectile — was still below the maximum stress of the projectile material. Projectile was able to pierce the plate surface to approximately half of the plate thickness. Because of the properties of the plate that still ductility, bulge was formed on the back side of the plate.

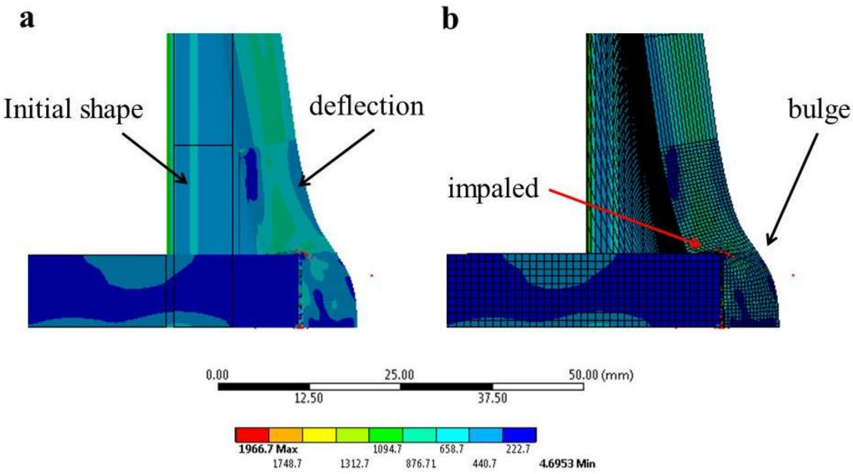

Figure 3. Seconds to 3.18 x 10^{-4} projectile initial velocity 215 ms^{-1}
a) equivalent stress b) meshing looks

4. Conclusions

The results of finite element based simulation with various projectile initial velocity variations in the S45C commercial medium carbon steel material which has been justified by using an induction machine at 900°C which was quenched in oil media are:

- Ballistic limit velocity using a blunt deformable projectile with a diameter of 20 mm, a length of 80 mm and a mass of 0.197 kg with an angle of attack of 90° against the target plate is 215 ms^{-1}.
- The projectile is able to pierce the plate surface up to half of the plate thickness.
- The plate still shows its ductility properties by showing deformation and bulge on the back side.

5. Acknowledgment

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