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Haider et al

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Effect of Intercritical Annealing Parameters on The Hardness Property: Statistical Study Using Taguchi

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ABSTRACT

Dual-phase steel is characterized by good strength and hardness with high ductility. This type of steel has a wide range of uses in the modern-day industry, especially in the automobile industry. This paper reports an experimental study ofthe effect of intercritical annealing parameters such as temperature and soaking time on hardness. The Taguchi method based on L_9 was used with a temperature range from 750 ºC to 800 ºC and a soaking time range from 30 min to 60 min. All samples were treated in the furnace at a specified temperature and soaking time quenched in water. It is observed that the hardness increases with increasing the intercritical temperature and soaking time. On the other hand, temperature has a significant effect more than soaking time on the hardness.

KEYWORDS: Intercritical Annealing, Dual-phase Hardness, Taguchi.

1. INTRODUCTION

Dual-phase (DP) steels have become the preferred materials for many modern industries, particularly in the automotive sector, due to their energy-saving, lightweight, and safe properties[1]. This is because DP steels are composed of different phases, with martensite as the hard phase and ferrite as the ductile soft phase[2]. The martensite phase is dispersed within the ferrite matrix, resulting in a material that is both strong and ductile, making it ideal for applications that require high strength and good formability[3, 4].

DP steel possesses excellent mechanical qualities such as high tensile strength, improved formability, continuous yielding behavior, crashworthiness, high strength-ductility, and high work hardening rates, which make it a reliable and affordable material for the manufacturing sector, including welding[5-8]. The microstructure of DP steels is significantly influenced by heat treatment, particularly during intercritical annealing, which creates a ferrite-martensite structure[9,10]. The mechanical properties of DP steels are further enhanced by factors such as annealing, quenching medium, cooling rate, grain size and pattern, and the chemical composition of the parent material [11]. Finer grain size is preferred as it results in better mechanical properties [12].

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While much research has been conducted on the microstructure and mechanical properties of DP steels [13-16], little has been done to predict their hardenability resulting from austenite. Therefore, this study applies the Taguchi method to investigate the effect of process parameters such as temperature (T) and soaking time (ST) on the hardness property of DP steel.

2. METHODOLOGY

2.1. Material

The low-carbon steel was utilized as a workpiece, which was manufactured at the Musrata Steel Factory and had a chemical composition as presented in Table 1.

Table 1. Chemical composition of the low-carbon steel

C	Si	Mn	P	Ni
0.23	0.17	0.68	0.03	0.14
Cr	Mo	Cu	Co	V
0.12	0.02	0.5	0.01	0.01

The study employed an intercritical process for the intercritical annealing of low-carbon steel, as illustrated in Figure 1. The process involved heating the steel to the intercritical temperature, holding it at that temperature for

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a specific duration, and then cooling it down to room temperature using water.

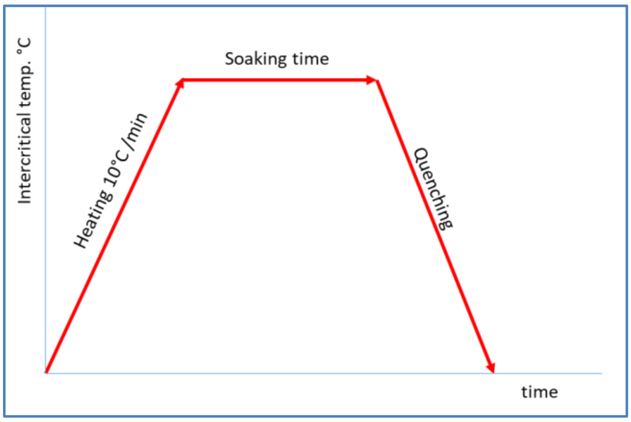

Fig. 1. Intercritical annealing procedure.

It is important to note that the upper and lower critical temperatures (Ac1 and Ac3) of alloy steel can vary depending on its chemical composition. Andrews' empirical formula, expressed in Equations (1) and (2), provides an estimate of the approximate critical temperatures[17].

Ac1 (C) = 723-10.7(%Mn)-16.9(%Ni) + 29.1(%Si) +16.9(%Cr) + 290(%As) + 6.38(%W) (1)

Ac3 (C) = 910- 203 %C -15.2(%Ni) + 44.7(%Si) +104(%V) + 31.5(%Mo) +13.1(%W) (2)

Based on the chemical composition of the low-carbon steel, as given in Table 1, the adjusted Ac_1 and Ac_3 temperatures can be estimated as 720°C and 870°C, respectively.

2.2. Taguchi method and design of experiments

2.2.1. Taguchi Method

During this study, two process parameters with three levels were selected as presented in Table 2. These experimental factors were used to evaluate the impact of each parameter on the hardness property of the DP steel. The L9 orthogonal array, consisting of nine experiments was chosen to determine the relationship between the input and out parameters.

Table 3 shows the results from heating the samples to a specific temperature and then holding them for the duration of the soaking time. All heat-treated samples were then quenched in water.

Table 2. Process Parameter and their levels

	Parameter	Level 1	Level 2	Level 3
A	Temperature (˚C)	750	775	800
B	Soaking time (min)	30	45	60

The signal-to-noise ratio (S/N)

In Taguchi analysis, the responses were converted into signal-to-noise (S/N) ratios. As the goal of this study was to maximize the response (hardness), the higher-the-better performance characteristics were utilized to calculate the S/N ratio using Equation (3) [18].

$$S/N = -10 \log \left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (3)$$

where n is the number of replications for each experiment and y_i the result value for the ith performance characteristics.

2.2.2. Analysis of variance (ANOVA)

ANOVA is a statistical method used to determine the individual contributions and interactions of each parameter within an experimental design. It was employed in this study to investigate the effects of temperature and soaking time on the hardness of the low-carbon steel. ANOVA is a useful tool in determining the order of importance of the influencing parameters on the response, which helps in validating the results obtained through the Taguchi method [19].

3. RESULTS& DISCUSSION

3.3. Analysis of a response (Hardness)

The experimental design and results of intercritical annealing are presented in Table 3. Each hardness value represents an average of five measurements. Experiment number 9 yielded the highest hardness value, with an HRA of 62.9, while experiment number 1 had the lowest hardness value, with an HRA of 57.4.

Table 3. Experimental results and their S/N ratios

Run	A Temperature (°C)	B Soaking time (min)	Average Hardness (HRA)	S/Nraios
L1	750	30	57.4	35.1782
L2	750	45	57.8	35.2386
L3	750	60	58.0	35.2686
L4	775	30	59.2	35.4464
L5	775	45	59.8	35.5340
L6	775	60	60.2	35.5919
L7	800	30	62.4	35.9037
L8	800	45	62.6	35.9315
L9	800	60	62.9	35.9730

Figure 2 displays the average hardness value for each run, as well as the hardness value of the as-received sample. It is evident that the hardness increased with all heat treatment runs when compared to the as-received hardness of 55.9 HRA. However, for runs 1, 2, and 3, when the temperature was 750℃ and the soaking time was 30, 45, and 60 min, respectively, the hardness increased only slightly from 57.4 HRA to 58.0 HRA. Similarly, runs 4, 5, and 6, when the temperature was 775℃ and the soaking time was 30, 45, and 60 min, respectively, resulted in an increase in hardness from 59.2 HRA to 60.2 HRA. In contrast, the hardness increased significantly from 62.2 HRA at run 7, where the temperature was 800℃ and the soaking time was 30 min, to 62.9 HRA at run 9, where the temperature was 800℃ and the soaking time was 60 min. Additionally, the hardness increased noticeably with an increase in temperature from 58 HRA at a temperature of 750℃ and a soaking time of 60 min to 62.9 HRA at a temperature of 800℃ and a soaking time of 60 min.

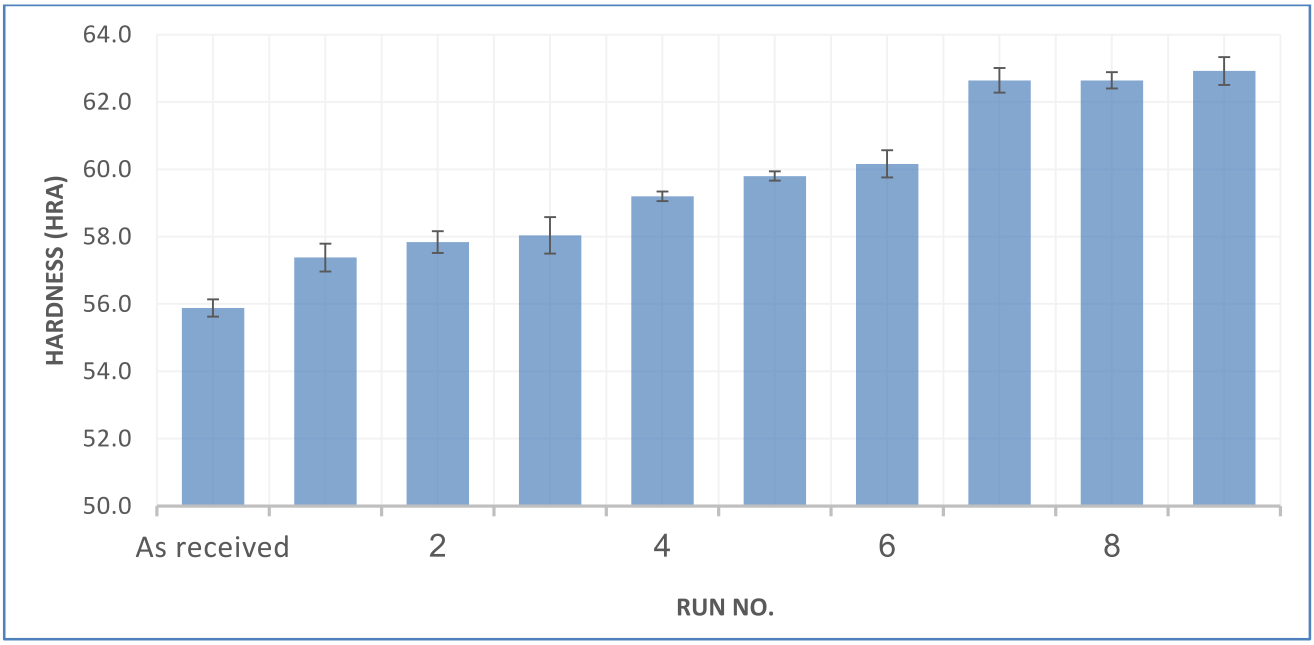

Fig. 2. Hardness vs. runs

Analysis of the signal-to-noise ratio (S/N)

Table 4 displays the average S/N ratios and the ranking of the importance of the process parameters on the hardness value. The results indicate that the temperature had a greater impact on the hardness of the low-carbon steel than soaking time, with temperature being ranked as the more important process parameter. Both the main effect plots of the Taguchi method and the ANOVA results produced a similar ranking of the effect of the process parameters on the hardness of the low-carbon steel.

Table 4. Response for S/N ratios larger is better (Hardness via temperature and soaking time).

Level	Temperature (C)	Soaking Time (mins)
1	35.23	35.51
2	35.52	35.57
3	35.94	35.61
Delta	0.71	0.10
Rank	1	2

In Figure 3, the main effect of each parameter on the hardness of the low-carbon steel is depicted. When there is a small variation between the highest and lowest S/N ratios, it indicates that the parameter has a relatively low effect on the response. On the other hand, the level of the design parameter with the maximum S/N ratio indicates the optimal conditions of the system. Therefore, the process parameters that yield the maximum hardness are determined to be a temperature of 800°C and a soaking time of 60 minutes, as shown in Figure 1. This implies that the highest hardness can be achieved when the heat treatment is performed at a heating temperature of 800°C with a soaking time of 60 minutes. Thus, the optimal hardness within the operating condition range of this study can be obtained by conducting the heat treatment process under optimal working conditions.

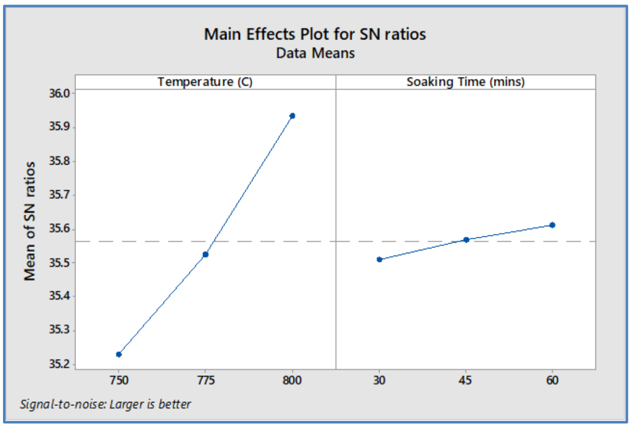

Fig. 3. The main effect plots for S/N ratios on hardness (Taguchi).

Analysis of the interaction

As we know, when experimental designs incorporate multiple factors, the potential for each factor to interact with one or more other factors increases exponentially. Interaction refers to the effect of one factor's levels on the impact of another parameter. If the lines on an interaction plot are parallel, it indicates that there is no relationship between the inputs, whereas a deviation in the lines indicates a relationship. In Figure 4, the influence of various inputs on hardness is illustrated. Within the parameter ranges of this study, no significant interaction is observed between temperature and soaking time on hardness.

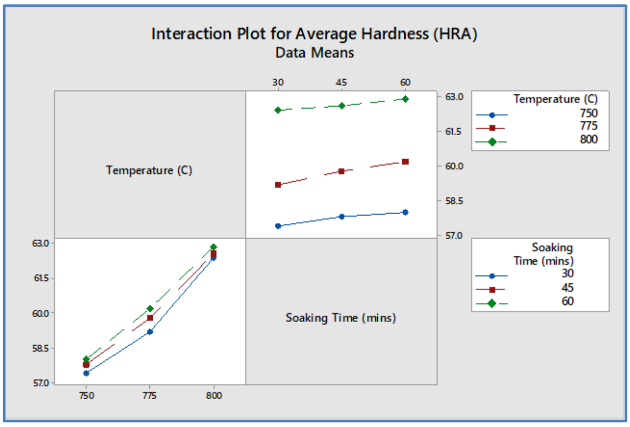

Fig. 4. Main and interaction plots created by experimental and Taguchi-predicted data sets

The effects of Temperature and soaking time on hardness, depending on the S/N ratio values. The values show that the temperature has more significant effect than soaking time as resulting from Table 4 which illustrated the rank of temperature is 1 and soaking time is 2. The graphical representation of S/N ratio data is given in Figure 3 and Figure 4. As per the graph, with an increase in the temperature, the value of S/N ratio for the hardness increases. This directly indicates that a high temperature results in more hardness during the intercritical annealing.

In the current study, surface hardness, is taken as response (output) while temperature and soaking time are considered as independent (input) variables. Assuming no interaction between input parameters, after performing all experiments and obtaining the output parameter, the regression model can be explicitly formulated involving the independent variables. The experimental results for average surface hardness can be migrated to a linear regression model equation as shown in Eq. (4):

$$\text{Average Hardness (HRA)} = -16.97 + 0.09800\ \text{Temperature (°C)} + 0.02333\ \text{Soaking Time (mins)} \quad (4)$$

Equation 4 specifies regression model obtained for surface hardness. The R-square (coefficient of determination) which is representative for efficiency of correlated model, was found to be 98.68%. The closer the R-square value to 1.00, the effective the model is and represents the highest proportion of total variability in the response variable. The R-Sq(adj) which is 98.25%, specifies the amount of variation in the regression equation, and the R-Sq(pred) which is 97.19%, determines how accurate the regression equation predicts the response value. As the value of both R-Sq(adj) and R-Sq(pred) are very high (greater than 91%), and they are also so close to the value of R-Sq, it is confirmed that the design models fit the new experimental data very fine.

4. CONCLUSION

In conclusion, this study aimed to investigate the effect of temperature and soaking time on the surface hardness of low-carbon steel through intercritical annealing. The results showed that the hardness increased with all heat treatment runs, and the highest hardness was obtained at run 9, where the temperature was 800°C and the soaking time was 60 min. The signal-to-noise ratio analysis indicated that temperature had a greater impact on hardness than soaking time. The regression model obtained for surface hardness had a high R-square value of 98.68%, indicating the effectiveness of the model in representing the total variability in the response variable. Overall, the study provides valuable insights into optimizing the heat treatment process for achieving the desired surface hardness of low-carbon steel.

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