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Multiparametric Optimization and Prediction of Tool Steel Machined Surface Quality in Accurate Wire Electrical Discharge Machining

Abstract: - This article explains the multiparametric optimization of machined surface quality and provides mathematical models that can predict the high productivity of the WEDM process for tool steels as well as the superior quality of a precisely machined surface. The experimental study was carried out using four technological factors and the full DoE factorial design method. The output quantitative parameter Material Removal Rate (MRR) and the observed output qualitative parameter Surface Roughness (SR) were evaluated using Grey Relational Analysis (GRA) and Analysis of Variance (ANOVA). To represent the diverse responses of the tool steels being studied, Multiple Regression Models (MRM) were developed using a regression tool set. Although the parameters were linked to the positive outcomes of the output-dependent parameters SR and MRR.The multiparametric optimization findings demonstrated a link between the input variable parameters of the electrical discharge process in the case of low peak current I, low value of pulse on-time duration ton, low voltage of discharge U, and high value of pulse off-time duration toff. The multiparametric optimization produced significant results that demonstrated the reciprocal dependence between the observed output process parameters. An ideal SR value of 1.50 μm and an MRR value of 12.50 mm3·min−1 were obtained using L8-level settings using the input variable parameters I, ton, U, and toff (2 A, 32 μs, 90 V, and 20 μs, respectively).

Keywords: optimization, accuracy, surface quality, steel tool, and electrical discharge machining of wires.

I.INTRODUCTION

In practically all production technologies, there is a genuine need to improve the quality of machined surfaces. This is also true with Wire Electrical Discharge Machining (WEDM) technology. The issue, though, is that improving the quality of the machined area—particularly in precision WEDM—is linked to a decline in total process efficiency and productivity. This technique must meet the high standards of the current level of science and technology, which is focused on producing high-quality machined surfaces while also attaining high productivity of machining operations, in order to become generally competitive.

This issue seems to have a good answer in multiparametric optimization. Qualitative indicators of the machined surface are particularly important in multiparametric optimization because they have a big influence on the overall quality of the final product and the overall productivity of the electrical discharge process. Multiparametric optimization of a machined surface is carried out by looking for an appropriate combination of

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settings for the primary technological parameters. Technological parameters include pulse on-time duration (ton), pulse off-time duration (toff), peak current (I), and discharge voltage (U).

The mechanical and physical characteristics of the material being machined, the wire electrode's characteristics, its tension, the wire's diameter, the dielectric liquid's characteristics, and other machining-related elements that have a substantial impact on the machined surface's quality and the electro erosion process's productivity are all considered process parameters. In order to determine the ideal values of the output indicators, a suitable combination of the settings of the primary technological and process parameters of the electro erosion process is sought. Several pertinent experimental studies have been conducted to date with the goal of improving the quality of machined surfaces following EDM with a wire electrode in terms of dimensional and geometric accuracy and precise surface quality in terms of roughness parameters from the point of view of low thermal impact on surface and subsurface layers, according to an analysis of the current state of the given issue. These experiments were conducted from several perspectives. The goal of a number of experimental studies was to increase the MRR and total electrical productivity while reducing the wear of the wire tool electrode (TWR). The impact of machining factors on overall performance is key for today's modern industry, particularly when it comes to attaining a higher MRR, good dimensional accuracy, and outstanding performance. At the same time, precise WEDM's low production issues are still present. Because of this, multiparametric optimization with various responses in tool steel machining seems to be a very current topic. Thus, achieving a major advancement in the optimization of machined surface quality while preserving high electrical discharge process productivity was the goal of the conducted experimental research. In order to maximize the efficiency of the

experimental research, the primary contribution was the acquisition of Multiple Regression Models (MRM) to forecast the setting of specific input technological parameters technique of electrical discharge while producing a superior machined surface.

II.MATERIALS AND TECHNOLOGY EMPLOYED IN THE EXPERIMENTAL RESEARCH PROJECT

In the course of the experimental investigation, samples were made using three different types of tool steel: EN X37CrMoV5-1 (W.-Nr. 1.2343), EN 35CrMo8 (W.-Nr. 1.2311), and EN X210Cr12 (W.-Nr. 1.2080), which is a low-alloy tool steel. In addition to having excellent hardenability, high heat strength, and resistance to tempering, EN X37CrMoV5-1 is a chromium-molybdenum-silicon-vanadium tool steel that can be hardened in both air and oil. When exposed to both normal and high temperatures, it exhibits good plastic qualities and resilience to cracking. When heat treated, it can reach a strength of $Rm \geq 1800\ N\cdot mm^{-2}$. It is both hot-formable and well-machinable.

It produces hot forming tools (die and die liners), die-casting molds for aluminum, zinc, and magnesium alloys and their stationary and moving components, and water-cooled tools such dies, mandrels, jaws, punches, shears, etc. The chromium-molybdenum tool steel EN 35CrMo8 has excellent heat strength and hardenability. With a strength of $Rm \geq 2000\ N\cdot mm^{-2}$, it can be used for nitriding, cementing, and hardening. Because of its good machinability when annealed, it is used for thermally stressed tools and sections of molds and hot forming tools. It is also appropriate for die-casting molds and big injection molds for plastic materials. Both hot-formable and machinable.

The chrome ledeburite tool steel EN X210Cr12, which has an alloying element percentage of 1.80–2.05% C and 11.0–12.5% Cr, is distinguished by its great resistance to abrasion wear and its ability to tolerate dimensional changes even at high temperatures. With a strength of $Rm > 2300\ N\cdot mm^{-2}$, it can be hardened in both oil and air. It has very high compressive strength, low toughness, and good cutting qualities. It is ideal for producing complexly formed and highly stressed cold shearing tools because of these characteristics.

The Swiss company GF makes the AgieCharmilles CUT E 350 wire electrical discharge equipment, a contemporary, small, and self-sufficient electro erosion tool for cutting metallic electrically conductive materials with a wire tool electrode. Among the numerous special features and capabilities of this electro erosion equipment are the ergonomic AC CUT HMI interface with a 19" touch screen, the Thermoset module for wire preparation, automatic wire threading, bevel cutting capability, and many more.

In the presence of a liquid dielectric made of demineralized water with an electrical conductivity of less than 10 μS·cm−1, the experimental samples were subjected to electrical discharge machining (EDM). A 0.25 mm wire electrode with the marking AC Brass LP 1000 was employed as a tool. The electrode is a brass multipurpose electrode that can be used for a variety of tasks on contemporary electrical discharge devices. Given the cost-effectiveness of the electrical discharge technique, it is particularly well-suited for accurate machining and is therefore classified as a universal wire electrode.

The quality of the machined surface and the effectiveness of the electrical discharge process in WEDM of tool steels are primarily determined by the combination of settings of the primary input technological parameters, as was already indicated in the introduction. The evaluated output parameters SR and MRR of the electrical discharge process are also influenced significantly by the peak current I (A), the pulse on-time duration ton (μs), the pulse off-time duration toff (μs), and the discharge voltage U (V), according to the analysis that was conducted.

III.EXAMINATION OF VARIOUS ASPECTS OF MULTIPARAMETRIC OPTIMIZATION OF THE ELECTRICAL DISCHARGE PROCESS'S OUTPUT PARAMETERS MRR AND SR

A number of factors must be taken into account while doing multiparametric optimization of the electrical discharge process's output parameters, SR and MRR. The meticulous creation of Multiple Regression Models (MRMs) is the crucial stage in accomplishing a pertinent multiparametric optimization of the output quantitative performance parameter MRR of the electrical discharge process and the output qualitative parameter SR of the machined surface. Deterministic approaches, which are not bound by the same rigorous mathematical reasoning as traditional optimization techniques, were thus used in the design . However, because it can occasionally be challenging to get pertinent gradient data, making objective functions impossible to construct, conventional gradient-based methods are not always appropriate for modelling.

One advantage of stochastic and metaheuristic procedures over traditional approaches is that they don't require extra data to be included. Furthermore, these methods add a random step size to the numerical iteration that is based on calculations. This indicates that because of random initialization, algorithms in this category frequently don't need any initial guess values. ANOVA is helpful for determining the effects and the percentage contribution. Simultaneously, components can be removed from the MRR without negatively affecting the output monitored indicators, SR and MRR.

The study that was carried out made it possible to separate the contributions of each parameter and the error from the total response variability, which is the sum of the squared deviations around the grand mean. To determine the significance of the chosen response, the p-value (probability of significance) is typically computed using the F-value or Fisher's F-ratio. The significance was assessed using a p-value, where a $p\text{-value} < 0.05$ indicates that the input factors had a substantial impact on the response variable. On the other hand, input factors with a value of p˜ 0.05 could be eliminated from the MRR without having any negative effects because they have no effect on the response variable. Degrees of freedom (DF), as well as the

availability of independent data, are required to assess the Mean Square (MS)Squared sums (SS). The Mean Square Deviation (MSD) and F-values in an ANOVA analysis are computed as follows: F = MS for Source Parameter/MS for error and MS = SS/DF.

However, as previously stated, a mutual combination of the input MTP settings determines both the electro erosion process's productivity MRR and the machined surface's final quality (SR). Therefore, it is necessary to approach these two output indicators of the electro erosion process in a sophisticated manner when multiparametric ally optimizing machined surface quality and maximizing productivity during WEDM of tool steels by mathematical modelling. The conventional Taguchi approach is limited to optimizing a single objective and is unable to simultaneously resolve numerous parameters. This indicates that this method can only optimize the SR and MRR parameters independently, and that setting one response parameter optimally does not guarantee.

As a result, it is preferable to choose a technique that maximizes all goals while offering the ideal input parameter settings. In order to analyse the correlation between many response parameters throughout the multiparametric optimization process, the Grey Relational Analysis (GRA) method was utilized. This approach additionally computes the Grey Relation Coefficient (GRC) and normalizes the response parameters. The performance of the electrical discharge process with various responses may then be assessed by averaging the GRC relational coefficient for each chosen response, which yields the overall relational degree. The greatest degree Grey Relation is then obtained by transforming the multi-response problem into a single-response optimization scenario using the best parametric combination

IV. PLANNING AN EXPERIMENT WITH THE DOE METHOD

The design of the experimental plan was based on the DoE approach. In this way, a 4-factor analysis was performed on two tiers of MTP-dependent input settings. After accounting for the peak current I, the discharge voltage U, the pulse on-time duration ton, the pulse off-time duration toff, and the pulse on-time duration ton, this produced 16 experimental samples for each tool steel. This resulted in a total of 48 experimental samples. Figure 3 shows the experimental samples made from the EN X37CrMoV5-1, EN 35CrMo8, and EN X210Cr12 tool steels using the WEDM technique. Separate surfaces, each 30 mm by 15 mm, were made at the MTP setup's L1 level.

Fig.4.1.WEDM-produced experimental samples of tool steels EN X37CrMoV5-1, EN 35CrMo8, and EN X210Cr12 at the L1 level of the MTP parameters.

The parameters I, ton, toff a, and U were used to set the input-independent MTPs at two levels, Low Value (LV) and High Value (HV), in the order indicated in Table 4 (LV: 2 A, 8 µs, 1 µs, and 70 V; HV: 19 A, 32 µs, 20 µs, and 90 V). The quality of the machined surface SR and the efficiency of the electrical discharge process were experimentally determined using the MRR parameter during WEDM of tool steels No. 1 (EN X37CrMoV5-1).

According to the experimental measurements, tool steel No. 3 (EN X210Cr12) had the lowest value of SR = 0.18 µm. Level L3 was set for the input-independent MTPs of the electrical discharge process (I = 2 A, ton = 8 µs, toff = 20 µs, and U = 70 V). When the input-independent MTPs of the electrical discharge process were set to level L14 (I = 19 A, ton = 32 µs, toff = 1 µs, and U = 90 V), tool steel No. 1 (EN X37CrMoV5-1) had the highest value of SR = 3.98 µm.

When the input-independent MTPs were set to level L14, Tool Steel No. 1 had the highest MRR = 26.87 mm3·min−1 value. 3.21 mm·min−1 was the lowest MRR value for tool steel No. 3 when the input-independent MTPs were set to level L3. The results of the experimental measurements show that the mandatory values of the output parameters of the electroerosion process (maximum MRR and minimum value of Ra) are incompatible with each other. Furthermore, tool steel No. 3 clearly had the lowest values of both output-dependent parameters under the same input-independent MTP settings.

However, tool steel No. 1 did have the highest values noted. This suggests that because of the characteristics of the machined material, the final output parameters of the electro erosion process may differ even when the input-independent MTPs are the same. This variation in the output quality parameter (SR) of the machined surface during WEDM varied between 0.02 and 0.07 μm for tool steels No. 1, No. 2, and No. 3. mm3·min−1 is the range of the electroelution process's output performance parameter (MRR). We considered the mean value of the output-dependent parameters, SR and MRR, for the multiparametric optimization and subsequent analysis. Then, using a DoE factor analysis on the recorded data, the main effect of the chosen procedure was identified.

V. THE GRA METHOD IS USED TO ANALYZE THE OUTPUT PARAMETERS SR AND MRR DURING TOOL STEEL ELECTROEROSION.

The objective of multi-parametric optimization of the electro erosion process's output qualitative parameter (SR) and quantitative performance parameter (MRR) is for the MRR parameter to reach higher values (HB) and the SR parameter to reach lower values (SB).

The output quality parameter SR = 0.20 μm for WEDM of tool steels had the lowest average value (SB) when the input-independent MTPs of the electrical discharge process were set at the L3 level, as can be seen. The output quantitative performance metric MRR = 26.81 mm3·min−1 had its highest average value (HB) when the input-independent MTPs were set at the L14 level. Utilizing the GRA method for analysis, the GRC and GRG of the output observed.

It is true that the relationship between the ideal sequence, $x*0(k)$, and the given sequence, $x*i(k)$, is stronger the higher the assessed GRG value. Consequently, the optimal response to the process under the experimental setup is the ideal sequence $x*0(k)$. As a result, the combination of process input parameters that is closest to its ideal configuration has the highest GRG. This is equivalent to the electrical discharge process's combination of input MTPs in our situation, which was used in tests L3 and L14. The combination of the input-independent MTP settings during tool steel WEDM with the main focus on SR parameter minimization correlated with the L3 level setting at the same time.

The best parametric combination of the electrical discharge process's input-independent MTPs was chosen using Table 8's highest mean GRG values. Higher mean GRG values suggest minimal SR values and maximum MRR values, which in turn indicate greater performance and a stronger correlation with the reference sequence. When WEDMing tool steels with a wire electrode, the output quality parameter of the machined surface is more important, as seen by the GRG weights of 0.50895 for SR and 0.49105 for MRR.

VI.UTILIZING THE ANOVA METHOD TO ANALYZE THE RECORDED VALUES OF THE ELECTROEROSION PROCESS'S INPUT AND OUTPUT PARAMETERS IN RELATION TO GRG

The next step was to use the Analysis of Variance (ANOVA) method to examine the impact of the input-independent MTP settings on the quality of the machined surface SR and the electrical discharge process MRR performance after identifying the ideal combination of these settings during WEDM of tool steels. The goal was to determine, at a 95% confidence level, how key input technological elements affected the various replies in order to provide crucial information about the experimental results.

Given that their p-values are less than 0.05, the ANOVA table indicates that I, ton, and toff are the significant parameters of the electrical discharge process that influence numerous responses. Following the conclusion that the impact of each individual electrical discharge process input parameter on the output indicators SR and MRR during tool steel WEDM was significant, a confirmatory experiment was conducted to enhance the GRG indication.

A verification test of the empirical and experimental values of SR and MRR obtained during WEDM of tool steels with respect to GRG revealed improvements in both responses of the output-dependent parameters, with improvements of 1.6% for the MRR parameter and 2.8% for the SR parameter. It was found that the GRG indicator for SR improved at a level of 0.03514 for the electrical discharge process's projected input parameters and 0.06622 for the experimental ones. For the projected input parameters of the electrical discharge process, the GRG indicator for the MRR improved to 0.08058, whereas for the experimental ones, it improved to 0.11142.

VII.MRM PROPOSAL FOR SR AND MRR OUTPUT PARAMETER PREDICTION DURING TOOL STEEL WEDM

Multiparametric optimization of the output dependent qualitative indicator (SR) of the machined surface and the quantitative performance indicator (MRR) of the electrical discharge process in tool steel machining with a wire electrode was accomplished by compiling Multiple Regression Models (MRMs) at a 95% confidence level. The SR and MRR parameters were predicted using peak current I, pulse on-time duration ton, and pulse off-time duration toff as MRM input parameters.

The determination coefficient R2, which for the output quality parameter SR takes a value of 0.9972, indicates the accuracy of the calculated MRM. This indicates a 0.28% difference between experimentally measured and empirically determined values.

The prediction of the impact of the individual input factors I, ton, and toff on the output qualitative parameter SR of the machined surface during WEDM of tool steels with regard to its minimization can be seen based on the Multiple Regression for SR results shown in Figure 8. Simultaneously, the anticipated set-up of five input factor settings is shown in relation to the minimization of the obtained parameter SR in the 0.34–2.355 μm range.

At the level of 0.13%, the variation between experimentally measured and empirically determined values is represented by the value of the determination coefficient R2 for the calculated MRM of the output performance parameter MRR, which comes out to be 0.9987.

Individual input parameters I, ton, and toff have an impact on the output quantitative performance parameter of the electrical discharge process in the machining of tool steels with respect to its maximizing, according to the Multiple Regression for MR.

Simultaneously, the maximum MRR parameter is maximized in the range of 23.9225 to 7.51375 mm3·min−1 by combining the five settings of the input factors indicated.

Several facts can be noted from the Multiple Regression reports that were acquired for the purpose of predicting and optimizing the performance parameter MRR during WEDM of tool steels and the output dependant quality parameter SR of the machined surface. First, it is evident that during WEDM of tool steels, the output quality parameter SR significantly increases as the parameters I and ton decrease and the toff parameter increases. When I = 2 A, ton = 23 μs, and toff = 20 μs are combined, the result is 0.74 μm. Nevertheless, the MRR productivity value of the electrical discharge process is at a low level of 7.51375 mm3·min−1 with the specified combination of input-independent MTPs.

On the other hand, during WEDM of tool steels, the output quantitative parameter MRR significantly increases as the I and ton parameters increase and the toff parameter decreases. When I = 19 A, ton = 8 μs, and toff = 1 μs are combined, the result is 17.2725 mm3·min−1. The machined surface's output qualitative parameter, with the specified combination of input MTPs, is SR = 2.355 μm.

VIII.MAXIMIZATION OF MRR PRODUCTIVITY DURING WEDM OF TOOL STEELS BY OPTIMIZATION OF THE MACHINED SURFACE QUALITY PARAMETER SR

Based on the data collected, a mutual optimization of the machined surface SR's output qualitative indicator was then conducted in order to maximize the electrical discharge process MRR's productivity during tool steel WEDM. The output parameter SR is graphically optimized in Figure 10 in order to maximize the MRR parameter.

The output qualitative parameter of the machined surface SR is projected to increase in value in tandem with the rising value of the electrical discharge process MRR's output quantitative parameter during tool steel WEDM. Setting the input technological parameters at the L1 level results in the MRR = 5.05 mm3·min−1 and the expected value of SR = 0.05 μm. When the L16 level of input technological parameters is used, the MRR = 29.5 mm3·min−1 and the projected value of SR = 3.75 μm are obtained. The optimal combination of input technological parameter settings for WEDM of tool steels, according to the optimization that was carried out, seems to be at the L13 level, with I = 19 A, ton = 32 μs, and toff = 1 μs.. The expected values of MRR and SR at this setting level are 22.50 mm3·min−1 and 2.75 μm, respectively. Levels L11 through L15 comprise a range of parameters with an appropriate optimization extent. For the specified values, the MRR ranges from 18.0 to 27.50 mm3·min−1, while the expected value of SR ranges from 2.25 to 3.50 μm.

The same trend as the predicted values can be seen based on the graphical optimization of the machined surface's real quality parameter SR values that was done without focusing on maximizing the quantitative performance parameter MRR during WEDM of tool steels. This implies that the real value of the output qualitative parameter SR of the machined area rises in tandem with the increasing value of the output quantitative parameter of the electrical discharge process MRR during WEDM of tool steels. The actual values of SR and MRR are 0.18 μm and 4.95 mm3·min−1, respectively, when the input MTP is set at the L1 level.

When the input MTPs are set to the L16 level, the MRR is 26.75 mm3·min−1 and the true value of SR is 3.95 μm. The L8 level during WEDM of tool steels seems to have the best combination of input MTP settings, which includes I = 2 A, ton = 32 μs, and toff = 20 μs, according to the graphical optimization that was carried out. The MRR is 12.50 mm3·min−1 and the true value of SR is 1.50 μm at this setting level. Levels L6 through L10 comprise a range of parameters with an appropriate optimization extent. The MRR ranges from 9.14 to 17.19 mm3·min−1, while the true SR value falls between 0.98 and 2.33 μm for the specified range of values.

VIII.CONCLUSION

The experimental study aimed to predict and multiparametric ally optimize the output-dependent parameters SR and MRR during WEDM of tool steels using a 0.25 mm diameter brass wire electrode. Regarding MTP settings, the SR and MRR parameters were predicted and multiparametrically optimized. Four input variables (I, ton, toff, and U) were evaluated from the standpoint of MTPs. During WEDM, discharge current I was found to be the most significant parameter in relation to SR and MRR, followed by ton and toff. The Mean GRG values were used to determine an appropriate combination of settings (I1-ton1-toff2-U1) for the input MTPs of multiple responses for SR during WEDM of tool steels.

The developed MRMs produced for the chosen output response variables represent experimental results with tiny, insignificant errors that help the model optimization, even though the WEDM process has a phase dependence on the MTPs. The remarkable predictability of the MRR and SR parameters is confirmed by their respective deviations of values of 0.13% and 0.28%. To discover the greatest MRR and minimum SR, the results were examined using GRA. The importance of the machined surface's output qualitative characteristic during WEDM of tool steels is indicated by a greater weighted Mean GRG = 0.50895 for SR compared to a weighted GRG = 0.49105 for MRR.

The GRG indicator was improved for SR at 0.03514/0.06622 and for MRR at 0.08058/0.11142, respectively, by conducting a verification test to improve the GRG indicator at settings of I1-ton1-toff2-U1 and I2-ton2-toff1-U2 of the input (predicted/experimental) technological parameters during WEDM of tool steels with respect to their initial setting at levels of I1-ton1-toff1-U1 and I2-ton2-toff2-U2 of the initial setting. The SR and MRR values derived via graphic optimization differ by 2.8% and 1.6%, respectively, from the confirmation experiment.

The output power parameter MRR is maximized at the ideal value of 2.75 μm found for the SR parameter. Without focusing on maximizing the quantitative performance parameter MRR during WEDM of tool steels, the optimal value of the qualitative parameter SR of the machined area, as indicated by experimentally acquired values, was 1.50 μm at the L8 level of the MTP parameters. A broader range of tool steels, including low-, medium-, and high-alloy steels, were used within the experimental research's parameters. Consequently, the complete class of alloy tool steels can benefit from the experimental results that multi-parametric optimization produced.

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