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Optimization of Hardness Improvement of Bucket Wheel Excavator (BWE) Trackplate Bushing Material Based on the Taguchi Method

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ABSTRACT

This research focuses on optimizing the increase in hardness of the Bucket Wheel Excavator (BWE) trackplate's bushing material made of AISI 4340 steel through heat treatment designed using the Taguchi method. The heat treatment process includes several key parameters, namely austenitizing temperature, austenitizing time, quenching media, and tempering time, which are systematically evaluated to maximize the increase in material hardness. The experimental design employs the Taguchi method with an L9 orthogonal array to determine the optimal combination of parameters from four factors and three levels of variables, including austenitizing temperatures of 870°C, 900°C, and 925°C; austenitizing times of 25, 30, and 35 minutes; quenching media of water, salt water, and oil; and tempering times of 1.5, 2, and 2.5 hours. Hardness testing conducted using the Rockwell HRC scale shows that the optimal combination is achieved at an austenitizing temperature of 925°C, an austenitizing time of 35 minutes, salt water as the quenching media, and a tempering time of 2.5 hours. This combination successfully increases the material hardness to 56.9 HRC, representing an increase of 67.84% from the initial hardness of 33.9 HRC. S/N ratio analysis reveals that quenching media and austenitizing temperature significantly impact the increase in hardness. At the same time, tempering time plays a role in stabilizing the martensitic structure without reducing the achieved hardness. The results of this study demonstrate that the Taguchi method effectively determines the optimal heat treatment parameters for bushing materials, thus producing material hardness that meets the required technical specifications.

Keywords: *AISI 4340 Steel, bushing, hardness improvement, heat treatment, Taguchi method, S/N ratio analysis.*

Introduction

The development of the heavy equipment industry, particularly in the mining sector, demands the use of materials with high strength and wear resistance [1]. The bushing track plate of the Bucket Wheel Excavator (BWE), as one of the critical components in heavy machinery, must withstand extreme working conditions, including high dynamic loads and intense friction [2]. In this context, the bushing material, AISI 4340 steel, known for its superior mechanical properties, is an appropriate choice. However, to maximize the performance of this material, proper heat treatment is required to enhance its hardness and durability [3]. The problem addressed is determining the optimal heat treatment parameters to increase the hardness of AISI 4340 bushing material significantly. With variations in parameters such as austenitizing temperature, austenitizing time, quenching media, and tempering time, it is important to conduct a systematic analysis to find the most effective combination [4].

Previous research has significantly improved steel hardness, but structured and systematic approaches using the Taguchi method for optimizing heat treatment parameters are still limited [5]. This method is recognized for its ability to reduce variability and determine the influence of each factor in the production process. While many studies focus on optimizing the mechanical properties of materials, those specifically employing the Taguchi method for AISI 4340 bushings are rare, making this research a novelty in the field. Studies on AISI 4340 steel indicate that both manual calculations and simulations using Ansys software show that this material provides safe and efficient performance for use in the axle shaft of sugarcane transport trains. This also suggests that the axle shaft's structural design has considered relevant factors and can withstand the specified load effectively. [6]. The contribution of this study lies in developing a practical methodology to improve the hardness of trackplate bushings systematically and data-drivenly. This research is expected to provide new insights for the industry regarding using the Taguchi method in heat treatment processes and how to adapt parameters to achieve the desired results.

This research will implement the Taguchi method to determine the optimal combination of heat treatment parameters. As a solution to the identified issues, it is hoped that this approach will significantly increase material hardness, allowing AISI 4340 bushings to meet the required technical specifications.

Research Method

This research method is designed to evaluate and optimize heat treatment parameters to enhance the hardness of AISI 4340 steel trackplate bushings [7]. The stages of the research method include initial data collection, experimental design, heat treatment implementation [8], hardness testing [9], and data analysis using the Taguchi method to determine the optimal parameter combinations [5]. The Taguchi method was chosen for this study due to its distinct advantages over other optimization techniques, such as full factorial designs and response surface methodology (RSM). Unlike full factorial designs, which require testing all possible combinations of parameters, the Taguchi method uses an orthogonal array to evaluate multiple factors at different levels with a limited number of experiments. This approach reduces the experimental trials needed, thus saving time and resources without compromising the accuracy of the results [10].

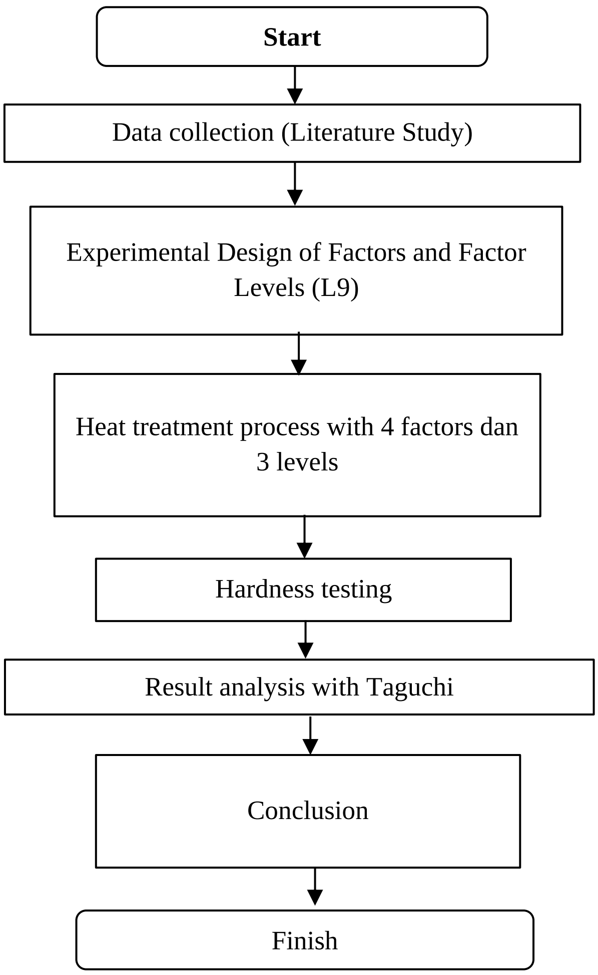


Figure 1. Research Flow Diagram

1. Data Collection

The initial step in data collection involves obtaining information about the mechanical properties and chemical composition of AISI 4340 steel, as well as the hardness values used as references for subsequent processes [11]. This data is gathered through laboratory testing and literature studies related to the effects of heat treatment on steel. This foundational data helps formulate the heat treatment parameters to be tested.

2. Experimental Design with the Taguchi Method

The Taguchi method has several strengths that make it an effective choice for optimizing heat treatment processes. The primary advantage of this method is its ability to identify the optimal parameter combinations with a minimal number of experiments. In heat treatment, where various parameters (such as austenitizing temperature, austenitizing time, quenching media, and tempering time) significantly influence hardness outcomes, Taguchi offers a systematic approach to evaluate each variable efficiently. The Signal-to-Noise (S/N) ratio analysis in the Taguchi method is also a valuable asset, as it helps reduce variability in results due to uncontrollable factors, resulting in stable and consistent parameter settings [12]. However, the Taguchi method also has some limitations in material optimization, particularly for complex heat treatment processes. One major limitation is that the method only considers linear effects between parameters, which may not fully capture the complex interactions that can occur in these processes. Additionally, the method may be insufficient when external factors, such as measurement uncertainties or significant environmental fluctuations, impact results. Therefore, while the Taguchi method is highly beneficial for this research, it is essential to consider additional approaches or further studies to address these limitations. The experimental design in this research is conducted using the Taguchi method to facilitate efficient combinations of heat treatment tests [13]. An L9 orthogonal array matrix is employed in this study, allowing the testing of nine combinations of parameters from four heat treatment factors, namely:

- **Austenitizing Temperature (A):** 870°C, 900°C, and 925°C
- **Austenitizing Time (B):** 25 minutes, 30 minutes, and 35 minutes
- **Quenching Media (C):** Water, Salt Water, and Oil
- **Tempering Time (D):** 1.5 hours, 2 hours, and 2.5 hours

These experimental combinations are determined based on Taguchi's principle of orthogonality [14].This allows each parameter to be tested efficiently without trying all possible combinations. The application of the Taguchi L9 orthogonal design in other studies, such as in the article analyzing welding joints through bending tests, indicates that the V amp with a current of 120 amperes produces the highest bending strength. In comparison, the K amp with a current of 110 amperes produces the lowest strength. This difference highlights the importance of selecting the appropriate parameters, such as electric current and amplitude, to improve the strength of the weld joint. [15].

3. Heat Treatment Process

The heat treatment process is carried out in three stages as follows:

1. **Austenitizin**g: AISI 4340 steel is heated to the specified temperature (870°C, 900°C, or 925°C) for varying times (25, 30, or 35 minutes) in a furnace, aiming to achieve uniform temperature distribution in the material [16].
2. **Quenching**: The material that has undergone austenitizing is then rapidly cooled using the quenching media (water, salt water, or oil) to form a hard martensitic structure [17].
3. **Tempering**: The material is reheated to 200°C for varying durations (1.5, 2, or 2.5 hours) to improve toughness and reduce internal stress without compromising hardness [18].

4. Hardness Testing

Hardness testing is conducted using the Rockwell Hardness Test (HRC) at four identical points on each sample [19]. Each sample is tested to ensure consistency and accuracy of results. The hardness data will later be used for further analysis and to determine the effect of each heat treatment combination [20] on material hardness improvement [7].

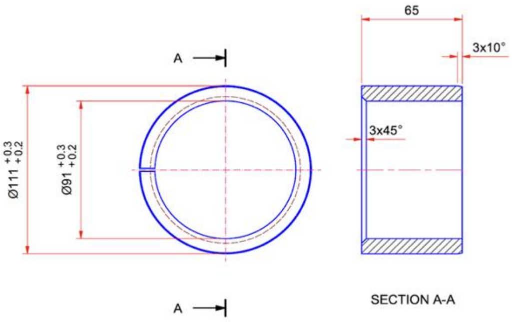
5. **Data Analysis Using the Taguchi Method**

After testing, the data is analyzed using the Taguchi method to identify the parameter combinations that most significantly affect hardness improvement [9]. This analysis includes:

- **Signal-to-Noise (S/N) Ratio Calculation:** The S/N ratio is calculated for each trial. This ratio is used to maximize hardness while minimizing result variation.
- **Identification of Significant Parameters:** The S/N ratio analysis will indicate which parameters impact hardness enhancement most, thus determining the optimal parameter settings to achieve maximum hardness results.

Result and Discussion

1. Technical Specification Data



Description : *Bushing Trackplate BWE*
Material : *DIN 1.6582 34CrNiMo6*
Hardness, 52 – 58 HRc
Neartly Rolled and Calibrated

Figure 2. Drawing and Technical Specifications of the BWE Trackplate Bushing

The initial stage of this research involves collecting data related to the required technical specifications and the chemical composition of AISI 4340 steel. Based on Figure 2, it is noted that the required hardness of the bushing ranges from 52 to 58 HRC. The chemical composition of the bushing has been tested using a Laser Induced Breakdown Spectroscopy (LIBS) Analyzer, yielding the following results [21]:

Table 1. Results of Chemical Composition Testing for BWE Trackplate Bushing

Chemical Composition	Composition Value (%)
Iron (Fe)	95,7
Nickel (Ni)	1,74
Chromium (Cr)	0,851
Manganese (Mn)	0,703
Carbon ©	0,377
Molybdenum (Mo)	0,246
Silicon (Si)	0,217
Copper (Cu)	0,118

This data is the basis for determining the parameters to be tested, namely austenitizing temperature and time, quenching media, and tempering time. Collecting this data is essential as a reference for evaluating the effectiveness of the heat treatment combinations [22].

2. Experimental Design

The experiments are designed using the Taguchi method with an L9 orthogonal array, allowing for the testing of nine combinations of four heat treatment parameters as follows [10]:

Table 2. Heat Treatment Process Parameters and Their Levels

Symbol	Process Parameter	Level Factor		
		1	2	3
A	Quenching Media	Water	Salt Water	Oil
B	Austenitizing Temperature (°C)	870	900	925
C	Austenitizing Time (min)	25	30	35
D	Tempering Time (hour)	1,5	2	2,5

The following table shows the combinations of parameters tested in this study.

3. Hardness Test Result

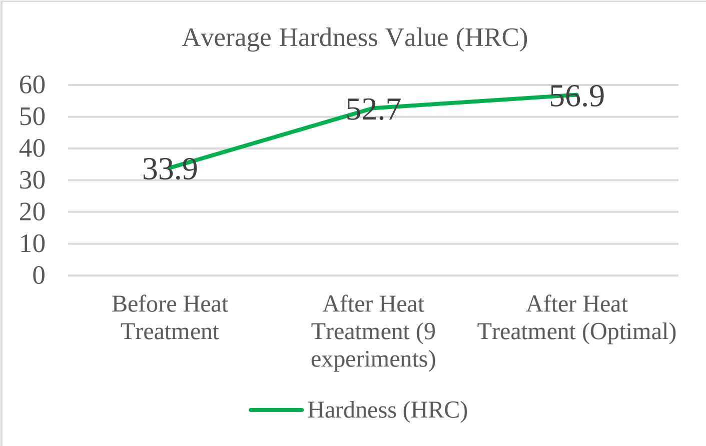


Figure 3. Average Hardness Value (HRC)

Based on the data processing results in Figure 3, the average hardness of the trackplate bushing material before heat treatment is 33.9 HRC. After conducting nine experiments, the hardness increased to 52.7 HRC (55.46%). Using the recommended optimal parameters, the hardness reached 56.9 HRC, representing a 67.84% increase from the pre-heat treatment condition [13][23]. This indicates a significant improvement in hardness at all testing points [9][24]The results demonstrate that heat treatment effectively enhances average hardness, indicating the experiment's success in improving the performance of the track plate bushing material.

4. Influence of Heat Treatment Parameters

The S/N ratio analysis helps identify the impact of each heat treatment parameter on hardness [6]. Below are the effects of each parameter:

Table 3. Experimental Result with S/N ratio (Software MiniTab)

Ext	Process Parameter				Quenching Media	AustenitizingTemperature (C)	Austenitizing Time (min)	Tempering Time (Hour)	S/N Ratio	Hardness (HRC)
runs	A	B	C	D						
1	1	1	1	1	Water	870	25	1,5	33,8886	49,48
2	1	2	2	2	Water	900	30	2	34,5671	53,50
3	1	3	3	3	Water	925	35	2,5	34,9482	55,90
4	2	1	2	3	Salt Water	870	30	2,5	34,3201	52,00
5	2	2	3	1	Salt Water	900	35	1,5	34,7327	54,53
6	2	3	1	2	Salt Water	925	25	2	34,6318	53,90
7	3	1	3	2	Oil	870	35	2	34,1480	50,98
8	3	2	2	3	Oil	900	25	2,5	34,4164	52,58
9	3	3	1	1	Oil	925	30	1,5	34,2412	51,53

The results presented in Table 3 showcase various experimental runs, detailing the combination of different heat treatment parameters and their corresponding hardness values measured in HRC (Rockwell hardness scale). The analysis of these results utilizes the signal-to-noise (S/N) ratio, a statistical measure used to determine the influence of each parameter on the hardness outcome.

Key Parameters:

- **Quenching Media (A)**: The liquid cools the material after austenitizing (e.g., water, salt water, oil).
- **Austenitizing Temperature (B)**: The temperature to which the material is heated to form austenite, a phase of iron and steel.
- **Austenitizing Time (C)**: The duration for which the material is held at the austenitizing temperature.
- **Tempering Time (D)**: The duration of the subsequent heat treatment to reduce brittleness after quenching.

Table 4. Response Table for Signal-to-Noise Ratios (Software MiniTab)

Level	Quenching Media	Austenitizing Temp. (C)	Austenitizing Time (min)	Tempering time (hour)
1	34.27	34.12	34.31	34.29
2	34.56	34.57	34.38	34.45
3	34.47	34.61	34.61	34.56
Delta	0.29	0.49	0.30	0.27
Rank	3	1	2	4

Larger is better

Table 4 summarizes the S/N ratios for each parameter across different levels. In this context, the goal is to maximize the hardness, hence the analysis follows the "larger is better" criterion.

- **S/N Ratios**: Higher S/N ratios indicate better performance regarding hardness. The table shows the average S/N ratios for each parameter at three levels (1, 2, and 3), along with the calculated delta values, which represent the range of impact for each parameter.
- **Delta Values**: These indicate the difference between the maximum and minimum S/N ratios for each parameter, helping to rank their significance:
    - **Austenitizing Temperature (C)**: With a delta of 0.49, it ranks highest, showing that changes in temperature have a substantial effect on hardness.
    - **Austenitizing Time (min)**: This ranks second with a delta of 0.30, indicating its notable influence.
    - **Quenching Media (A)**: Ranks third with a delta of 0.29, showing a moderate effect.
    - **Tempering Time (hour)**: Ranks fourth with a delta of 0.27, suggesting it has the least influence compared to the others.

The S/N ratio analysis from the experimental data effectively identifies the impact of each heat treatment parameter on the hardness of the material. Among the parameters studied, austenitizing temperature is the most significant factor affecting hardness, followed by austenitizing time, quenching media, and tempering time. This analysis helps in optimizing heat treatment processes to achieve desired mechanical properties in materials, guiding metallurgists in making informed decisions for specific applications.

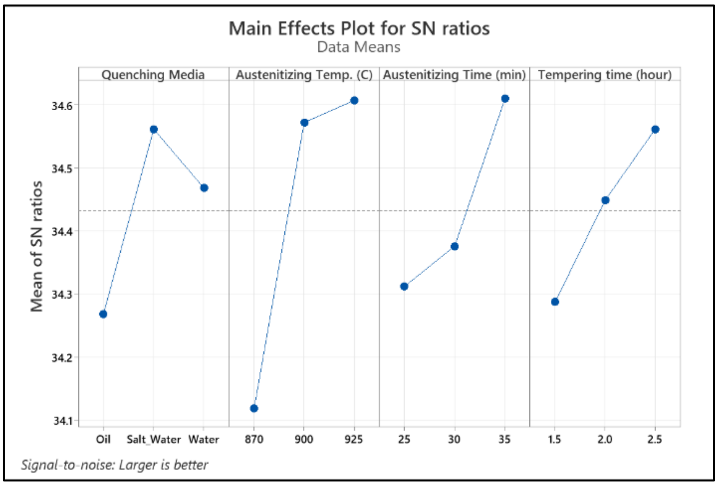


Figure 4. Main Effects Plot for SN Ratios Graph (Software MiniTab)

Based on the S/N ratio analysis results in Figure 3, it is evident that the Austenitizing Temperature emerges as the most critical parameter in the heat treatment process for enhancing the hardness of the trackplate bushing material. This is followed by Austenitizing Time and Quenching Media, while Tempering Time has a smaller but still significant effect. From this analysis, the optimal parameters needed to achieve optimal hardness results can also be obtained. The combination is as follows:

- **Quenching Media:** Salt Water
- **Austenitizing Temperature:** 925°C
- **Austenitizing Time:** 35 minutes
- **Tempering Time:** 2.5 hours

This combination of parameters yields optimal hardness results and aligns to improve the performance of the trackplate bushing material. These parameter combinations have been verified and achieved optimal hardness results (Figure 3).

5. Practical Implications of Hardness Improvement

The significant increase in hardness of the AISI 4340 bushing material can be interpreted as an enhancement in wear resistance, which is crucial for extending the service life of components in demanding applications such as Bucket Wheel Excavators. Higher hardness levels contribute to reduced wear rates, thereby decreasing the frequency of maintenance and replacements, resulting in lower operational costs. Economically, the initial investment in optimizing heat treatment processes can lead to substantial savings over time through reduced downtime and maintenance costs.

Furthermore, the optimized bushing material has potential applications beyond heavy machinery. Industries such as automotive, aerospace, and manufacturing could benefit from enhanced AISI 4340 steel components, where durability and performance are critical. In real-world conditions, the optimized hardness can improve the material's performance under high-stress scenarios, leading to greater reliability and efficiency in various applications.

Conclusion

This study successfully determined the optimal heat treatment parameters to enhance the hardness of Bucket Wheel Excavator (BWE) trackplate bushings made from AISI 4340 steel using the Taguchi method. Based on the testing results and S/N ratio analysis, the optimal parameter combination was found to be: austenitizing temperature of 925°C, austenitizing time of 35 minutes, quenching media of salt water, and tempering time of 2.5 hours. This combination increased hardness to 56.9 HRC, representing a 67.84% improvement from the initial hardness of 33.9 HRC. Higher hardness levels contribute to reduced wear rates, thereby decreasing the frequency of maintenance and replacements, resulting in lower operational costs. Economically, the initial investment in optimizing heat treatment processes can lead to substantial savings over time through reduced downtime and maintenance costs.

The effectiveness of the Taguchi method in this study also highlights its potential for broader applications in industries requiring process optimization, such as automotive, aerospace, and manufacturing sectors that rely on wear-resistant steel components. By adopting the Taguchi method, these industries can enhance material performance and increase component durability efficiently.

For future research, it is recommended to evaluate the optimized parameters under varying environmental conditions, such as different humidity levels, cooling rates, or high-temperature environments, to assess the stability of the hardness results. Additionally, applying this optimization method to various types of steel beyond AISI 4340, including high-alloy or stainless steels, could provide further insights into the generalizability of the results and the Taguchi method's effectiveness across different material types. This would expand the applicability of the findings and potentially benefit a wider range of industrial applications.

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