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Quenching and tempering parameter on Indonesian hot rolled plate steel for armour steel

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Abstract. Armour steel is a high strength and hardness steel used to protect damage by an object, individual or vehicle from the direct pressure of projectile. This steel used for military and commercials equipment in Indonesia and produced out of hot rolled plate steel made by PT. Krakatau Steel (Persero) Cilegon, Banten, Indonesia. By using quench (with water sprayed) and temper heat treatment produced Quenched & Tempered Steels. The aim of the study to obtain optimum quenching and tempering parameter in hardness and impact energy of HRP Steel. Method of this study by optimizing austenite temperature; austenite holding time; temper temperatures; hardness and impact energy. The result of this study is austenite temperatures 900^{o}C (held 45 minutes) and temper temperatures 125^{o}C (held 45 minutes). Prediction of both hardness and impact energy is 569.96 HVN (536.00 BHN) and 30.50 J respectively.

1 Introduction

Armour steel is a high strength and hardness steel used to protect objects from projectile damage or pressure during combat. In Indonesia, this steels made of hot rolled plate steel - HRP Steel which heat treated quench and tempered, and the names Quenched and Tempered Steel or Q&T Steel. Q&T Steel can be used to produce military (combat vehicles eg panzer, tanks, etc.) and commercial (vehicle frame, excavator etc.) equipment which need high strength and hardness steel. In fact, this steel has a wide of hardness due to the quench and tempered parameters used not optimal. Therefore, the range of hardness must be minimized in order to achieve the better quality of Q&T Steel.

Optimization of quench and temper heat treatment parameters to obtain armour steel based on HRP Steel made in Indonesia will be investigated.

The aim of the study to obtain optimum quenching and tempering parameter in hardness and impact energy of HRP Steel.

The output of this research is the quenching and tempering heat treatment parameter properly to produce Indonesian armour steel for an export commodity.

Armour steel is a protective covering that is used to prevent damage from being inflicted on an object, individual or vehicle by direct contact weapons or projectiles.

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During combat or from damage caused by a potentially dangerous environment or action [1]. The potential danger is caused by the ballistic impact energy on the target. The ballistic performance of various armor steels is characterized based on their hardness [2], and projectile penetration resistance of various armor steel depends on their hardness [3]. Hardness increases caused by martensite structure of the quench heat treatment, and the ductility increases due to temper temperatures. Industrially, to preserve as much of the strength of as-quenched martensite as possible, tempering is performed at low temperatures, between 150ºC and 200°C [4]. The formation of martensite can be induced if the steel is austenitized and then cooled at a sufficiently high rate in order to avoid the formation of ferrite, pearlite, and bainite [5]. The temperature of martensite finish calculated by following formula [6],

$$\mathbf{M_f = 175\ ^oC - 265\ ^oC} \text{ lower of } M_s \quad (1)$$

Fine austenite zone located nearest and above Ar_3 line, and calculated by [7],

$$\mathbf{Ar_3\ (^oC) \sim 910 - (310C) - (80Mn) - (80Mo) - (55Ni) - (20Cu) - (15Cr)} \quad (2)$$

And

$$\mathbf{Ms\ (^oC) = 561 - 474C - 33Mn - 17Ni - 17Cr - 21\ Mo} \quad (3)$$

Formula (2) used in steel 0.2% - 0.8% carbon.

Q&T steels are used in military applications due to high hardness, high strength to weight ratio and excellent toughness. [8]. Q&T steels are used in armour applications for combat vehicle construction as they possess high hardness, excellent toughness, and high strength to weight ratio, and toughness, i:e, the combination of strength and ductility, and hardness of the material [9]. The working principle of a typical armour material depends on the reality of stopping the attack by the sharp tip of -steel or other heavy metal-based penetrators, with its high hardness [10]. Adequate toughness is called for, to avoid cracking tendency and consequent disintegration of the material [11]. Quenching prevents the formation of ferrite or pearlite and allows the formation of bainite or martensite [12]. The impact toughness and fracture toughness increase significantly with increasing the quenching temperature, respectively [13]. Martensite carbon content is reliant on ferrite and martensite volume fractions developed as a result of ferritic and martensitic phase transformations after successive soaking and quenching treatments [14]. Distribution of austenite grains was heterogeneous in the microstructure [15].

2 Materials and Method

The material used in this study is Hot Rolled Plate Steel (thick = 10 mm) made by PT. Krakatau Steel (Persero) Cilegon, Banten, Indonesia.

The research procedure is carried out with the following steps,

Set up specimen 20 mm × 20 mm × 10 mm in size and tested using spectrometer (Optical Emission Spectrometer Machines ARL type 3460) to obtain chemical composition, and the results as shown in Table 1.

Table 1. Chemical composition

Element	C	Cr	Cu	Mn	Mo	Ni	Fe
% weight	0.293	0.550	0.083	1.412	0.193	0.279	97.189

Set up specimen 200 mm × 200 mm size (10 pieces) are heated on: 675ºC; 700ºC; 725ºC; 750ºC; 775ºC; 800ºC; 825ºC; 850ºC; 875ºC; 900ºC (held 30 minutes) and cooled in fresh water. Heating specimen by using Nabertherm Furnace.

Set up the specimen in size 3 mm × 3 mm × 1 mm and tested using microhardness testing machines ZWICK Type Zhu (in Vickers) to obtain hardness value, and plot in Figure 1.

Set up the specimen in size 10 mm × 10 mm × 55 mm and tested using Charpy Impact Testing Machine WOLPERT Type PW 30/15 [16] to obtain impact energy absorbed, and plot in Figure 2.

Optimization for austenite temperature; austenite holding time; temper temperature; hardness and impact energy by using Taguchi Optimization Method.

3 Results and Discussion

Base on carbon content (= 0.2923%) that HRP Steel steel concluding heat-treatable steel as shown

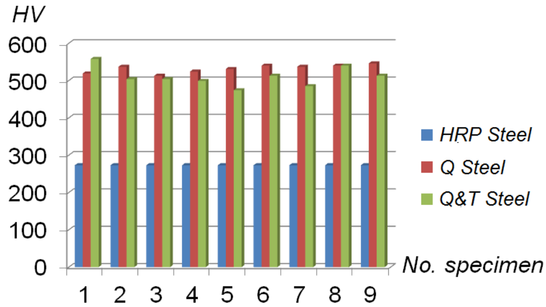

Fig. 1. Hardness for HRP Steel, Q Steel and Q&T Steel

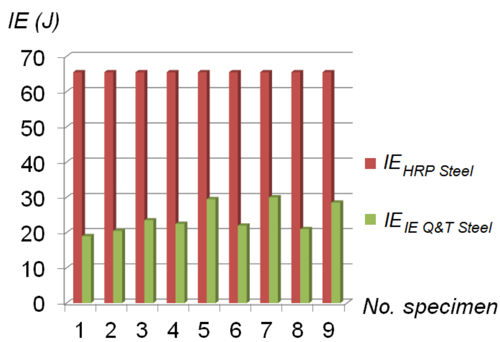

Fig. 2. Impact energy absorbed by HRP Steel, Q Steel dan Q&T Steel

shown by Jefferson [17], and mean that steel can be heat treated. Temperature Ar_3 of HRP steel ≈ 665°C (based on formula 1), austenitization must be done higher than 665°C. Martensite starts temperature Ms ≈ 357°C (based on formula 2), and martensite finish temperature M_f = 91°C - 182°C lower than Ms (formula 3).

Austenite temperature is Ar_3 + 50°C can be selected to obtain finest austenite structure [9] because the higher temperature will be obtained coarse austenite structure.

Temper temperature must be lower than Mf to avoid decreasing martensite structure by temper heat then 125°C, 150°C, and 175°C are selected. These temperatures are suitable to reduce residual stress prior quenching process.

Optimation heat treatment parameter by using Taguchi Method and consist of four following steps [18],

1. Three characters smaller, better and larger are the better.

2. Three free factors were chosen in this study: austenitization (A), austenite holding time (H) and tempering (T), Table 2. Control factors are hardness and Impact Energy (Figure 3).
3. Calculation degree of freedom DF obtains 6 so that the selected orthogonal array must be equal to or greater than 3 (three) DFs, shown in Table 3.
4. In this study consist of nine experiments with different parameters and levels. Each experiment adjusted the orthogonal conditions of the array. Both hardness and impact energy shown in Table 4 to Table 6.

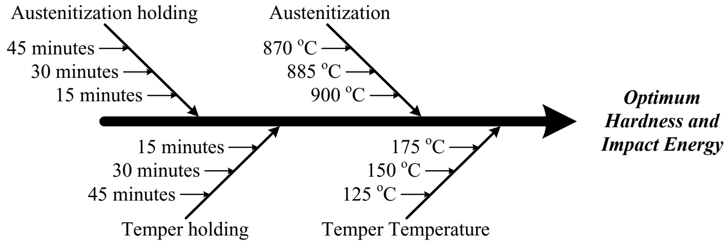

Fig. 3. Choose the level

Table 2. Design of parameter and level

P	L		
	1	2	3
A	870	885	900
H	15	30	45
T	125	150	175

Table 3. Orthogonal array L_9

E	Factor		
	A	H	T
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4. Hardness, Impact Energy dan signal/noise

E	Kekerasan					Impact Energy			
	Replication			$\overline{H}$	S/N	Replication		$\overline{IE}$	S/N
	H_1	H_2	H_3			IE_1	IE_2		
1	571	552	561	561.67	54.982	20.00	18.00	19.00	25.54
2	533	533	542	536.00	54.583	20.00	21.00	20.50	26.23
3	551	533	524	536.00	54.578	22.00	25.00	23.50	27.37
4	524	533	533	530.00	54.485	21.00	24.00	22.50	26.99
5	515	505	490	503.33	54.032	29.00	30.00	29.50	29.39
6	542	542	551	545.00	54.722	23.00	21.00	22.00	26.82
7	515	515	515	515.00	54.236	29.00	30.00	29.50	29.39
8	571	581	571	574.33	55.182	22.00	20.00	21.00	26.41
9	542	551	542	545.00	54.727	28.00	29.00	28.50	29.09

Table 5. Response to mean hardness and impact energy rata rata

L	Average hardness			Average Impact Energy		
	A	H	T	A	H	T
1	544.44	535.44	560.11	21.00	23.67	20.67
2	526.00	537.89	537.00	24.67	23.67	23.83
3	544.78	541.89	518.11	26.33	24.67	27.50
Selisih	18.78	6.44	42.00	5.33	1.00	6.83

Rank	2	3	1	2	3	1

Table 6. Response S/N

L	Hardness			Impact Energy		
	A	H	T	A	H	T
1	54.714	54.568	54.962	26.38	27.31	26.26
2	54.413	54.599	54.598	27.73	27.34	27.44
3	54.715	54.676	54.282	28.30	27.76	28.72
Difference	0.303	0.108	0.680	1.92	0.46	2.46
Rank	2	3	1	2	3	1

In ANOVA table can be seen the percentage of contribution for each parameter, hardness and impact energy are shown in Table 7 (have the strong contribution to tempering). $F_{calculate}$ compared to F_{table} so that there are two total columns and the error is not counted. If $F_{calculate} > F_{table}$ then the hypothesis is acceptable.

Prediction optimal performance

In the calculation of ANOVA obtained optimal results from each parameter. Then based on the

ANOVA. SS = sum of square; SM = square of mean; F_c= F calculate; F_{Tot} = F total; C = contribution; Err. = error; T = total

L	Hardness						Impact Energy					
	SS	DF	SM	F_c	F_{Tot}	C	SS	DF	SM	F_c	F_{Tot}	C
A	2066.074	2.00	1033.037	9.45	3.49	16.54	89.333	1.00	89.333	24.85	4.60	31.46
H	191.630	2.00	95.815	0.88	3.49	1.53	4.000	1.00	4.000	1.11	4.60	1.41
T	8051.852	2.00	4025.926	36.85	3.49	64.44	140.333	1.00	140.333	39.03	4.60	49.41
Err.	2185.185	20.00	109.259			17.49	50.333	14.00	3.595			17.72
Tot.	12494.741	26.00				100.00	284.000	17.00				100.00

results obtained the calculation of optimal predictive value to measure whether the confirmation test within the tolerance limit or not.

1. Prediction for hardness ($H_{Prediction}$)

$H_{prediction} = A_3 + B_3 + C_1 – 2y = 544.78 + 541.89 + 560.11 – 2 \times (538.41) = 569.96$

Trust interval.

$$n_{eff} = \frac{\text{number of experiments}}{1 + \text{number DOF}}$$

DOF = Degree of freedom per parameter.

$$\eta_{eff} = \frac{9 \times 3}{1 + 6} = 3.86$$

$$CI = \pm\sqrt{F_{0.05;2;20} \times MS_e \times \left(\frac{1}{\eta_{eff}}\right)} = \pm\sqrt{3.49x110.43 \times (\frac{1}{3.86})} = \pm 10$$

$H_{prediction}$ = 569.96 ± 10

2) Prediction for Impact Energy ($IE_{Prediction}$)

$IE_{prediction} = A_3 + B_3 + C_3 – 2y = 26.33 + 24.67 + 27.50 – 2 \times (24) = 30.50$

Trust interval

$$\eta_{eff} = \frac{9 \times 2}{1 + 6} = 2.57$$

$$CI = \pm\sqrt{F_{0.05;2;20} \times MS_e \times (\frac{1}{n_{eff}})} = \pm\sqrt{3.98 \times 4.57 \times (\frac{1}{2.57})} \pm 2.66$$

$$IE_{prediction} = 30.50 \pm 2.66$$

4 Conclusion

Optimum heat treatment parameter that gives powerful effect to hardness is austenite temperature 900ºC (austenite holding time 45 minutes) and temper temperature 125ºC with hardness prediction 569.96 HVN (536.00 BHN).

Optimum heat treatment parameter that gives powerful effect to impact energy are austenite temperature 900ºC (austenite holding time 45 minutes) and temper temperature 175ºC with impact energy prediction 30.50 Joule.

Acknowledgements

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