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The Effect of Tempering Temperature on Medium Carbon Steel Plate of Surface Hardening Result Using Induction Heating as Ballistic Resistant Material Study

Helmy Purwanto[1*], Muhammad Dzulfikar[1], Mohammad Tauviqirrahman[2], Rifky Ismail[2] and Nyoto Lestari[1]

[1]Department of Mechanical Engineering, Engineering Faculty, Universitas Wahid Hasyim, Semarang – Indonesia
[2]Department of Mechanical Engineering, Engineering Faculty, Universitas Diponegoro, Semarang – Indonesia

*E-mail: helmypurwanto@unwahas.ac.id

Abstract. Steel that has been heat treatment using quenching is hard but brittle. Tempering was done to remove the agility caused by the residual stress. The objective of this paper writing is to know and analyze the effect of tempering temperature on the mechanic property of steel plate of the surface hardening result. Steel plate with thickness of 8 mm of surface hardening result quenched by oil media was tempered at temperature of 100, 200, 300 and 400ºC. Simulation based on finite element method was conducted to know the ballistic resistance. Experiment result showed that heating through induction and quenching on oil resulted in surface hardening. Tempering treatment decreased the hardness but at low temperature, the tensile strength increases. The simulation result showed that quenching and tempering material at temperature of 100ºC was more able to resist the ballistic rate compared to other various temperatures.

1. Introduction

Medium carbon steel's physical and mechanical nature in solid condition can be changed through heat treatment. Heat treatment through quenching produces very hard martensitic structure but brittle. The presence of residual stress or stress relieves during rapid cooling causes weak ductility and toughness. Removing the stress relieved as well as improving the ductility and toughness was conducted through tempering heat treatment. Tempering was conducted by heating the martensitic steel below eutectoid temperature in certain period of time and cooled slowly.

There are many factors affecting quench-temper process result on medium carbon steel. Chemical material composition takes role on transformation phase. The additional of alloying elements on low carbon steel will affect the size of austenite particle so that it produces various physical and mechanical properties after the quenching [1]. Heating method in quenching-tempering process also affects the result. Hardening through pre-heating was continued by repeated heating until it reached austenite temperature and decreases until it reaches temperature of $\alpha + \gamma$ and quenched to produce high strength and toughness

[2]. In addition to the composition elements, heating method and temperature, cooling media also affects the hardening result. Quenching marula oil media was able to produce hard sample without any cracked and distortion compared to quenching water media [3].

Tempering temperature affects the mechanical properties, in which the higher the tempering temperature, then change the broken-brittle properties into broken-tough [4]. However, tempering at low temperature can increase the steel's mechanical properties [5]. Cooling rate in tempering process affects the formed structure transformation. Increasing the cooling rate or decreasing the temperature on-line tempering contributes to resist the austenite transformation into ferrite, and simultaneously maintain more austenite to transform into perlite [6].

Ballistic resistant material is a material which is able to resist ballistic rate. In army, ballistic resistant material is a material which is able to resist projectile rate. The ultra-high velocity impact of projectile must be resisted by target material of special properties. Combination between hardness, force and toughness is needed in ballistic resistant material [7]. Target hardness affected the hole of projectile impact shape [8], since it was affected by different deformation ability [9]. Difference in hardness value due to tempering temperature is studied on the depth of projectile penetration on high strength armor steel [10].

Simulation method based on finite element was used in ballistic testing was more efficient. Finite element modeling along with optimization probabilistic hole distribution modeling is a fast , robust and effective tool used in parametric study to maximize the efficiency of perforated armor systems [11]. Through the simulation, the ballistic hole morphology and energy absorbed in the test can be predicted [12]. Good agreement between the experiment test and simulation was conducted on steel plate shot using blunt ended projectile on velocity above ballistic limit [13].

There were many reviews regarding ballistic resistant steel making using quench temper. However, the use of surface hardening using induction heating is still rarely found. The objective of this research is to know and analyze the effect of tempering temperature on medium carbon steel plate done through quenching treatment on oil media towards the hardening distribution and ballistic resistant through simulation based on finite element.

2. Method

Composition of medium carbon steel plate on Table 1 with the size of Ø150 x 8 mm was austenitized at temperature of 900°C through induction heating in one of its surface for 3 seconds. After the temperature and time was fulfilled, plat was quenched on 15 liters oil media. The quenching result was treated using tempering heating by putting the sample on the furnace. Tempering temperature variety chosen were 100, 200, 300 and 400°C, while the holding time was for 15 minutes. The quench result and quench-temper result was made into specimen for micro-Vickers hardness and tensile. Micro-Vickers hardness test was conducted on cross-section as many as 20 points from the surface to the bottom. Tensile test specimen was in accordance with ASTM E8/E8M. The experiment test result data was used as reference in implementing simulation of ballistic test. Simulation based on finite element was validated using the previous research Børvik et al. [13]. The simulation was conducted on the plate based on experiment test data using blunt deformable projectile with diameter of 20 mm, length of 80 mm, mass of 0.197 kg and initial velocity of 303.5 m/s. Other boundary condition in the simulation was presented in Table 2 and Table 3. Fine meshing size was 0.5 mm as seen in Figure 1.

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. Projectile material properties [13]

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

Table 3. Target material properties [13]

Description	Notation	Nominal
Modulus young	E (MPa)	200000
Poisson ratio	v	0.33
Density	ρ (Kg/m^3)	7850
Yield stress	A (MPa)	ET
Strain Hardening	B (MPa)	807
Constant	n	0.73
Viscous effect	C	0.012
Thermal Softening Constanta	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
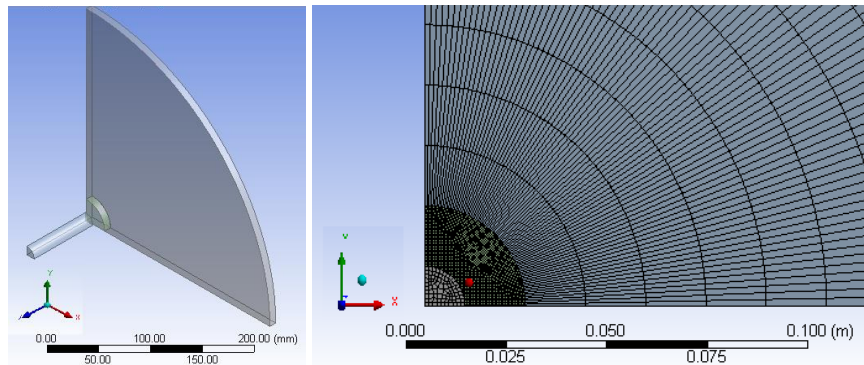
Figure 1. Modeling and meshing scheme

3. Result and Discussion

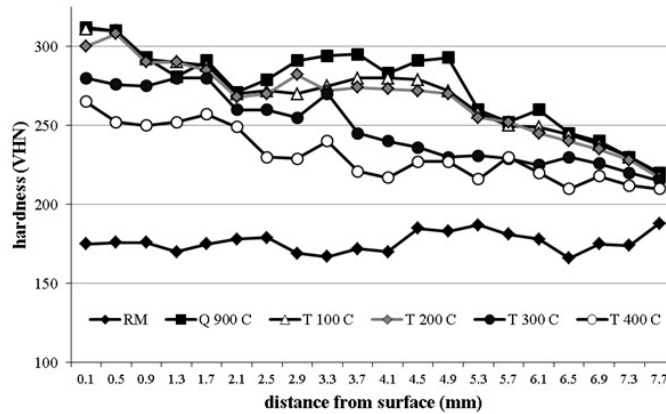The test result of hardness distribution using micro-Vickers method is presented in Figure 2.

Figure 2. Distribution of cross-section plate hardness using various tempering temperature

Figure 2 is graph of hardness distribution presenting the mean hardness of raw material which is 176.2 VHN. From the experiment with various austenization temperatures, the optimal result was obtained at temperature of 900°C using quench oil media. The mean hardness on the surface was 312 VHN, in the middle was about 290 VHN, while in the bottom area was about 220 VHN. This proves that by using induction heating, hardness could occur in one of parts of the surface. While on the other surfaces, the hardness was maintained in order to maintain its ductility. Hard material due to quenching produces remaining tension. A very hard material which is exposed to ballistic weight can experience failure. The increase of hardness on steel plate does not affect linearly on the ballistic penetration and resistance [10].

Treatment of tempering at the temperature of 100, 200, 300 and 400°C decreases the hardness. The hardness does not decrease significantly at the tempering temperature of 100 and 200°C. Meanwhile, the tempering at temperature of 300 and 400°C, the hardness decrease more. The hardness on the surface at tempering temperature of 100°C was 311 VHN and its hardness decreases into 219 VHN at the bottom. The biggest decrease of the hardness occurred at tempering temperature of 400°C, in which on the surface, it decreased into 265 VHN, while at the bottom, it decreased into 210. However, the hardness value was still above raw material hardness which is 175 VHN. This proves that the higher the tempering temperature, the bigger the decrease occur on the hardness value, as reported by Mishra et al. [14] on tempered high strength steel.

Tempering temperature also affected the tensile strength. Figure 3 presents the effect of tempering temperature variety on tensile strength.
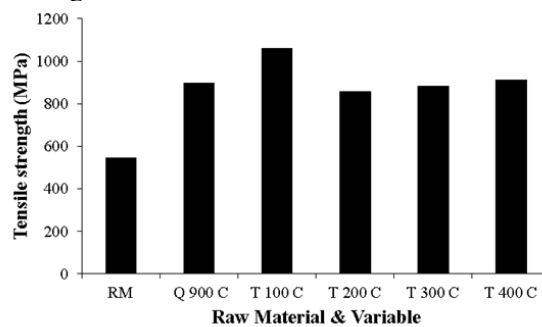

Figure 3. Graph of Tensile Strength on Various Tempering Temperature

The tensile strength of quenched steel plate was 900 MPa, which significantly increased to 548 MPa. The tensile strength of a steel plate occupied at 100°C increase to 1063 MPa from the quenched steel plate which was 900 MPa. Meanwhile, the tensile strength of tempered steel plate at temperature of 200 and 300°C experienced decrease into 848 and 883 MPa. The tensile strength of steel plate at the tempering temperature of 400°C experienced small increase from the quenched steel plate which became 912 MPa.

The hardness value increased causes the tensile strength also increased, while the strain decreased. Hard material has high tensile strength but tends to fragile and decrease ductility. In this case, samples tempered at temperature of 100°C generally experienced increase in its tensile strength although there was small decrease in the hardness. This is different from the cases reported before. However, Xiao et al. [5] stated that tempering at low temperature can increase the steel mechanical properties. Such increase of hardness may be caused by low tempering temperature and samples' homogeneity, although there is sufficient samples amount.

Ballistic test through simulation based on finite element presents that all target plates with various temperature experienced perforation. Projectile with velocity of 302 m/s succeed in penetrating the plate with thickness of 8 mm. Therefore, the ballistic resistant analysis was conducted by measuring the projectile velocity after passing through the target plate. The result of ballistic test of the effect of various tempering temperature on remaining projectile velocity V_r and plugging velocity V_{rpl} is presented in Table 4 and Figure 4.

Table 4. Residual velocity projectile and plugging on various tempering temperature

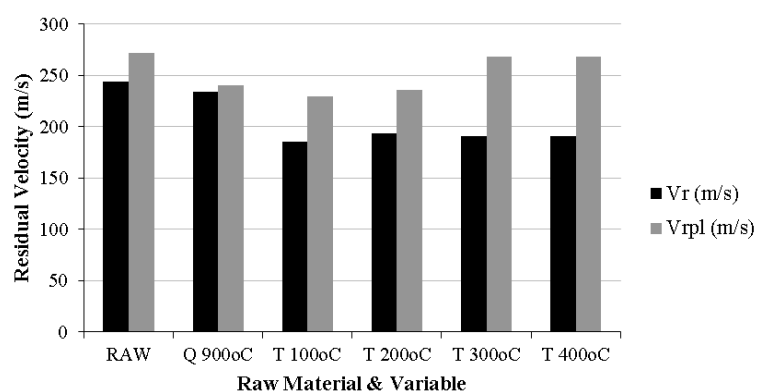| *No*	*Variable*	projectile velocity V_r (m/s)	plugging velocity V_{rpl} (m/s)
1	RAW	244.36	272.15
2	Q 900°C	234.46	240.39
3	T 100°C	185.9	230.03
4	T 200°C	193.89	236.12
5	T 300°C	191.28	267.98
6	T 400°C	191.02	267.98

Figure 4. Residual velocity projectiles and plugging on various tempering temperature

Steel plate that was tempered at temperature of 100°C has better ballistic resistant compared to other treatment. It was seen that the residual velocity projectile and plugging of plate that was the lowest was V_r 185.90 m/s and V_{rpl} 230.03 m/s. Ballistic resistant of a material is directly proportional with its tensile

strength. The higher the tensile strength, the more resistant it is towards the projectile impact. Simulation of ballistic test on target plate that was heated at austenization temperature of 900ºC, quenched using oil media and tempered at temperature of 100ºC is seen in Figure 5.
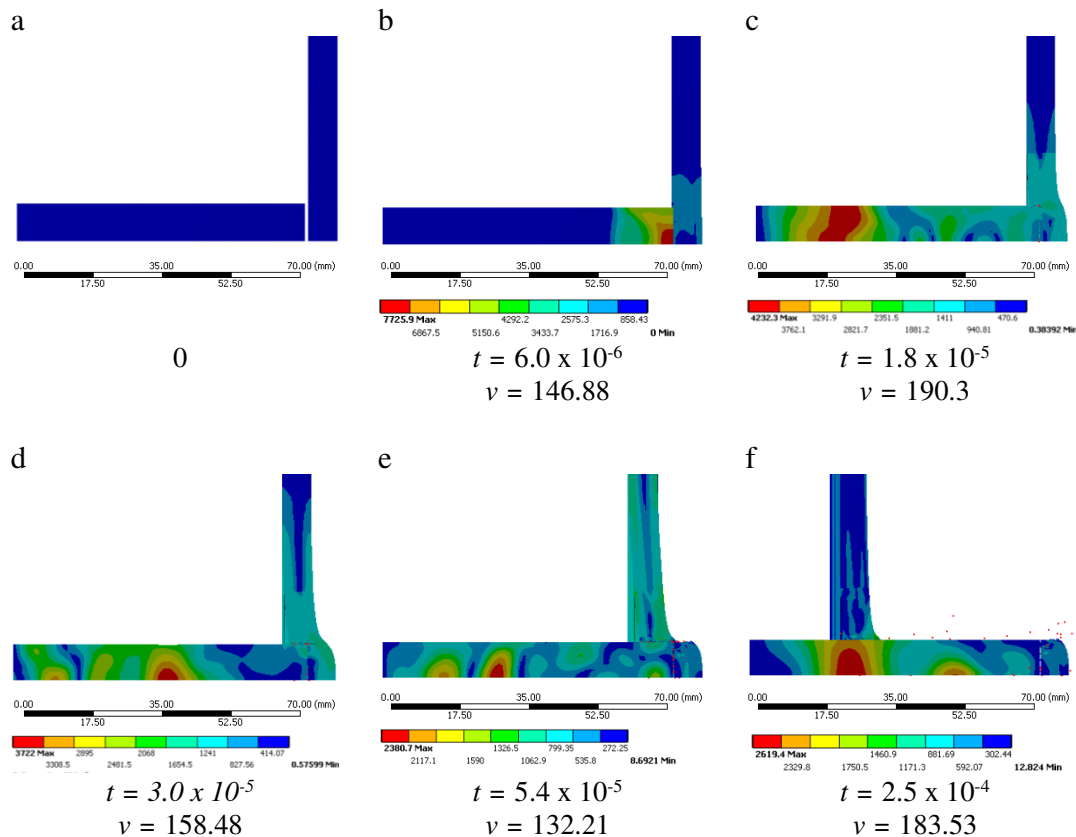

Figure 5. Residual velocity projectile and plugging at various tempering temperature

Projectile was given initial velocity of 301.2 m/s. Wend of the projectile touches the plate surface, the projectile velocity decreased to 146.88 m/s (Figure 5b). Maximum tensile stress occurred at the end of projectile and plate which were directly touched by the end of the projectile. However, when the projectile is succeed in broken the target plate or penetrating half of plat thickness, then the projectile velocity increases to 190.30 m/s (Figure 5c). This is due to quite big projectile's kinetic energy. Maximum tensile stress shifted to the back of projectile. Furthermore, the projectile's velocity decreased after perforation on the target plate. The velocity slowly decreased due to the fraction between the projectile's outer surface and hole's wall (Figure 5d, e and f). After the projectile passed through the target plate, the velocity became 185.90 m/s.

4. Conclusions

Based on the experiment and simulation result on low carbon steel plate through tempering heating, it can be concluded that:

1. Heating through induction and dipping on oil media results in higher surface's hardness compared to other surfaces.
2. Tempering temperature can decrease the hardness, but the tempering temperature at 100ºC can increase its tensile strength.

3. Through the simulation of finite element, all variation can be penetrated by the projectile. However, the quenched and tempered material at low temperature is more able to resist the projectile velocity compared to other various tempering temperature.

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