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Study of Hardening Process of AISI 1045 Steel Material with Variation of Heating Temperature, Media, and Cooling Media Volume for Shaft Application

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***Abstract*— Shafts are critical components in engines that facilitate power transmission and rotation. AISI 1045 steel is a cheap alternative for shaft manufacturing, but a proper selection of heat treatment parameters is required to optimize its mechanical properties. This research aims to study the process effect of heating temperature, type of cooling media, and volume ratio of cooling media on the hardness and wear of AISI 1045 material. The results show that the kind of cooling media significantly affects hardness and wear, while the heating temperature and cooling media volume ratio are not significant. The heat treatment process at 850°C with water cooling and a ratio of 12:1 resulted in a hardness of 60 HRC and a wear rate of 0.00335 grams. However, further studies on the tempering process and other parameter adjustments are required to achieve optimum performance.**

Keywords— Spindle Shaft, AISI 1045 Steel, Heat Treatment, Hardness, Wear.

I. INTRODUCTION

The shaft is one of the most critical engine parts. Almost all machines transmit power and rotation together or simultaneously with rotation. The shaft holds a role in such transmission. The shaft is a rotating part, usually round in cross-section, to which are attached elements such as gears [1]. According to the classification of load and use, the shaft can be divided into five types: axle, spindle, countershaft, jackshaft, and line shaft. However, part of this research is about the type of spindle shaft. The spindle shaft is a relatively short transmission shaft and functions to rotate other components connected to the shaft [2]In operation, the spindle shaft is paired with a gear and is subjected to abrasive loads or outclassed by the gear, resulting in thinning and wear. [1].

Current shaft materials, according to the ASM handbook are recommended using AISI 4340 steel and AISI 4140 steel [3]. These steels have a high raw material price of 209.9% and a longer machining process time than plain carbon steels[4]. One alternative material to solve this problem is AISI 1045 steel. AISI 1045 steel is medium carbon steel with 0.43%—0.50% carbon content (C) determined by the AISI (American Iron and Steel Institute) standard. Its properties are relatively high strength and hardness, good ability to be induced and subjected to heat treatment, and good resistance to wear and fatigue [3].

However, the mechanical properties and optimal applications may vary depending on the heat treatment and mechanical processing applied to AISI 1045 steel. Which in turn can match the properties of alloy steels with specific treatments as well [5]. In achieving this, the manufacture of shafts usually goes through initial machining, hardening, tempering, precision grinding, and finishing [6].

In the research, researchers took a study of heat treatment. Heat treatment, also known as heat treatment, is a method to change the mechanical properties of materials to suit the desired needs [7]. Heat treatment of various types of materials can result in multiple critical mechanical properties. Firstly, heat treatment can increase the strength of the material by organizing the crystal structure and eliminating crystal defects. Secondly, ductility can be improved through proper heat treatment, which allows the material to withstand plastic deformation without cracking. Thirdly, heat treatment can increase the hardness of the material by changing the microstructure and improving wear resistance. Lastly, the toughness of the material can also be enhanced with proper heat treatment, which helps to prevent cracks and improve tolerance to dynamic loads. Thus, heat treatment has a vital role in optimizing the mechanical properties of materials for different applications [7].

Research [8], from this study, shows that the Trouble Repair process on the Fehlmann P18S milling machine spindle has been carried out. However, the spindle still has deformation and geometric errors after the repair process. Calibration results showed that the spindle rotation error exceeded the permissible tolerance, while geometric test results showed significant differences in numbers and roundness. The suggestion was to replace the spindle with a new one and avoid using the machine until the spindle

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was replaced. The damage analysis revealed several conditions affecting the performance and reliability of the spindle, including contact surface wear, lubrication system failure, and structural cracks in the spindle.

The hardness data showed that the original spindle's hardness was outside the desired target range. Therefore, further evaluation of the new spindle to be used in manufacturing the spindle shaft is required to ensure optimal performance. The recommendation for this shaft is AISI 4340.

In terms of alternative materials that can be used as material for the shaft and are cheaper, AISI 1045 [3][9]. So, researchers want to examine whether the hardening of AISI 1045 material can be used for x-shaft applications. Which x shaft has specifications:

TABEL 1.
SPECIFICATION OF MATERIAL PROPERTIES FOR SHAFT X

Properties	**target (*Range*)**
struktur mikro	*Lathe* martensite
Tensile strength, ultimate	655 Mpa-95000 psi
Tensile strength, yield	415 Mpa- 60200 psi
Modulus of elasticity	Gpa (27557-30458 ksi)
Hardness, Brinell	373-550 HB
Hardness, Rockwell C	48-59 HRC
Specific Wear	0,0019 gram/km

To achieve this, the heat treatment process is necessary—material This research has previously been done on Anisa Nur Amalia. Research on the heat treatment process on AISI 1045 steel explores variations in heating, holding time, and cooling media. The main findings show that the combination of heating at 850°C for 1.5 hours and cooling with brine solution produces the highest hardness of 735 HV. Wear test results showed the best performance at heating to 900°C for 1.5 hours and cooling with brine solution. The microstructure shows lath martensite and residual austenite. It was found that higher heating temperatures, longer duration, and cooling media with high thermal conductivity resulted in higher hardness values and lower wear rates [10].

As well as research by Razak [11]. Based on the analysis of the mechanical properties testing data on S45C steel after heat treatment with varying weight ratios of cooling media, it was found that the hardness of the steel increased as the weight or volume of cooling media increased, reaching the highest value at 10:1 ratio with a range of 50.4-56.4 HRC. In contrast, the impact strength tends to decrease with an increase in the weight or volume of the cooling media, with the highest value at 2:1 between 4.0-6.1 N/mm2. The results suggest that the optimum ratio of cooling media weight or volume to specimen weight to achieve an optimum hardness of 54 HRC is 7:1. Thus, the choice of cooling media with the correct ratio can have a significant impact on the mechanical properties of steel after heat treatment.

The two studies have examined hardness and wear, as well as the ratio of cooling media. However, it is not one unit, so researchers research the analysis of hardness and wear of AISI 1045 material heat treatment results with variations in heating temperature, type of cooling media, and the ratio of cooling media for the application of the Fehlmann P 18 S Frais Machine Spindle Shaft.

II. MATERIAL AND METHOD

A. *Material Test*

For this research to reach the stage of solving the problem, tools are required, such as grinding grinders, heat treatment ovens, hardness test equipment, breadth test equipment, polishing tools, and microscopes. The primary material in this research is medium carbon steel with specifications following the AISI 1045 standard as follows:

TABEL 2.
COMPOSITION OF AISI 1045 STEEL MATERIAL

Training Data Set	C	Mn	P(Max	S(Max
Standardized range (%)	0,42-0,5	0,6-0,9	0,04	0,05
OES Results	0,47	0,72	0,01	0,004

TABEL 3.
INITIAL HARDNESS VALUE AND WEAR RATE OF AISI 1045 STARTING MATERIAL

Properties of the starting material	Value
Hardness	97 HRB
Rate of wear	0.2764 mg/min (testing).

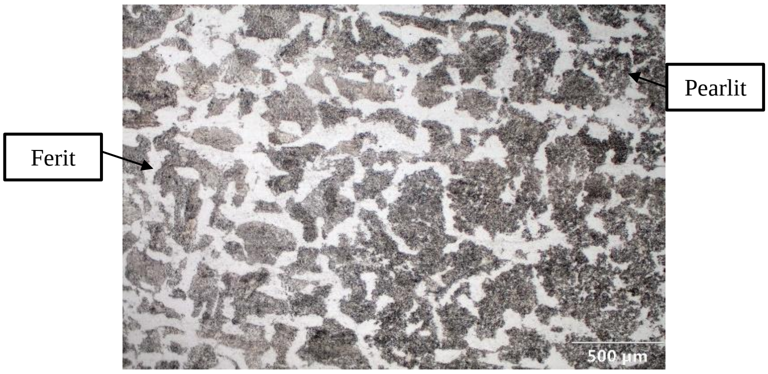


Figure 1. Initial Microstructure with Ferrite and Pearlite

B. Methode and process

1. Heat Treatment

The process of making shafts starts from planning and designing shafts, producing raw materials by machining, hardening heat treatment process, then tempering type heat treatment, and finally finishing [2]. In this study, the focus is trying to find the best parameters in getting hardness and wear resistance before the heat treatment process, which can be drawn as follows:

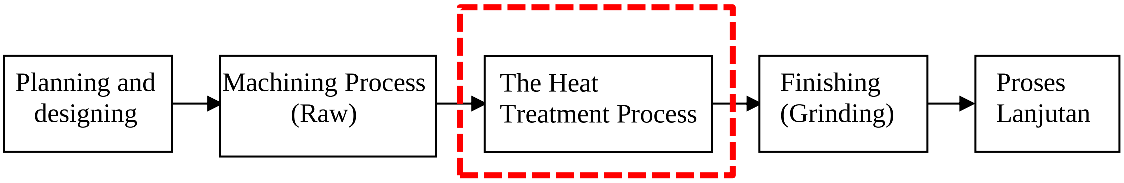


Figure 2. Mapping Area [2][5][12]

Before continuing the heat treatment process, the specimen's shape must be considered, and the testing equipment's testing standards and capabilities must be adjusted. Rockwell Hardness Testing ASTM E18 and wear testing with ASTM G99 standards and the ability of high accuracy scales at a maximum weight of 210 grams. To produce shapes that represent all testing needs.

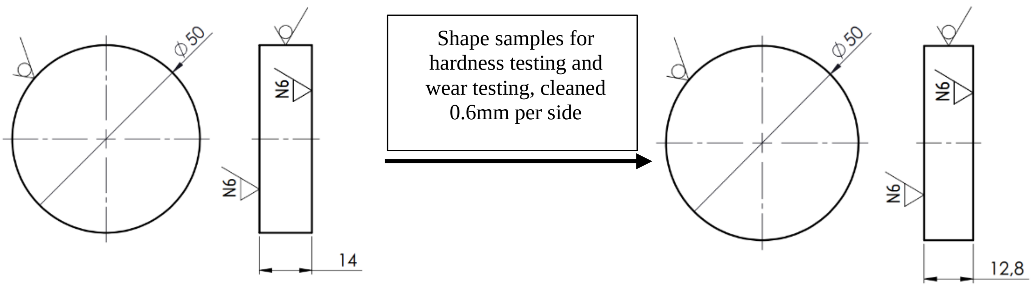


Figure 3. Specimen Shape

Heat treatment is distinguished by the output of its material properties. In this study, the hardening process involves heating the material to austenite temperature and then cooling it, with the aim of obtaining hard properties where ferrite and pearlitic phases become martensite.

In the heat treatment process, the manufacture of the shaft will undergo a hardening and tempering process where there are determining parameters, namely:

a. Temperature

Here, the temperature changes the phase and causes carbon to move for further cooling with a certain cooling medium for a specific purpose. Carbon levels of 0.45% of the austenite phase diagram at temperatures of 850OC and 900OC are shown.

b. Holding time

It is a heat retainer that gets a phase change evenly from the inside to the inside.

The holding time of the sample based on geometry is: holding time =1.4 x thickness of the object = 17.9 minutes. These results are rounded up to 20 minutes for Holding[13]

c. Type of Cooling Media

For AISI 1045 material, it is recommended to use water cooling media, but an alternative cooling media is oil, with a thermal conductivity of water 0.606 W / (m-K) against oil 0.155 W / (m-K) [14].

d.Ratio of Coolant to Object

Based on the Severity of Quench, how quickly the heat from the object is absorbed by the cooling media [14].

2. ASTM G99 Standard Wear Value measurement process

In this study, the samples were weighed first with Mettler Toledo ME 204 Department Foundry Engineering scales and then processed by the pin-on-disc method. Terakir was weighed again to determine its mass reduction.

$$\text{Wear rate} = \frac{Mass\ reduction\ (mg)}{Total\ time\ (minutes)}$$

Pin on disc process Using the following parameters, the pin uses steel ball (SKF) material with a diameter of 10 mm and is given a load of 1kg. The trace or ring (wear track) is 42 mm in diameter, and the pin will traverse the sample for 1 km. The rotation per minute set from the machine is 80 Rpm, so 1 sample takes 1 hour 34 minutes 47 seconds.

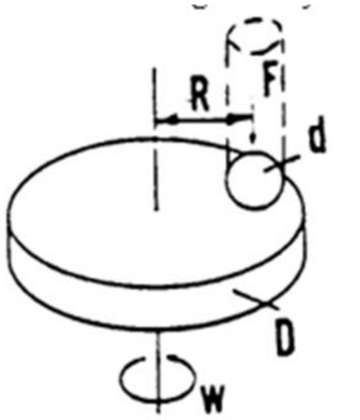


Figure 4. How Pin on Disc Works

3. Measurement Process of ASTM E18 Standard hardness value

In this study, American Standard Testing and Material (ASTM) E 18 is a hardness test with a diamond indenter. The tool used is the Rockwell Hardness Tester from Futur Tech, which uses the Rockwell testing method. The load used is 150 kgf, with an indentation identification trace of 5 points, and then the average value is taken.

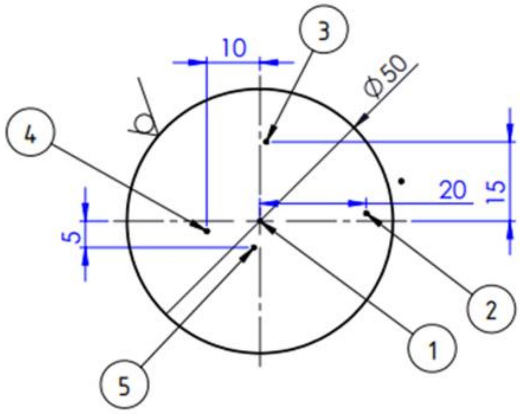


Figure 5. The Post Indentation location.

4. Experiment Design

The Taguchi method is one of the experiments that aim to achieve robustness and reliability in product or process design by minimizing variation and sensitivity to external factors, thereby improving overall quality and performance. In addition, this method is widely used to reduce the total time required for these experiments, and factorial experiments with replication and randomization are performed. The main focus is finding the optimal settings for various parameters to ensure the system or product performs consistently under different conditions. The parameters involved in this study are Temperature, Media, and Ratio of cooling media, which are considered variable parameters. The parameters and process levels are shown in Table 5.

TABEL 4.
PROCESSING PARAMETER AND THEIR LEVELS

Process parameters	Level	
	1	2
Temeperature	850	900
Cooling Media	Oli	Air
Cooling Ratio	4:1	12:1

Design of experiments (DOE) was conducted using Minitab software. The Taguchi method was performed on $L4$ (23), and twelve samples with three sides were heat-treated, as shown in Table 6.

TABEL 5.
EXPERIMENTAL OF L4 ORTHOGONAL ARRAY

No.	Temperature	Cooling Media	Ratio
1	850	Oil	(4:1)
2	850	Water	(12:1)
3	900	Oil	(12:1)
4	900	Water	(4:1)

III. Results and Discussions

A. Taguchi Method

TABEL 6.
HARDNESS AND WEAR RATE TEST RESULTS

Temperature	Cooling Media	Ratio	Hardness (HRC)	Wear Rate (Mg/Min)
850	Oil	(4:1)	47,52	0,1303
850	Water	(12:1)	60,42	0,0353
900	Oil	(12:1)	57,56	0,0844
900	Water	(4:1)	58,60	0,0992

Material heated at the austenitic temperature is then cooled into a medium that has a thermal value, such as water and oil, with a short time, it will have a high hardness [14]. Here there is a hypothesis from the existing parameters. Parameters that use higher temperatures than cooling media with more excellent thermal conductivity and cooling volume will get the highest hardness and wear resistance because hardness is directly proportional to wear resistance. However, in this study, the second experiment with parameters heated and held at a temperature of 850 0c and quickly inserted into a container of water with the amount of water in the ratio of 12:1 to the sample, has a high hardness and has a low wear rate compared to other experiments. This indicates that water cooling media and the amount of water give the effect of rapid cooling to produce martensite microstructures. Martensite itself is very hard, but higher temperatures will make the grains of the experiment with a temperature of 900 larger. As a result, large and coarse grains will make objects accessible to wear when working, and pairs will be easy to wear with the contact and workload.

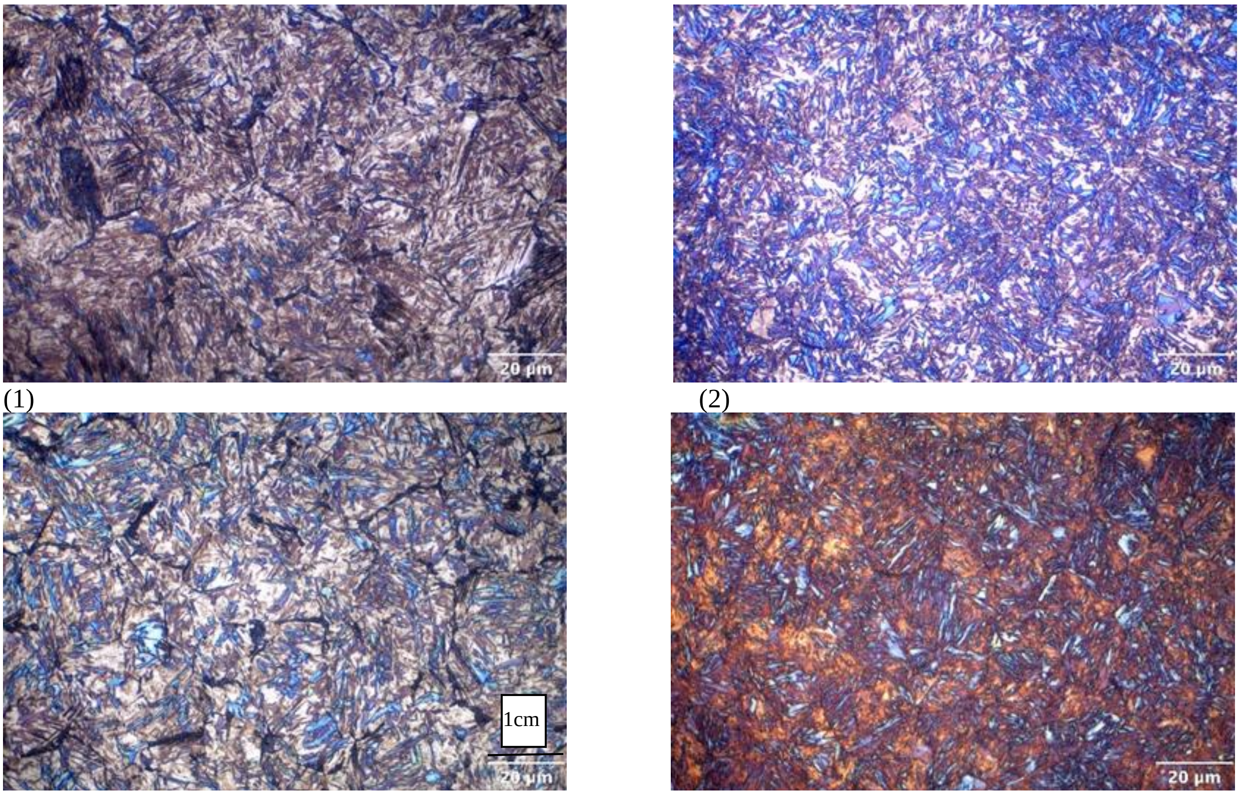


Figure 6. Microstructure Of Aisi 1045 After Heattreatment

Magnification of 500 x. Here, it has a martensite phase, the martensite grains of which are often tiny and can form needle shapes. It has a darker color [14].

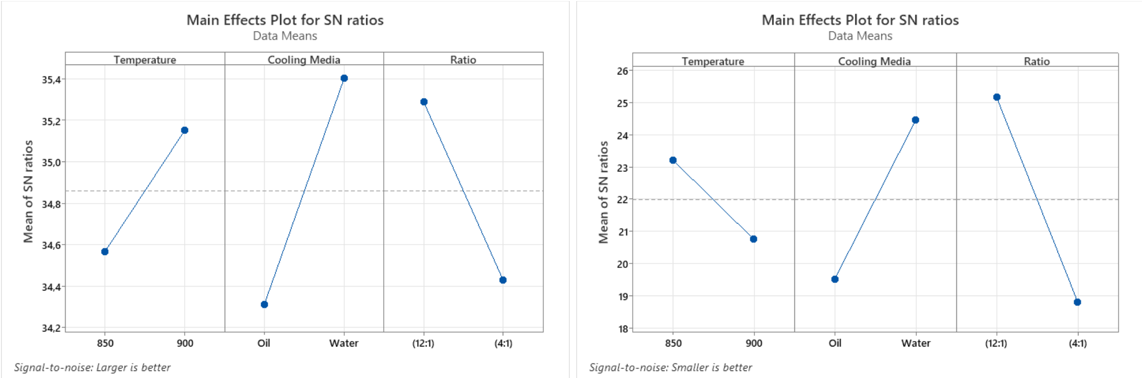


Figure 7. Main Effect Parameter Process

All the high parameters, such as media type and cooling media ratio, get the highest hardness, but the high temperature causes a greater rate of wear, evidenced in the main effect that materials that get higher temperatures in the austenite area will have large grains and reduce the wear resistance ability.

B. Analysis of Variance

Analysis of variance (ANOVA) is an efficient statistical testing method. It can test the degree of significant influence of relevant factors on the experimental results during the experiment. The variance analysis tables of tensile and compressive strength were obtained using Minitab data analysis software, presented in Tables 8 and 9.

The tables show that the hardness response is mainly affected by the type of cooling medium, while the wear rate response is mainly affected by the ratio of the cooling medium. Although the temperature is not very influential, it should be at the austenite temperature by balancing grain growth. Too high a temperature is not allowed. In this study, the optimum temperature was 850 OC.

TABEL 7.
ANALYSIS OF VARIANCE OF HARDNESS

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature	1	34,95	12,93%	34,95	34,953	16,60	0,004
Cooling Media	1	137,63	50,91%	137,63	137,634	65,35	0,000
Ratio	1	80,91	29,93%	80,91	80,912	38,42	0,000
Error	8	16,85	6,23%	16,85	2,106		
Total	11	270,35	100,00%				

TABEL 8.
ANALYSIS OF VARIANCE WEAR RATE

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature	1	0,000242	1,54%	0,000242	0,000242	1,18	0,308
Cooling Media	1	0,004823	30,66%	0,004823	0,004823	23,63	0,001
Ratio	1	0,009034	57,43%	0,009034	0,009034	44,26	0,000
Error	8	0,001633	10,38%	0,001633	0,000204		
Total	11	0,015731	100,00%				

Referring to Fig.8, the interaction between temperature and cooling media shows that an increased media type or thermal conductivity and lower temperature will result in higher hardness. Coupled with the amount of media, it makes cooling faster. However, for the wear rate, a lower temperature interaction at the austenitic temperature interacts with a cooling medium with a higher thermal conductivity, and a large ratio of cooling media makes a reasonable wear rate, as evidenced by finer and denser grains.

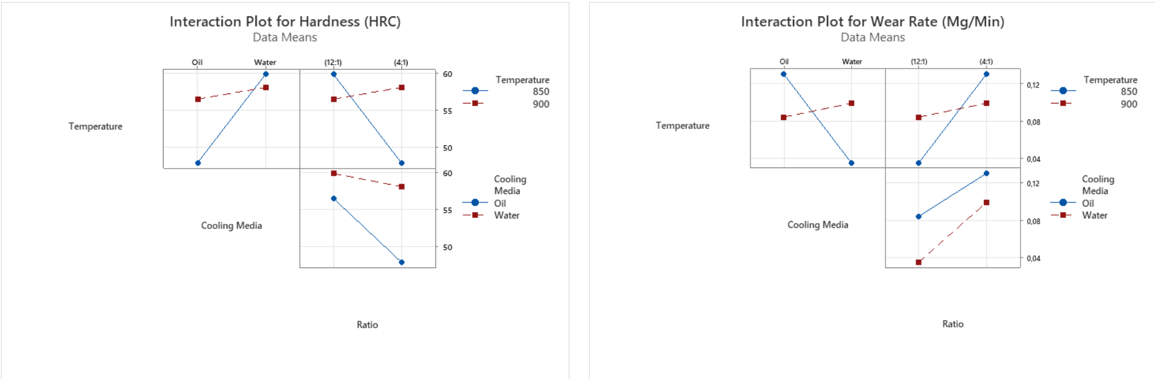
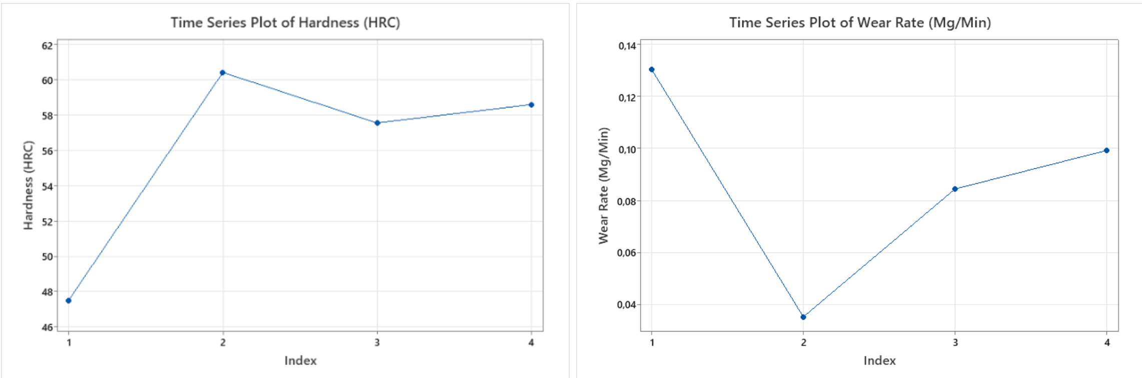


Figure 8. Interaction Plot For Hardness (Hrc) And Wear Rate (Mg/Min)

Of the four types of parameter experiments that have optimal hardness, the second experiment uses AISI 1045 material heated at 850OC and then held for 20 minutes and cooled in a container containing water in a ratio of 12: 1 to the test object. This parameter also has a small area value, which is very good for shaft applications or moving objects and pairs susceptible to friction. This lower temperature parameter is more time-efficient, faster, and more favorable.



C. Comparison of AISI 1045 before and after Heat treatment with Shaft material x

TABEL 9.
Comparison of AISI 1045 before and after Heat treatment with Shaft material x

Raw material AISI 1045	AISI 1045 (850 AIR 12:1)	shaft material x
	hardness	
97 HRB (20 HRC)	60 HRC	48- 59 HRC
	period reduction	
0,2 gram	0,00335 gram	0,0019 gram
0,2764 mg/min	0,0353 mg/min	0,0206 mg/min

Figure 9. Specimen Shape Before and After The Test

The results of the hardening study show that the experimental AISI 1045 material reached the shaft's hardness at 49-59 HRC. However, at the same hardness, the wear rate could not match the shaft application at a mass reduction of 0.0019 grams (0.0206mg/min). Although it has not met the study's target, the existing aramter is an option or reference for existing heat treatment and certain functions.

IV. CONCLUSION

Based on several tests that have been carried out, get some conclusions, namely:

The hardness and wear resistance of the sample were obtained by holding it at the holding temperature parameter 850 0C for 20 minutes. After that, the sample was put into water cooling media in a container with a volume of cooling media of 12: 1, which is 0.00335 grams of mass reduction or wear rate of 0.0353 mg/minute and a hardness of 60 HRC. The sample has a smooth martensite phase and even distribution.

1. Heating (holding) temperature serves to change the phase distribution, and cold will get a microstructure in the form of martensite. Higher temperatures can cause greater grain growth when held at austenising temperatures during quenching, so high hardness is obtained but not wear-resistant. Large grains make the material vulnerable to friction.
2. Type of cooling medium. Cooling Speed: Water is faster than oil, with a thermal conductivity of 0.606 W/(m-K) against 0.155 W/(m-K). This affects the formation of more martensite, which has a higher hardness and wear resistance.
3. Ratio of cooling media volume to weight. A larger cooling media volume (12:1 ratio of cooling media volume to weight) resulted in higher hardness, wear resistance, and martensite phase samples.

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References

[1] Sularso and K. Sugara, "Dasar Perancangan Dan Pemilihan Elemen Mesin," *Pap. Knowl. . Towar. a Media Hist. Doc.*, p. 200, 2014.

[2] V. B. Bhandari, *Machine Elements in Mechanical Design 6th Edition*. 2018.

[3] E. F. Cone, "ASM Handbook Volume 1: Properties and Selection Irons Steels and High Performance Alloys," *ASM Int.*, vol. STP 24, pp. 1–24, 1991, doi: 10.1520/STP38736S.

[4] F. R. Sidiq, G. Anggana, and N. Bilqis, "Produk Stationery Tools Box For Office Produk," Politeknik Manufaktur Bandung, Bandung 2022.

[5] Z. Cai, J. Zhao, and H. Ding, "ASM Handbook Volume 4: Heat Treating," *USA ASM Int.*, pp. 289–322, 1993, doi: 10.1201/9781315120577.

[6] F. Nurrafi, "MESIN FRAIS FEHLMANN P18S," Politek. Manufaktur bandung, Bandung 2023.

[7] G. Hultquist and C. Leygraf, "Material Science and Engineering An Introduction," *Mater. Sci. Eng. A*, vol. 42, no. 1, p. 181, 1980.

[8] L. Hasya, "TROUBLE REPAIR SPINDLE MESIN FRAIS FEHLMANN P 18 S (FR10)," Politeknik Manufaktur Bandung, Bandung, 2023.

[9] U. Logostik, "Logistik Politeknik Manufaktur Bandung," 2022.

[10] A. N. Amalia, "Analisis Pengaruh Perlakuan Panas Hardening Dengan Variasi Temperatur Pemanasan, Waktu Tahan, Dan Media Pendingin Pada Peningkatan Kekerasan Baja AISI 1045 Pada Komponen Axle Shaft," *Skripsi*, pp. 1–111, 2018.

[11] A. H. Razak and S. Rasyid, "Pengaruh Perbandingan Berat Media Quenching dengan Berat Spesimen Uji terhadap Sifat Mekanik Baja Karbon Sedang (S45C)," *Pros. Semin. Has. Penelit.*, vol. 2018, pp. 182–187, 2018.

[12] Wegst C.W., *Stahlschlüssel 18 edition*. 1998.

[13] G. E. Totten, *Failure Ananlysis of Heat Treated Steel Components*. Ohio: ASM International, 2007.

[14] G. Kraus, *STEELS: Heattreatment and Processing Principles*. Material Park, Ohio: ASM International, 1990.