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Parameter Optimization of Heat Treatment on AISI 4140 Material Hardness Value for Bucket Teeth Application Using Taguchi Method

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Abstract: In material aspect, AISI 4140 steel is categorized into low alloy steel or steel having alloy ≤2.5 %. AISI 4140 is mostly used in components requiring good mechanical properties such as bucket teeth excavator. However, hardness value of AISI 4140 material does not fulfill standard of bucket teeth (40 HRC). This is why this research using Taguchi method aiming to search optimum hardness value based on its heat treatment is conducted. Several factors influencing hardness value of AISI 4140 are hardening temperature (830, 850 and 880°C), holding time (30, 45 and 60 min), quenching media (oil, water, salt water) and tempering temperature (400, 500 and 600°C). From calculation using Taguchi method, optimum conditions in every level of factors are hardening temperature is 830°C, restraint duration is 45 min, quenching media is oil and tempering temperature is 400°C. Besides from ANOVA calculation, factors influencing ASI 4140 material hardness value are tempering temperature (96%) and quenching media (1.5%). The result of confirmation experiment reveals that hardness value of test result having optimum condition is 46.03 HRC. Mechanical properties of AISI 4140 material obtained from test result with optimum condition is 1515.745 N/mm^2 % elongation is 12.7% and impact strength is 5.67 kg/cm^2.

Key words: AISI 4140, bucket teeth, hardness, heat treatment, Taguchi, optimum, condition

INTRODUCTION

In now a days living, there are so many advancements in field of science and technology. It is compelety, so because the growth of science is demanded due to the fact of tight competition and needs of society which become more complex. From that fact, scientists attempt to make and look for a new method to fulfill and solve that condition while education practitioners also do the same thing in oder to add ideas and new nuances in terms of education which is needed by market. Moreover, in the momentum of global market, a competition regardless of seeing who how and where is demanded while the most important thing is facing and winning the competition in the global market itself as stated by Shaikh and Mulla (2015).

To anticipate the growth of development activities and to prevent human resources limits now a days, therefore, several alternatives of equipment as well as its supporting tools are needed to fulfill the needs, both from its quality aspect and from its capacity aspect. The needs of heavy equipment have been growing widely in several aspects adjusted with functions and capacity of the heavy equipment according to Tupkar and Zaveri (2015). Excavator is one of heavy equipment which is commonly used in construction, mining and other research requiring heavy elevation if it is done by human. Excavator comprises of some sizes and forms. As time goes by excavator is equipped with loader and buldozer in order to be able to perform many functions at once. Excavator has mover system which uses wheel chains (designated route) while some use wheel as stated by Ghodake and More (2015). In excavator, the part used for digging and loading material is called bucket excavator as stated by Mashloosh and Eyre (1985).

Bucket teeth is one of important parts of excavator. Bucket teeth functions as material digger. Besides, Deere by Deere and Bucket Tooth Catalogue stated that bucket teeth itself is divided into some components and the components can be divided into some subparts such as, bucket, adaptor and teeth. Bucket excavator is made from solid steel and it commonly has tooth protruding on cutting edge. Excavator bucket tooth must be able to get heavy load from material like wet soil and stone and must experience wearing because it is abrassive from soil particle when trying to break the material as stated by Dagwar and Telrandhe (2015). According to Hensley this bucket teeth will experience direct contact with soil during

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the use, so that, it gets quite high impact loading, therefore, the material used to make components of bucket teeth must have endurance properties on wearing, strength and tenacity which are quite high. One of bucket teeth commony used is mild carbon steel with its composition is about 0.33-0.5%. However, according to Gabor and Sumegi (2012), the material is not able to restrain loading and the hardness of material loaded on the bucket teeth of excavator.

Heat treatment can be a method to change physical properties and chemical properties of a material. It is commonly used in metal. Heat treatment involves heating and cooling on extreme temperature, then it is cooled by control which causes change of micro structure, so that, it can modify its properties. It is significantly needed to understand heat treatment in order to be able to make material properties in accordance with the expected needs as stated by Kumar *et al*. (2016).

Analysis of Variance (ANOVA) can be a method to analyze information in order to comprehend the explication of parameter variation among the information. The purpose is to know the result of several variations of heat treatment on medium carbon steel by analyzing heat treatment parameter. Technique utilized in this present research is Taguchi method made by Genichi Taguchi. Taguchi focuses on making technique to analyze variance in a simple method. This method is frequently used as a fixing method. In this case, this method is used to be able to understand how variation of heat treatment influences medium carbon steel as stated by Verma and Singh (2013).

MATERIALS AND METHODS

The stage of this research is to determine the experiment combination by using heat treatment process and to analyze it by using Taguchi method and ANOVA. The result of the best combination requires the test of its mechanical properties such as hardness test, micro structure test, tensile test and impact test. It is based on the flow of diagram shown in Fig. 1.

It has been stated previously that experiment method used is Taguchi method. Two main purposes that can be achieved from design of Taguchi experiment are to minimize various processes or products and to obtain robust and flexible design toward environment condition. Besides, two ways utilized in this parameter design are orthogonal array and S/N ratio. Orthogonal array is designed to study some parameter designs at once and can be used to estimate influence of every independent factors towards other factors. The function of orthogonal array is to provide layout of experiment that must be done. S/N ratio is the indicator of simple quality in which a researcher or a designer can evaluate the change effects of every parts of parameter design on a process or a product. S/N ratio is used with the purpose to minimize the sensitivity of quality characteristics. S/N ratio has superiority which is when the target value is changed, the optimum condition obtained by maximizing S/N ratio will stay valid. The steps of this present research are according to Raok (2013).

Selection of quality characteristics: The goal of this present research is to obtain higher material hardness through heat treatment process. Thus, the chosen quality characteristic is “Larger is better”.

Selection of controlled factor and free factor: In this research, controlled and free factors are chosen such as heating temperature, holding time, quenching media and tempering temperature. Its response is by using hardness with HRC scale. Table 1 is the parameter design (factor) and level of Taguchi.

Selection of orthogonal array: There are four parameters observed in this experiment in which every parameter consists of three levels. By calculation of degree of freedom of every factors, it is obtained result having 8° of freedom, so that, orthogonal array which has similar or higher degree of freedom is chosen as stated by Bhattacharya *et al*. (2009). In this research, orthogonal array L_9 (3^4) is selected as shown in Table 2.

Selection of material: AISI 4140 material, based on chemical composition is included into chromium molybdenum steel. This steel can get heat treatment with

Table 1: Material composition of medium carbon steel

	Level			
Parameters	1	2	3	Research result
Heating temperature	830	850	880	Hardness (HRC)
Holding time	30	45	60	
Quenching media	Oil	Water	Salt water	
Tempering temperature	400	500	600	

Table 2: Implementation of orthogonal array L9 experiment

	Controlled factors			
No. of trials	Heating temp. (°C)	Holding time (min)	Quenching media	Tempering temp. (°C)
1	830	30	Oil	400
2	830	45	Water	500
3	830	60	Salt water	600
4	850	30	Water	600
5	850	45	Salt water	400
6	850	60	Oil	500
7	880	30	Salt water	500
8	880	45	Oil	600
9	880	60	Water	400

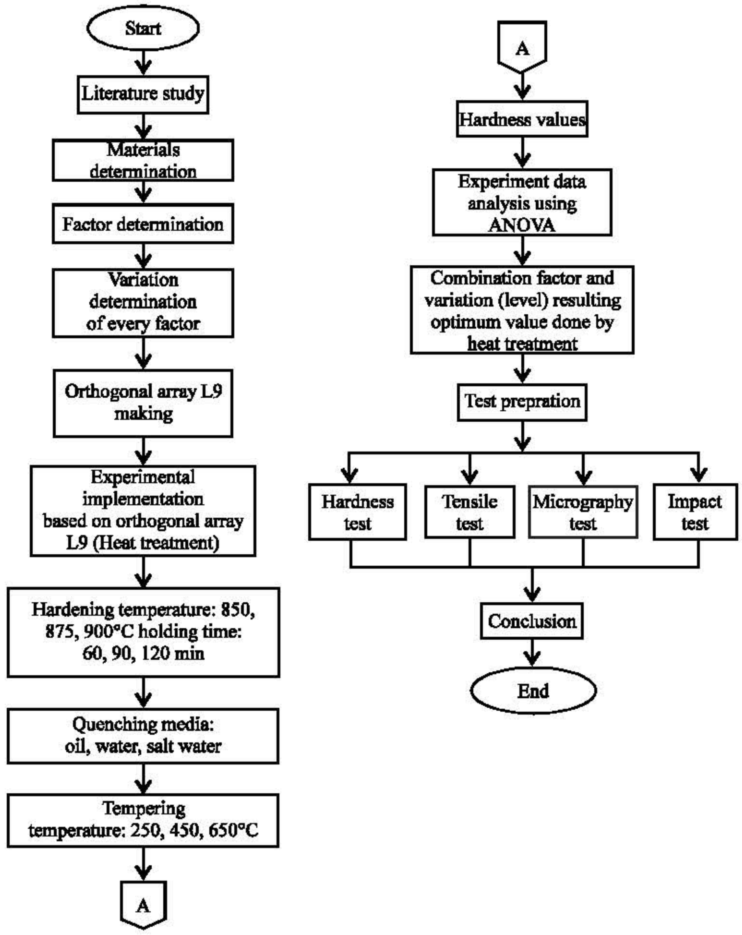

Fig. 1: Research flow diagram

Table 3: Material composition of AISI 4140 (%)

Fe	C	Si	P	Mn	Mo	Cr	S
96.97	0.40	0.34	0.01	1.03	0.24	1.00	0.01

quenching some media. This steel also can be used in high temperature but its strength will decrease fast in accordance with the increase of temperature. AISI 4140 material is provided in form of bar, wrought, sheet, plate, strip and castings. Furthermore, according to Berger and Berger (2002), AISI 4140 material is used on high-power machine like connecting rods, crankshaft, axles, piston rod, wrench and sprocket. Moreover, Table 3 explaining chemical composition of AISI 4140 is utilized in this research.

Experiment implementation: It is needed to provide 9 specimens which have different treatments. Specimens will pass hardening process phase with 850, 875, 900°C temperature, then it is held about 60, 90 and 120 min followed by fast cooling of quenching process using different cooling media such as oil, water and salt water. After quenching process, the next process is tempering process on 250, 450 and 650°C temperature. After conducting heat treatment process, the next is hardness test by using Rockwell hardness tester with three times replication. After experiment data are collected, then data analysis using ANOVA is done (ASTM E8M-08, 2008).

Theories

Heat treatment: Heat treatment is the combination process between heat and cooling controlled in metal or alloy in form of solid with purpose to obtain the expected material properties. According to Senthilkumar and Ajiboye (2012), heat treatment is divided into three parts, the heat process on certain temperature, heat holding (Table 4) (ASTM E8M-08, 2008).

Hardening is the heat treatment to harden steel. This process is conducted in furnace by heating steel in certain temperature on austenisation temperature then it is held on that temperature for quite long to make sure the heat uniformity and in order that all carbon turns into austenit

Table 4: Hardness test result

Trials	Heat temp.	Hold time	Quench media	Temper. temp.	Hardness 1	Hardness 2	Hardness 3	Mean	S/N ratio
1	830	30	Oil	400	45.0	46.4	46.3	45.9	33.2337
2	830	45	Water	500	39.0	41.0	40.5	40.2	32.0714
3	830	60	Salt water	600	33.1	33.2	34.2	33.5	30.4981
4	850	30	Water	600	33.5	33.0	33.1	33.2	30.4222
5	850	45	Salt water	400	42.5	45.0	45.0	44.2	32.8924
6	850	60	Oil	500	40.2	40.5	40.0	40.2	32.0914
7	880	30	Salt water	500	40.0	39.0	38.0	39.0	31.8156
8	880	45	Oil	600	34.0	35.0	34.5	34.5	30.7546
9	880	60	Water	400	44.3	45.1	45.0	44.8	33.0247

phase and then the steel is taken from furnace and given quenching by using right cooling media as stated by Daramola *et al*. (2010).

This research uses quenching media in form of water. Water can be used to cool heated steel with fast cooling flow. However, according to Zhen, water tends to absorb gases on air. When heated steel is cooled these gases tend to form bubbles on steel surface, so that, it can cause a hole which leads to crack.

Taguchi method: Taguchi method is a method used to change or to fix productivity during research and development in order that the high quality product can be made fast with low cost as stated by Montgomery (2009). According to Besterrfield (2003), there are two main phases of Taguchi method which are parameter design method and tolerance design. In general, Ross (1996) stated that the application of Taguchi method is only done until parameter design phase. It is caused by the setting of component tolerance on tolerance design will lead to manufacturing cost increase.

Taguchi method is a designing method focusing on quality improvement by reducing effects of variation without eliminating its causes. This can be otained through product optimization and process design to make strong performance towards some causes of variation of a product called parameter design as stated by Qasim *et al*. (2015). Taguchi uses a set of special matrix namely orthogonal array. This standard matrix is the step to determine a sum of minimum experiment that can give more information about all factors influencing parameter. According to Unal and Dean (1991), the main important part of orthogonal array is on selection of level combination of input levels for each experiment. In selecting the orthogonal array adjusted with experiment, it must be noted that the degree of freedom on standard orthogonal matrix should be higher or same as the calculation of degree of freedom on experiment as stated by Montgomery (2009) which is shown in Eq. 1:

$$\text{Degree of freedom} = (\text{The number of factor})\times(\text{The number of level-1}) \quad (1)$$

S/N ratio (Signal-to-Noise ratio) is used to choose factors which have contribution on reducing variation of a response. S/N ratio is a design to transform data replication into a value which is the caused variation size. S/N ratio is used to know which factor levels that influence the experiment result. S/N ratio comprises of some quality characteristics types which can be seen in Eq. 2-4 lower the better:

$$\frac{S}{N}R = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (2)$$

Leading to certain value:

$$\frac{S}{N}R = 10\log_{10}\frac{\mu^2}{\sigma^2} \quad (3)$$

Larger the better:

$$\frac{S}{N}R = 10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (4)$$

ANOVA: Analysis of variance is the calculation technique that enables to estimate contribution quantitatively of each factors on all response measurement. Analysis of variance that is used on parameter design functions to identify factor contribution, so that, model estimation accuracy can be determined as stated by Montgomery (2009). When analysis of variance has been used on a set of data and a number of squares has been counted, then this data can be used to divide sum of squares with relevant factors. By comparing these values towards total sum of squares, percent of contribution of each factors can be obtained. From this analysis of variance result, relative strength of a factor and/or an interaction to minimize variation can be known as well. Percent of contribution (r) can be calculated by using Eq. 5 and 6:

$$SS' = SA-VA.Vc \quad (5)$$

$$rA = \frac{SA'}{St} \times 100\% \quad (6)$$

Confirmation experiment: The purpose of this confirmation experiment is to conduct validity towards the obtained conclusion of every analysis phases. This is needed to do if it uses investigation experiment with low resolution and has fractional factorial form. Prediction of optimum value is granted to give views about differences of how far the value that can be predicted compared to the test result value. By this prediction of optimum value, it can be known whether the value obtained from test result is still on the permitted tolerance (range) as stated by Sow (2014). Moreover, the formula of confirmation value and trust interval prediction can be seen in Eq. 7 and 8:

$$\text{Prediction} = \sum Y_{(\text{the best level})} \text{-} (Y_{mean} \times \text{Total of factors-1}) \quad (7)$$

$$Cl = \sqrt{F_{\alpha,\, vi,\, v2} \times MS_{error} \times \left(\frac{1}{neff}\right)} \quad (8)$$

RESULTS AND DISCUSSION

Result analysis of this research consists of analysis data result of S/N ratio, mean of response of Analysis of Variance calculation (ANOVA) and test result of AISI 4140 mechanical properties in optimum condition. The purpose of S/N ratio analysis is to know the level combination of the best factor in finding out the heat treatment optimum condition in order to obtain the highest hardness value.

Hardness test result: Hardness value as dependent variable which is known by this test, uses rockwell hardness tester with HRC scale in which the scale has 150 kgf loading and diamond cone penetrator as stated by ASTM E18 by Anonymous (2003). The test is done by three times replication on different test points.

Table 5: Mean response for every levels of each factors

Levels	Heating temperature	Holding time	Quenching media	Tempering temperature
1	39.87	39.37	40.20	44.97
2	39.20	39.63	39.40	39.80
3	39.43	39.50	38.90	33.73
Delta	0.67	0.27	1.30	11.23
Rank	3.00	4.00	2.00	1.00

Table 6: Response of S/N ratio for every levels of each factors

Level	A	B	C	D
1	31.93	31.82	32.03	33.05
2	31.80	31.91	31.84	31.99
3	31.86	31.87	31.74	30.56
Delta	0.13	0.08	0.29	2.49
Rank	3.00	4.00	2.00	1.00

Calculation result of signal to noise ratio and mean of response: After obtaining mean of value and S/N ratio in every trials, the next phase is finding out S/N ratio (signal to noise ratio) and mean of response. S/N ratio that is used is larger the better. The calculation result of S/N ratio and mean is shown in Table 5 and 6.

Table 5 and 6 show that the best combinations to obtain the optimum hardness value are on heating temperature with temperature 830°C condition, holding time for 45 min condition, Quenching media using oil and tempering with temperature 400°C. Those results are also shown on the highest point of Fig. 2.

Calculation result of ANOVA (Analysis of Variance): Analysis of variance is used to see the influences of each parameters towards hardness value. Table 7 is the calculation result using ANOVA.

From the table and the figure above, it is seen that the most influential factors on hardness value of medium carbon steel material are tempering temperature 96.1%, quenching media 1.15%, holding time-0.17% and the last is heating temperature 0.12%. From the table, it is known that only tempering temperature and quenching media that are influential, since, F-value>F-table ($F_{(0,05;2;18)}$ = 3.55).

Prediction of hardness value and confirmation experiment: Prediction of hardness value functions to predict hardness value of AISI 4140 in optimum condition and compare it to test result. Based on Table 6 in this case, the highest level is chosen on this optimum condition because its characteristics hardness which is larger is better.

Prediction of hardness value in optimum condition:

$$\begin{aligned}\text{Prediction of hardness values} &= \bar{y}+(A_2-\bar{y})+(C_2-\bar{y})+(D_1-\bar{y}) \\ &= A_2+B_1+C_2+D_1+\bar{y}-\bar{y}-\bar{y}-\bar{y} \\ &= A_2+B_1+C_2+D_1-3\,\bar{y} \\ &= 39.87+39.63+40.20+44.97-(3\times39.5) \\ &= 46.17 \text{ HRC}\end{aligned}$$

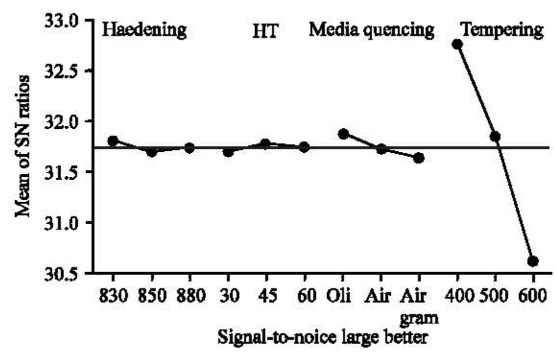

Fig. 2: Graph of S/N ratio with Minitab17 Software

Table 7: Analysis of variance of medium carbon steel hardness

Factors	df	Adj. SS	Adj. MS	F-values	SS	Percentage of contribution
Heating temperature	2	1.987	0.994	1.56	0.715	0.12
Holding time	2	0.272	0.136	0.21	-1.000	-0.17
Quenching media	2	8.023	4.011	6.31	6.751	1.15
Tempering temperature	2	567.967	283.984	446.83	566.695	96.1
Error	18	11.440	0.636	1	-0.008	2.8
Total	26	589.690	289.761	-	578.242	100

Table 8: Test of hardness in optimum condition

Measurement points				
1	2	3	Y-means	S/N ratio
46.00	46.10	46.00	46.03	33.261

Table 9: Tensile test result

	Strength (N/mm^2)			
Specimens	Lower yield	Upper yield	Tensile	Elongation (%)
1	432.133	1506.321	1506.321	13.10
2	452.011	1502.098	1502.098	13.80
3	444.224	1538.816	1538.816	11.30
Mean	442.789	1515.745	1515.745	12.73

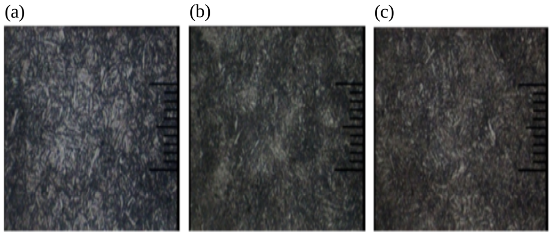

Fig. 3: Micro structure of AISI 4140: a) Raw; b) Hardening 830°C for 45 min with quenching media using oila and c) Hardening 830°C for 45 min with quenching media using oil accompanied by tempering on temperature 400°C

Trust intervel:

$$(n_{eff}) = \frac{\text{Sum of experimental total}}{1+\text{sum of degree of freedom mean}} = \frac{9\times3}{1+8} = 3$$

$$(Cl) = \pm\sqrt{F\ (0.05,\ 2,\ 8)\times MS_x\times\frac{1}{neff}}$$

$$Cl = \pm\sqrt{3.35\times0.636\times\frac{1}{3}}$$

$$= \pm 0.843$$

Prediction values = 46.17±0.843

Prediction of hardness value in optimum condition: From Table 8-10, it can be concluded that hardness value of test result is in line with prediction calculation of hardness in AISI 4140 material.

Table 10: Impact test result

Angle α (°)	Discharged energy (J)	Angle α (°)	Absorbed energy (J)	Width (mm^2)	Impact values (J/mm^2)
151.0	300	123.5	51.6	92.1	0.561
151.0	300	124.5	50.5	92.1	0.548
151.0	300	124.0	50.5	90.1	0.560
					0.566
Mean of impact value (J/mm^2)					

Table 11: Comparison of mechanical properties and test specimens and SNI 8050:2014

Variables	Hardness values (HRC)	Tensile strength (N/mm^2)	Elongation (%)	Impact strength (kg/cm^2)
SNI 8050:2014	≤40	≤800	≤5	≤2
AISI 4140 optimization result of heat treatment	46.03	1515.745	30.64	5.67

Mechanical properties of medium carbon steel material in optimum hardness condition

Test result of micro structure: Micrography test is given etching with 2% nital solution as stated by Oh *et al*. (2015). Test result of Microstructure shows that there is a phase change in AISI 4140 from raw material to every processes of heat treatment. In Fig. 3a, raw material which is not got heat treatment yet, reveals that the formed phases are Perlite (black or dark colored) and Ferrit (light colored). After doing hardening process with temperature 830°C and quenched with oil, then it forms Martensite micro structure (like needle) which is more dominant than Bainite (light colored). In the last phase, tempering process with temperature 400°C, Martensite phase is visible after the process of carbon diffusion occuring in metal.

Tensile test result: Tensile test utilizes Universal Testing Machine GD 1100-100 in Physical Metallurgy Laboratory of Mechanical Engineering in Diponegoro University. Specimens used is Rectangunal Subsize Specimens based on ASTM E23-02A by ASTM International (2002).

Impact test result: Impact test is conducted in Material Laboratory of Gadjah Mada University. Specimens used focuses on standard with Charpy Method by Anonymous (2015).

CONCLUSION

From experiment about optimization of hardness value in medium carbon steel using Taguchi method, it is concluded that. From experiment result, heat treatment that is done by using Taguchi method, then its best combinations are as follows, heating temperature with 830°C with holding time about 45 min accompanied by quenching media using water and tempering with temperature 400°C.

With ANOVA method, it can be known that factors influencing hardness value of AISI 4140 material significantly are tempering temperature and quenching media (F-ratio>F-table) in which F-table>F0, 05, 2, 18 (3.35) with $\alpha = 5\%$.

By employing ANOVA method, it can be known that the factors that influence hardness value most, based on its percentage of contribution are tempering temperature 96%, quenching media 1.15%, hardening temperature 0.12% and holding time-0.17%. Mechanical properties obtained from AISI 4140 material after being optimized are:

- The obtained hardness value is 46.03 HRC
- The obtained tensile strength is 1515.745 N/mm^2
- The obtained % elongation is 12.73 %
- The impact strength is 5.67 kg/cm^2

Mechanical properties obtained from AISI 4140 material after being optimized has fulfilled standard of bucket teeth SNI 8050:2014 as explained on Table 11.

SUGGESTIONS

Suggestions are used as evaluation of research in form of recommendation. These are some suggestions that can be given for further research:

- The next research can use more factor and factor level in order that the obtained hardness value or dependent variable is higher and more accurate
- The further research may give more replication of experiment result to obtain accurate and precise results

NOMENCLATURE

S/N×R	=	S/N Ratio
y_i	=	Hardness value
Ms_{error}	=	Variance of pooled error
n_{eff}	=	Total of effective observation
$F_{\alpha, v1, v2}$	=	Value of F-ratio from table
Adj. MS	=	Sum of squares divided by df
Adj. SS	=	Sum of Squares
Cl	=	Confidence Interval
DF	=	Degree of Freedom
HRC	=	Rockwell Hardness number C scale
RA	=	Percent of contribution
SA	=	Sum of factor squares
SS'	=	Sum of factor real squares
St	=	Total of Squares sum
VA	=	Variable of factor
Ve	=	Variable of error

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