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WEAR MODEL OF SURFACE TREATED LOW CARBON STEEL-BASED ON TAGUCHI EXPERIMENT METHOD USING THE GMAW PROCESS

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ABSTRACT

This article presents the results of optimizing semi-automatic welding process parameters using the Taguchi method and regression analysis. Experiments were designed with the semi-automatic welding process to identify the optimal parameters, which were validated through Analysis of Variance (ANOVA). Additionally, multiple regression analysis was conducted using the MINITAB software to develop a mathematical model predicting wear values under different welding conditions. The study experimentally investigated the effects of parameters such as particle size of the material, coating thickness, and current strength on wear. Results showed that the parameter with the most significant impact on wear was coating thickness, specifically the chromium content, followed by current and particle size of the material.

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1. INTRODUCTION.

Welding overlay methods are widely used for the restoration and hardening of metal surfaces [1]. These methods encompass all types of welding, including MMAW, GTAW, SWAW, and TIG.

Research has shown that optimizing welding parameters is crucial when improving metal surfaces using electric arc welding [2]. Key welding parameters include current strength (a), voltage (b), welding speed (U), type of filler material or electrode, deposition rate of the filler material, and electrode diameter and size.

Weimann elaborates on the study of welding procedure generation for the submerged-arc welding process [3]. The structure of the dissimilar welds by SAW process was studied by McPherson et al [4]. The effect of increasing deposition rate on the bead geometry of submerged arc welds was studied by Chandel et al [5]. Yang et al [6] studied the effects of SAW process variables on the weld deposit area. Prediction and optimization of weld bead volume for the SAW using mathematical models was carried out by Gunaraj et al. [7, 8]. The quality engineering methods of Taguchi, employing design of experiments provide an efficient and systematic way to optimize designs for performance, quality and cost. It is one of the most important statistical tools for designing high-quality systems at reduced cost [10 - 12].

The use of the Taguchi method simplifies the optimization procedure for determining the optimal welding parameters in the SAW process. Unal and Dean [13] explain the approach of Taguchi to obtaining design optimization in the manufacturing process. Abdul Ghani Khan et al. [14] explore the friction welding parameters that influence the output, namely tensile strength such as friction pressure, forging pressure, friction time, and forging time using the Taguchi method.

In this research, up to three of these parameters were selected to study their effects on the mechanical properties of the deposited surface.

In addition to welding parameters, the type and chemical composition of hardfacing materials is crucial to the quality of the deposited material. Hardfacing elements are commonly nickel-based, cobalt-based, or iron-based and are often used in powder form.

Chromium and chromium carbide-containing hardfacing materials are widely used. Many studies have applied high-chromium white cast iron with chromium carbide to improve surface properties [16 - 18].

Developing a mathematical model that combines welding parameters with the amount and composition of hardfacing materials is of significant importance both scientifically and practically.

The wear resistance and hardness of the deposited surface depend on the welding parameters and type of material used.

$$y = \rho\ (Y, U\ V, C\%)$$

The objective of this work is to develop a regression model. The regression model was created using the Taguchi design method and tested with statistical criteria, with the results expressed through ANOVA analysis.

II. GMAW PROCESS.

The semi-automatic welding process is depicted in the diagram (Figure 1). This method uses a self-shielded wire, which also melts internally. Compared to manual welding, it allows for increased weld weight, leading to higher productivity.

Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) and metal active gas (MAG) is a welding process in which an electric arc forms between a consumable MIG wire electrode and the workpiece metal(s), which heats the workpiece metal(s), causing them to fuse (melt and join). Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from atmospheric contamination.

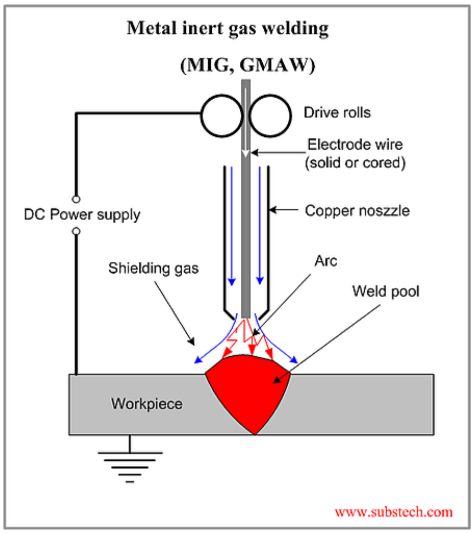

Fig 1. GMAW welding process.

The impact of surface overlay using the semi-automatic welding method to improve surface wear properties depends on several parameters. These include:

- The penetration depth of the weld is influenced by the current.
- The particle size of the material being deposited.
- It also depends on factors such as the coating thickness.

A small change in some of these factors can significantly impact the penetration depth.

2.1. Taguchi Method.

The quality engineering methods of Taguchi, employing design of experiments (DOE), is one of the most important statistical tools for designing high-quality systems at a reduced cost.

The Taguchi method provides an efficient and systematic way to optimize designs for performance, quality, and cost.

Optimization of process parameters is the key step in the Taguchi method to achieve high quality without increasing cost. This is because optimization of process parameters can improve quality characteristics and the optimal process parameters obtained from the Taguchi method are insensitive to the variation of environmental conditions and other noise factors.

Classical process parameter design is complex and not an easy task. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with a small number of experiments only. Furthermore, Taguchi has created a transformation of the repetition data to another value, which is a measure of the variation present. The transformation is known as signal-to-noise (S/N) ratio. The S/N ratio consolidates several repetitions (at least two data points are required) into one value, which reflects the amount of variation present. There are several S/N ratios available depending on the type of characteristic; lower is better (LB), nominal is best (NB), or higher is better (HB). The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the quality of the quality characteristic, a large S/N ratio corresponds to a better-quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. A statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant.

III. MATERIALS AND METHODOLOGY.

The experiment was conducted at the National University of Science and Technology of Mongolia. The welding process used an EWN brand semi-automatic welding machine, and the welding current was selected in three modes: 80A, 100A, and 120A. The surface overlay was performed on low-carbon steel workpieces prepared for the experiment.

The dimensions of the workpieces were 30x60x0.5 mm. Additionally, the surface of the steel was overlaid with chromium-based alloy powders of particle sizes 0.5, 0.6, and 0.7 mm, applied with coating thicknesses of 1, 1.5, and 2 mm. The hardness of the overlaid workpieces was measured in Rockwell units. The overlaid workpieces from the experiment are shown in the following image.

Fig 2. Coated test specimen.

In this study, we considered the following three factors. These include:

1. Particle size of the wear-resistant chromium powder material, mm (X_1)
2. Coating thickness, mm(X_2)
3. Current, A (X_3)

Welding current directly influences the depth of penetration and the extent of base metal fusion.

Table 1. Welding parameters and their levels.

№	X_1	X_2	X_3
1	0.5	1	80
2	0.6	1.5	100
3	0.7	2	120

Welding current affects the shape of the weld bead and the penetration depth, which are also influenced by the electrode diameter or particle size. Proper selection of welding parameters has a positive impact on the quality of the weld. Therefore, while many direct and indirect parameters influence the quality of the semi-automatic welding process, the three main process parameters considered are welding current, particle size of the filler material, and coating thickness, each analyzed at three different levels. The values of the welding process parameter levels are shown in Table 1.

IV. RESULTS AND DISCUSSION.

4.1.Creating Taguchi Design Using Minitab software.

"To select the optimal values of input parameters, input the parameters into the Minitab software and create the Taguchi L9 (3^3) orthogonal array."

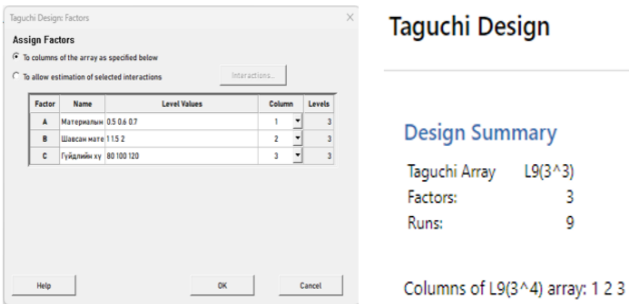

Fig 3. Entering three factors, three levels of naming, and numerical values into Minitab.

4.2. The results of the Taguchi design for the surface hardening of low-carbon steel with a chromium alloy coating show the outcome of the cladding process.

"Using Minitab software, the experimental matrix for determining the key parameters for surface hardening of structural steel with chromium alloy for wear resistance was generated by the Taguchi method, as shown in Table 2."

Table 2. Levels of process parameters used in Taguchi L9.

№	X_1	X_2	X_3
1	0.5	1.0	80
2	0.5	1.5	100
3	0.5	2.0	120
4	0.6	1.0	100
5	0.6	1.5	120
6	0.6	2.0	80
7	0.7	1.0	120
8	0.7	1.5	80
9	0.7	2.0	100

The **Signal-to-Noise (S/N) ratio** is an important performance measure in Taguchi's robust design methodology, used to optimize process parameters. In your case, you are interested in **wear resistance** and want to apply the **"Smaller is Better"** principle, meaning lower wear levels (or wear resistance) are more desirable. Here's how the **S/N ratio** is applied in your study:

Table 3. S/N Ratio Table (lower wear levels).

Түвшин	Particle size of the wear-resistant chromium powder material	Coating thickness	Current
1	4.53	4.96	5.06
2	1.94	1.27	0.1
3	-0.61	-0.37	0.77
Делта	5.14	5.33	4.96
Ранк	2	1	3

Table 4. Response Table for Means.

Level	Particle size of the wear-resistant chromium powder material	Coating thickness	Current
1	0.69	0.65	0.64
2	0.8	0.86	1.03
3	1.1	1.08	0.92
Delta	0.4100	0.4267	0.39
Rank	2	1	3

From Table 4, the most suitable levels for the most significant values are as follows. This shows that the coating thickness is one of the most important parameters, significantly influencing the improvement of abrasion resistance.

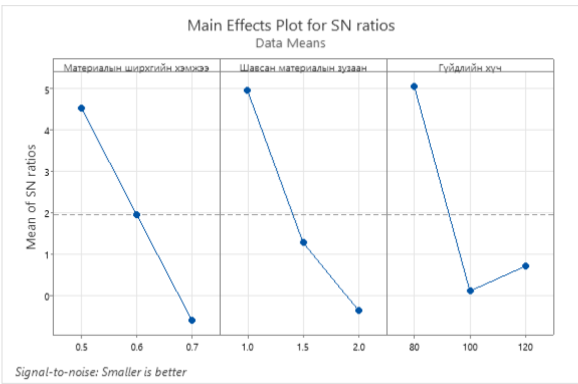

Fig. 4. Effect of process parameters on S/N ratio.

Delta Statistics in the context of Taguchi's method is used to quantify the effectiveness of each factor on the response variable (in your case, wear resistance). It represents the difference between the highest and lowest average values of the response for each factor at different levels. The larger the delta, the more significant the factor is in influencing the response.

4.3. Analysis of Variance (ANOVA).

In your case, the **experimental data** was analyzed using **MINITAB 14** software, a statistical analysis tool commonly used for such purposes. MINITAB provides a robust framework for performing ANOVA, helping to identify significant parameters in the process.

To determine whether the parameters such as chromium alloy powder material (X_1), thickness of the coating material (X_2), and welding current (X_3), along with their interactions, have a statistically significant effect on the abrasion resistance of the chromium-alloy-coated steel surface, Analysis of Variance (ANOVA) was performed on the experimental data.

In Table 5, you would summarize these findings, showing the F-values, p-values, and the percentage of variance explained by each factor, which helps in understanding their significance.

By performing this **ANOVA analysis** in **MINITAB 14**, you can make data-driven decisions on how to adjust the parameters to optimize the abrasion resistance of the material.

Table 5. Analysis of Variance.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.6456	0.21521	7.34	0.028
X_1	1	0.2522	0.25215	8.60	0.033
X_2	1	0.2731	0.27307	9.31	0.028
X_3	1	0.1204	0.12042	4.11	0.099
Error	5	0.1466	0.02932		
Total	8	0.7922			

Table 6. Coefficients.

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-1.713	0.588	-2.91	0.033	
X_1	2.050	0.699	2.93	0.033	1.00
X_2	0.427	0.140	3.05	0.028	1.00
X_3	0.00708	0.00350	2.03	0.099	1.00

Since the **T-value** is greater than the theoretical value of **2.01**, it confirms that the parameters are **statistically significant** and have a significant impact on the process. This emphasizes the importance of these factors in optimizing the process.

Table 7. Model Summary.

S	R-sq	R-sq(adj)	R-sq(pred)
0.1712	81.5%	70.4%	49.8%

These results suggest that optimizing the three key parameters will likely have a **significant impact** on improving the abrasion resistance, but other unaccounted factors may still play a role in the overall wear behaviour.

4.4. Applications of Regression Analysis.

A mathematical model to predict the abrasion resistance of low carbon steel surface, based on process parameters such as abrasion-resistant chromium alloy powder, coating thickness, and current strength, was developed using regression analysis in MINITAB statistical software.

Regression Equation.

$$\text{Wear rate} = -1.713+2.050(X_1) + 0.427(X_2) + 0.00708(X_3) \quad (1)$$

Here:

- Y – Minimum wear (gram/min)
- X_1 – Material particle size, (mm)
- X_2 – Thickness of the plaster material, (mm)
- X_2 – Current, (Amper)

In this study, the abrasion results showed a good fit with the regression models, as evidenced by an R^2 value of **0.82**. This means that 82% of the variation in abrasion is explained by the selected process parameters in the regression model, suggesting that the model is reliable and provides a strong correlation between the parameters and the abrasion resistance.

The mathematical model was developed using **MINITAB** software with the goal of evaluating the abrasion resistance of the coated steel surface. The results predicted by the model were calculated based on the input data provided. The abrasion values obtained from the experiments are shown in the following table.

Table 8. Measured values from the test specimen.

№	X_1	X_2	X_3	Элэгдлийн хэмжээ, гр
1	0.5	1.0	80	0.25
2	0.5	1.5	100	0.87
3	0.5	2.0	120	0.96
4	0.6	1.0	100	0.75
5	0.6	1.5	120	0.85
6	0.6	2.0	80	0.8
7	0.7	1.0	120	0.96
8	0.7	1.5	80	0.87
9	0.7	2.0	100	0.95

V. CONCLUSION.

This article presents a methodology for determining the optimal parameters of a semi-automatic welding process using the Taguchi method and regression analysis. The research work was conducted based on the Taguchi experimental design. ANOVA was used to study the effects of welding parameters, and a mathematical model was developed using **MINITAB** software for prediction. The proposed mathematical model is fully applicable under the given welding conditions.

The analysis indicates that the particle size of the material, the thickness of the coated layer, and the welding current are key parameters that significantly influence abrasion resistance. This is confirmed by the results of the ANOVA analysis.

1. The variance analysis shows that the parameters that have the most significant impact on abrasion resistance are the coating thickness and the particle size of the material.
2. The regression analysis predictions align well with the results of the validation experiments.

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