Загартована і відпущена сталь класифікується як сталь високої міцності і твердості, в основному використовується для броні. Твердість і зносостійкість необхідні для стандартів якості сталевої броні. З іншого боку, температура аустенізації і відпуску впливає на ударну в'язкість поглиненої енергії і зносостійкість загартованої і відпущеної сталі. Мета цього дослідження – оцінити вплив аустенізації і часу витримки на енергію і твердість гарячекатаної листової сталі. Матеріал для дослідження являє собою гарячекатану плиту виробництва Krakatau Steel Indonesia Company Limited з вмістом вуглецю близько 0,29 %. Використовуваний метод полягав в нагріванні трьох зразків при 900 °C (витримка 45 хвилин), 900 °C (витримка 30 хвилин) і 900 °C (витримка 15 хвилин), і всі вони охолоджувалися в воді після закінчення нагрівання. Три зразки нагрівали при 885 °C (протягом 45 хвилин), 885 °C (протягом 30 хвилин) і 885 °C (протягом 15 хвилин) і охолоджували в воді. Три зразки нагрівали при 870 °C (витримували 45 хвилин), 870 °C (витримували 30 хвилин) і 870 °C (витримували 15 хвилин) і охолоджували в воді. Потім остаточне охолодження дев'яти зразків проводили при 150 °C протягом 30 хвилин і охолоджували до температури навколишнього середовища. П'ять зразків перевірені на твердість за Шарпі і Вікерсом. Потім їх розташовували в ортогональних матрицях; розраховували ступені свободи; відношення сигнал/шум, квадратичні параметри; середній квадрат відгуку; відношення середнього квадрата відгуку джерела до похибки; параметри вносяться; прогностичну цінність і довірчий інтервал. З наведеного вище розрахунку виходить, що параметри термічної обробки мають сильний вплив на енергетичний вплив і питомий знос. Найбільш впливовим параметром енергетичного впливу є температура відпуску, оскільки цей параметр є пом'якшенням, спричиненим зниженням залишкової напруги, викликаного попереднім процесом охолодження. Дрібнозерниста структура збільшує міцність і енергетичний вплив прямим чином

Ключові слова: крихкість, пластичність, твердість, нагрів, витримка, удар, гарт, відпуск, вода, знос

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EFFECT OF AUSTENITE TEMPERATURE AND HOLDING TIME TO IMPACT ENERGY AND WEAR ON HRP STEEL

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1. Introduction

Quenched and Tempered Armor Steel (Q&T Armor Steel) widely used in the military because of its high hardness and strength; good weight; good toughness ratio; excellent ballistic penetration resistance [1–6].

Refinement the microstructure of quenched & tempered martensitic steels expected to increase strength especially final toughness [7]. One significant property for armor steel is wear related to hardness, fracture resistance, and thermal stability for high-temperature wear [8]. Smoother surfaces produce a lower coefficient of friction [9]. Adequate toughness is needed to avoid the tendency to crack and disintegrate materials [10]. The steel armor, which has the highest ballistic resistance, is AISI 4340, with 50 HRC (Hardness of Rockwell Cones)=485 BHN (Brinel Hardness Number) [11].

Therefore, this research is devoted to finding the optimum value of austenite temperature, holding time and tempering temperature on the amount of impact energy absorbed, and wear hot rolled steel plate as-quenched and temper armor steel.

2. Literature review and problem statement

The distortion that occurs during martensitic platelet formation leads to an increase in the strength and hardness [12]. Because during the quenching process, there is also shrinkage by compressive residual stress, that causes inter-structure close together, known as mechanical hardening. Hardness increase caused by fully martensitic structures only determined by the carbon content (low carbon steel), and this is equal to the maximum hardness of the steel [13]. Maximum hardness is metallurgical hardness; increased hardness can occur with compressive residual stress. The microstructure is the main factor that affects hardness when fully austenitized by increasing cooling speed and decreasing the temperature of the phase transition is microstructure (microhardness increases gradually) [14]. The brittle martensite properties have lower wear resistance [15]. Coarse martensites reached in the austenite zone, which is getting further away from the Ar_3 transformation line. With the increase of quenching temperature, the content of retained austenite initially increased, gradually reached a maximum and then decreased again whereas the carbon concentration in the retained austenite showed an opposite trend with the content of retained austenite [16, 17]. While, spheroidizing heat treatment processes can be used to reduce wear in ultra-high carbon steel [18]. Because of spheroidizing cause a more homogeneous structure. Meanwhile, to maintain martensite and only reduce residual stress, forging is done at 150 °C [19]. Heating to this temperature not defuse martensite, providing that is below the martensite finish temperature. The shape of the fine grain structure approaches the ball; in this study, obtained from austenitization close to the Ar_3 line produces fine austenite [20]. The fine-grained structures considered to have a spherical structure so that its elasticity and strength increase. The hardness decreases with increasing temper temperature, which produces a corresponding increase in penetration depth [21]. Before and after tempering, heterogeneous and homogeneous microstructures respectively. Homogenous structures cause the hardness is homogenous [22]. Temper almost does not affect the texture of the steel [23]. The optimal combination of austenite and fine carbide grain sizes increases absorption energy, and fine austenitic grain sizes obtained previously at low temperatures, and fine carbide deposits at low tempering temperatures [24]. The optimal combination of austenite and fine carbide grain increases absorption energy, and fine austenitic grain sizes obtained previously at low temperatures and fine carbide deposits at low tempering temperatures [25]. Absorption of the energy steel depends on the percentage of carbon elements contained to a certain extent, and lower carbon content has higher energy absorption and is suitable for components that need to absorb energy impact [26]. Impact and fracture toughness increase significantly with the increase in quenching temperature [27]. Here the impact energy has a relation with a grain size that will affect the toughness and impact energy absorbed. Heat-treated steels improve service conditions, especially in fatigue resistance [28] and are suitable for continuous heat exposure.

3. The aim and objectives of the study

The study aims to obtain the effect of austenite temperature and holding time to impact energy and wear on steel plates used for armor steel.

To achieve this aim, the following objectives are accomplished.

– conduct test for Charpy impact and specific wear used as the response of selected heat treatment parameters;

– determine the contribution of the heat treatment parameter for impact energy;

– determine the contribution of the heat treatment parameter for specific wear.

4. The formula used in research

4. 1. Impact Energy

The Charpy impact test is a high strain rate test that determines the amount of energy absorbed by a material during a fracture and determined by [22],

$$E = W \times R \times (\cos\beta - \cos\alpha), \quad (1)$$

where E – energy absorbed; R – hammer center distance; W – hammer weight; α – actual capacity lift angle; β – angle after contact.

4. 2. Wear

Specific wear (SW) is the material wear rate; wear rates tested using swivel disk friction on the content, and the test is carried out using the Ogoshi method (Fig. 1 shows the intended test scheme). The specific wear of the tested material and determined using the following formula, [29]

$$SW = \frac{B^2 \times b_o}{8r \times P_o \times L_o}, \quad (2)$$

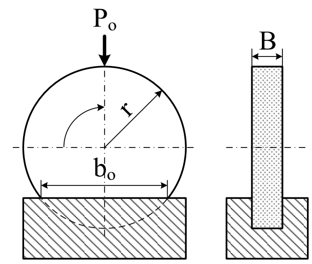

Fig. 1. Scheme of Ogoshi wear test: B – width of revolving disc; b_o – wear length; r – radius of disc; P_o – load; L_o – abrasion distance

Quench and temper parameters is used as a basis to determine the impact of energy absorbed and wear which were done by conducting the following steps: The first step is done by determining the quench and temper heat treatment parameters, levels, and orthogonal matrix. Then, the second step is through the application of quench and temper heat treatment to HRP Steel is followed by testing for impact and wear (after heat treatment is complete).

4. 3. Experimental Design by Taguchi and ANOVA – Analysis of Variance

The third step is processing the test results using Taguchi and ANOVA methods to find out the effects of quench and temper heat treatment parameters on the impact energy absorbed and wear.

The fourth step or the last step is conducting calculation to predict the optimum impact and wear value using based on quench and temper heat treatment parameters.

The orthogonal matrix of this research is obtained [30] using the following formula (3):

$$OM = L_a\left(b^c\right), \quad (3)$$

where OM – orthogonal matrix; L – latin square; a – number of row; b – number of level; c – number of column.

Standard values for the 3-level matrix are $L_9(3^4)$, L_{27}(313), L_{81}(340). Furthermore the used standard 3-level orthogonal matrix value must have a degree of freedom equal to or more than the degree of freedom of the experiment. Such determination of used value is necessary to determine the level of freedom of the experiment to be carried out by equation (4),

$$DF = N_F \times (N_L - 1), \quad (4)$$

where DF – degree of freedom; NF – number of factor; NL – number of level.

Using equation (4), in this study, DF is obtained 6, so the orthogonal matrix design is $L_9(3^4)$, which has 8 DF. The design parameters+level shown in Table 1, and the orthogonal matrix are in Table 2. Then the orthogonal matrix that has been prepared is processed using the Minitab software.

Table 1

Parameter design and level

Factors	Levels		
	1	2	3
Austenite (°C)	870	885	900
Holding (minutes)	15	30	45
Tempering (°C)	125	150	175

Table 2

Heat Treatment

Experi-ment	Austenitization (°C)	Austenite Holding Time (Minutes)	Temper Temperature (°C)
1	870	15	125
2	870	30	150
3	870	45	175
4	885	15	150
5	885	30	175
6	885	45	125
7	900	15	175
8	900	30	125
9	900	45	150

The test result data is processed using the Taguchi method to get the optimal combination of parameters and levels and to predict the response value. The first step is determining the effect of each parameter on the resulting response. This process begins by calculating the average response of each effect parameter on the resulting response, and the average response of each experiment as well as the value of the S/n ratio from the test data. S/n ratio was calculated using the following equation.

$$\eta = -10Log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right], \quad (5)$$

where n – frequency of sample.

Process begins by calculating the average response of each effect parameter on the resulting response, and the average response of each experiment as well as the value of the *S/n* (The ratio of signal intensity to noise intensity) ratio from the test data.

From the average results and the *S/n* ratio, responses, and average ratios obtained. To obtain the order of the effect parameters on the resulting response, calculated the average value of the test results and the *S/n* ratio at that temperature.

After knowing the effect of each parameter, the next step is to determine whether or not the parameter significantly influences the response generated using ANOVA. These calculations were based on the idea that in experiments with some tests, the v will be equal to n, whereas many (level-1) n degrees of freedom are influenced by the testing parameters, and other factors influence the rest. ANOVA calculation starts with counting the sum of the Total Square, Average Square, square parameter, and square error. This calculation used the following equations (6) to (8),

$$S_{Total} = \sum Response^2, \quad (6)$$

where S – square;

$$S_{mean} = n \times \left(response_{mean}\right)^2; \quad (7)$$

$$S_{parameter} = \frac{\left[response_{level-1}\right]^2}{a} + \frac{\left[response_{level-2}\right]^2}{a} \quad (8)$$

and

$$S_{error} = S_{total} - S_{mean} - S_{parameter_1} - \ldots S_{parameter_n}. \quad (9)$$

Response level n is the total number of responses because the level n parameters reviewed, and a is the number of replications in the test. These values were measured to calculate the average value of the squares of the response and F_{ratio}. Value calculation was performed using equations (8) and (9),

$$MS = \frac{S_{source}}{v_{source}}, \quad (10)$$

$$F_{ratio} = \frac{M_{source}}{M_{error}}, \quad (11)$$

where M – mean square; v – level of freedom.

The number of DF for a parameter is the number of level-1. Only 1 degree of freedom has an average square value, while the value of the square of error has all the remaining degrees of freedom. Then, F_{ratio} value was compared to the total value, which is the F_{ratio} value of all parameters at a certain level of significance α. α is the research probability to invalidate the null hypothesis (whether the research parameters affect the response generated or not). If the $F_{ratio} \leq F_{total}$, the parameter does not have a significant effect on response. If $F_{ratio} > F_{total}$, the parameter has a significant effect on the response. The final step was to calculate the contribution (p %) of each source to the response generated. The calculation of the contribution of parameters was not compared to the average value of the square. Equations (10) and (11) used to calculate the contribution of each parameter, and then get:

$$S_t = S_{total} - S_{mean} \quad (12)$$

and

$$p\,\% = \frac{S_{source}}{S_t} \times 100\,\%. \quad (13)$$

The final step in optimization using the Taguchi method is determining the optimal predictive value. In addition to the predicted value, the value of the confidence interval was calculated to measure the deviation of the predicted value. Prediction values and confidence intervals were calculated using equations (12)–(14).

$$Value_{Prediction} = response_{mean} + \left(parameter_{mean} - response_{mean}\right) + \left(parameter\ n_{optimum} - response_{mean}\right). \quad (14)$$

Confidence of Interval calculate by,

$$CI = \sqrt{\frac{F_{total} \times M_{pooled\_error}}{\eta_{eff}}}. \quad (15)$$

Number of effective calculated by,

$$\eta_{eff} = \frac{Total_{test}}{Total_{DF}\ on\ mean\ prediction}. \quad (16)$$

Then the response value is determined as,

Value=Predicted value±CI.

The specific impact and wear energy change due to heat treatment parameters and the level used.

The study began with a literature study, an experimental design of the Taguchi method, then making a specimen and continued with quench and temper heat treatment. In addition, heat-treated specimens subjected to wear and impact tests. After that, test data is processed using Taguchi and ANOVA to determine the essential parameters and the order of their effects.

The final step of this study was to calculate the optimal predictive value of impact strength and wear resistance based on obtained essential parameters.

5. Material and Method

5. 1. Material

The material of this research is HRP Steel (Hot rolled plate steel with 8 mm thick and element content, as shown in Tables 3, 4 with 8 mm thick) made by PT. Krakatau Steel (Persero), Cilegon, Banten province, Indonesia.

Table 3

Chemical composition of hot rolled plate steel [31]

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

Table 4

Temperature, hardness and wear of HRP Steels

Ar_3 (°C)	M_S (°C)	M_F (°C)	Hardness (HVN)/BHN	SW (mm²/kg)
765	357	182–192	288/273	7.34×10^{-9}

5. 2. Method

The research method consisted of:

a) Heating the specimen to austenite temperature and held for the selected time, and after heating is complete, each sample is cooled into fresh and cleaned water medium.

b) The specimens heated to 150 °C, held for the selected time (such as 15 minutes, 30 minutes. And 45 minutes), then cooled in atmospheric air.

c) Prepare the specimens for hardness, impact test, and wear test on heated treated HRP Steel. Impact testing conducted using the Charpy Impact method. Test specimens of quenched and tempered steels machined, as shown in Fig. 2.

d) Conduct Charpy and wear impact tests, and each impact energy data is absorbed and used. The data obtained arranged into an orthogonal matrix and processed according to Taguchi and ANOVA using Minitab software.

e) After completing point d), the discussion and conclusion are carried out, and conclusions made.

6. Discussion of experimental results

The impact energy and wear for average, and *S/n* ratio shown in Table 5. Impact average and *S/n* response for austenitization, held time, and temper show in Table 6.

For wear shown in Table 7 the result of ANOVA processing for the impact test is shown in Table 6, and for wear test is shown in Table 8.

Based on the results of the average response and the *S/n* ratio, temperature of temper has the highest effect on impact energy (Table 5). High temper temperature affects the amount of residual stress tanpa mendefusikan martensite. The fact that the M_F temperature of HRP Steel is 167.5 °C at level 3 is 175 °C, expected that martensite will not turn into austenite. Tempering this temperature is reducing the residual stress resulting from the previous quenching. The decrease in residual stress will increase the distance among structures so that there is a decrease in hardness due to a decrease in structure density. Tempering also increases ductility, which also directly increases toughness, and is very suitable for the needs of components that require absorption of impact energy (such as absorption of impact energy due to ballistic impact on armor steel).

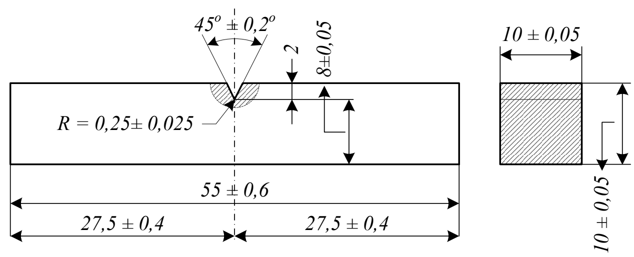

Fig. 2. Charpy Impact Specimen based on ASTM E

Table 5

Average results of impact and wear testing and with *S/n* ratio

Specimen	1st test		2nd test		Average		*S/n* Ratio	
	Impact Energy	Wear $\times10^{-7}$	Impact Energy	Wear $\times10^{-7}$	Impact Energy	Wear $\times10^{-7}$	Impact Energy	Wear
1	20.00	1.69	18.00	1.97	19.00	1.83	25.54	134.74
2	20.00	1.56	21.00	1.69	20.50	1.62	26.23	135.80
3	22.00	1.82	25.00	1.56	23.50	1.69	27.37	135.42
4	21.00	2.28	24.00	2.28	22.50	2.28	26.99	132.85
5	29.00	1.97	30.00	2.12	29.50	2.04	29.39	133.79
6	23.00	1.56	21.00	1.97	22.00	1.76	26.82	135.02
7	29.00	2.12	30.00	2.44	29.50	2.28	29.39	132.82
8	22.00	2.44	20.00	2.12	21.00	2.28	26.41	132.82
9	28.00	3.84	29.00	1.82	28.50	2.83	29.09	130.44

Table 6

Average and response *S/n* impact

Level	Austenitization		Hold time		Temper	
	R_{mean}	$RA_{S/n}$	R_{mean}	$RH_{S/n}$	R_{mean}	$RT_{S/n}$
1	21.00	26.38	23.67	27.31	20.67	26.26
2	24.67	27.73	23.67	27.34	23.83	27.44
3	26.33	28.30	24.67	27.76	27.50	28.72
Difference	5.33	1.92	1.00	0.45	6.83	2.46
Rank	2		3		1	

Austenite temperatures have the most significant influence on the wear, as shown in Tables 6, 7. The austenite zone is related to the martensite needed to obtain a low coefficient of friction. Wear resistance needs a low coefficient of friction when the size of the grain structure is small size. When heating to austenite temperature close to the Ar_3 line, the small austenite structures obtained, and after quenching is finish, it produces fine martensite. With fine martensite will increase hardness with better ductility. With a fine martensite structure, it reduces the coefficient of friction.

Table 7

Average response and response S/n wear

Level	Austenitization		Hold time		Temper	
	R_{mean} ×10^{-7}	*Resp. S/n*	R_{mean} ×10^{-7}	*Resp. S/n*	R_{mean} ×10^{-7}	*Resp. S/n*
1	1.71	135.32	2.13	133.47	1.96	134.19
2	2.03	133.89	1.98	134.14	2.24	133.03
3	2.46	132.03	2.09	133.63	2.00	134.01
Difference	0.75	3.29	0.15	0.67	0.28	1.16
Rank	1		3		2	

Table 8

ANOVA for impact test

Source	S_{Source}	ν	M_{source}	F_{Ratio}	F_{Total}	Contribution, %
Austenitization	44.67	2.00	22.34	14.70	3.98	33.46
Holding	2.00	2.00	1.00	0.66	3.98	1.50
Tempering	70.16	2.00	35.09	23.09	3.98	52.56
Error	16.67	11.00	1.52	–	–	12.48
Total-1	133.50	17.00	–	–	–	100.00

The heat treatment parameter that is most influential on wear is the austenite temperature. The larger austenite grain size causes a decrease in hardness and brittle because the higher austenite temperature causes grain growth to occur. After knowing the order of the effect of parameters on the responses generated in each test-data processed, uses ANOVA. Therefore the role of temper is critical in efforts to increase ductility, which directly slightly reduces hardness.

Table 7 shows the ANOVA of the impact test data from equations (7) to (14). Based on ANOVA, the impact test and austenitization have: F_{ratio} (14.70)>F_{Total} (3.98), holding time has F_{ratio} (0.66)<F_{Total} (3.98). For the impact value, the first contribution gave by the tempering effect. Temper affects hardness and ductility. Austenite temperature affects the value of hardness and ductility if done above near the Ar_3 line. Holding time affects the homogeneity of the grain structure and thickness.

Impact energy, the optimal significant parameter is temper temperature at level 3, and austenite temperature at level 3. In wear resistance, the significant optimal parameters are the austenitization temperature at level 1, and the tempering temperature at level 1. Because the research data obtained by one parameter is not essential for impact energy and wear resistance, these parameters combined into error parameters in ANOVA calculations. Therefore, the new M_{pooled_error} value is 1.44 for the impact test, and 0.478 10^{-14} for the wear test.

In the austenite temperature, wear test data (Table 9) has F_{ratio} (34.91)>F_{total} (3.98), holding time has F_{ratio} (1.84)< <F_{total} (3.98), tempering temperature has (4.98)>F_{total} (3, 98). Tempering temperature has F_{ratio} (23.09)>F_{total} (3.98).

Table 9

ANOVA for wear test

Source	S_{Source}, ×10^{-14}	v	M_{Source}, ×10^{-14}	F_{Ratio}	F_{Total}	Contribution, %
Austen.	8.867	2.00	4.434	34.91	3.98	73.89
Holding	0.467	2.00	0.234	1.84	3.98	3.89
Tempering	1.266	2.00	0.633	4.98	3.98	10.55
Error	1.400	11.00	0.244	–	–	11.67
Total-1	12	17.00	–	–	–	100.00 %

Using equations (13)–(15), the predicted optimal impact energy and specific wear values are 29.83±1.262 J or 3.8±0.268 kg/cm^2 and (1.60±0.73)×10^{-7} mm^2/kg obtained respectively. The value of energy impact exceeded to wear-resistance steel.

Changing the quench and temper heat treatment parameters will change the impact of absorbed energy and wear of metals. These parameters include austenite temperature, austenite containment time, and forging time.

Wear and hardness both are related; materials with more delicate grain structures have higher surface energy and higher strength directly than coarser grain structures of material. Wear resistance produced by materials with delicate microstructures, which means the friction coefficient of finely structured materials, is lower than the rugged grain structure. Hardness increases significantly when the metals dominated by martensite. Fine Austenites obtained close to the Ar_3 transformation line (but still above the Ar_3 line), and after fat cooling (in this study), it produces fine ductile martensite. Martensitic affects the value of wear and hardness.

At higher austenitization temperatures, there is little effect on grain size or mechanical properties. Slow heating of austenite grain size in undeformed material by allowing discontinuous grain growth occurs. Slow heat does not coarsen the austenite grain size of deformed metal.

The use of steel for armor must have the right combination between hardness and strength. The hardness needed to resist the projectile, the hardness needed, and flexibility acts as a crack barrier. Power is necessary when undergoing the manufacturing process, such as the bending process.

Any changes in austenitic temperature, holding time, and temperature will affect the impact of energy value and wear. The best impact energy and wear values obtained by optimizing the heat treatment parameters using the Taguchi and ANOVA methods.

The research results are based on three heat treatment parameters that affect the impact of energy and the specific wear of nine experiments with three levels. The research will be more accurate if the chosen level is more than three (for example, heating rate, austenite temperature, holding time, and tempering temperature, and so on). The amount of data is more, but the cost is expensive. But that can produce the effect of the selected heat parameter on the chosen response.

7. Conclusions

1. Charpy impact values and specific wear of nine experiments are (19.00–29.50) J and (1.62–2.83)×10^{-7} mm^2/kg respectively.

2. The calculation of contribution to impact energy includes tempering temperature, austenitization, and austenite holding time. These are 52.56 %, 33.46 %, and 1.50 %, respectively. The tempering temperature reduces the residual stress that density decrease and ductility increases to inhibit the crack. Prediction values of optimal impact energy 3.8±0.268 kg/cm^2.

3. The calculation of contribution to wear includes austenitization, tempering temperature, and holding time are 73.89 %, 10.55 %, and 3.89 %, respectively. The water quench of fine austenite produces the fine martensite that reduces in friction coefficient and increases. Prediction values of optimal specific wear values are (1.60±0.73)×10^{-7} mm^2/kg.

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