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Effects of wire-EDM machining variables on surface roughness of newly developed DC 53 die steel: Design of experiments and regression model

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Abstract

DC53 is a newly developed cold die steel from Daido Steel, Japan. It is an improvement over the familiar cold die steel SKD11. Because DC53 is a new die steel, only little information is available in literature for its machining characteristics. This paper presents an investigation of the effects of machining variables on the surface roughness of wire-EDMed DC53 die steel. In this study, the machining variables investigated were pulse-peak current, pulse-on time, pulse-off time, and wire tension. Analysis of variance (ANOVA) technique was used to find out the variables affecting the surface roughness. Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. Quantitative testing methods on residual analysis were used in place of the typical qualitative testing techniques. Results from the analysis show that pulse-on time and pulse-peak current are significant variables to the surface roughness of wire-EDMed DC53 die steel. The surface roughness of the test specimen increases when these two parameters increase. Lastly, a mathematical model was developed using multiple regression method to formulate the pulse-on time and pulse-peak current to the surface roughness. The developed model was validated with a new set of experimental data, and the maximum prediction error of the model was less than 7%.

Keywords: DC53 die steel; Wire-EDM; Surface roughness; Analysis of variance; Analysis of residuals; Multiple regression

1. Introduction

Die-making industry is very important to down-stream industries such as deep drawing, cold forging, and plastic injection molding. Any technological changes in the die-making industry surely affect those in down-stream manufacturing. One of the technological developments in die-making industry is novel materials for making various kinds of dies. New die steels have been continuously introduced to the die manufacturers, and affect their die-making processes or to their die quality. DC53 is a newly developed cold die steel from Daido Steel, Japan. It is an improvement over the familiar cold die steel SKD11. DC53 eliminates the disadvantage of insufficient hardness and toughness, resulting from high-temperature tempering found in SKD11, and is intended to replace SKD11 in use for general purposes and precision dies [1]. Because DC53 is a new die steel, little information is available in literature for its machining characteristics.

New materials with high hardness and toughness, such as die and tool steels, are being developed. Those materials are difficult to be machined by conventional manufacturing techniques such as milling, drilling, and turning. Hence, non-traditional machining processes including electrochemical machining, ultrasonic machining, and electrical discharge machining (EDM) are employed. Wire electrical discharge machining (wire-EDM), a form of EDM, is a non-traditional machining method that is widely used to pattern tool steels for die manufacturing. Wire-EDM uses electro-thermal mechanisms to cut electrically conductive material. The material is removed by a series of discrete discharges between the wire electrode and the workpiece in the presence of a dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The region in which discharge occurs is heated to extremely high temperatures, so that the work surface is melted and removed. The flowing dielectric then flushes away the removed particles. The strength and hardness of the work material are not factors in EDM. Only the melting point of the work material is an important property. Although wire-EDM machining is a complex system, the use of this machining process in industry has increased because of its capability in

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cutting complicated forms, especially created in hard materials [2–6].

Surface roughness is a machining characteristic that plays a very critical role in determining the quality of engineering components. A good quality surface improves the fatigue strength, corrosion and wear resistance of the workpiece [7–10]. The main purpose of this paper is to investigate effects of machining variables on surface roughness of wire-EDMed DC53 die steel. The investigated machining variables were pulse-on time, pulse-off time, pulse-peak current, and wire tension. Analysis of variance (ANOVA) was used as the analytical tool in studying effects of these machining variables. Another objective of this paper is to emphasize the importance of assumption checking when using ANOVA. Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. Quantitative testing methods on residual analysis were employed instead of the typical qualitative testing techniques. Lastly, a mathematical model was developed using multiple regression method to predict surface roughness of wire-EDMed DC 53 die steel.

2. Experiment

2.1. Materials and methods

Material employed in this study was DC53 cold die steel. It is a high alloy tool steel, and well known for high hardness and toughness. Because the patent of DC53 die steel is pending, its chemical composition is not yet revealed [1]. As received DC53 bar was machined into desired dimensions. The width, length, and thickness of the specimen were 27, 65, and 13 mm, respectively. The specimens were then heat treated to relieve the residual stresses. Each specimen was wire-EDMed along its length into two halves as shown in Fig. 1.

The wire-EDM machine used in this study was Sodick model A280 with the wire electrode made from Cu–35 wt.%Zn. The wire was KH Sodick with 0.25 mm in diameter, and can tolerate a tension up to 95 $\mathrm{kg_f/mm^2}$. After machining, the specimen was measured surface roughness of the EDMed surface along the cutting direction. The surface finish parameter employed to indicate the surface quality in this experiment was the arithmetic mean roughness (R_a). The surface profiler used in this study was Precision Device model PDD-400-bo. On each machined surface, the surface roughness was measured three times at three different locations—left, right, and middle of the machined surface. The average value of these three measurements was used as the surface roughness of the specimen. The scan length and cut-off length of the measurement were 12.7 and 0.80 mm, respectively.

2.2. Experimental designs

The experiment performed in this study was a screening experiment. The experimental strategy used in this experiment was full factorial design (2^k) with three replications where k is the number of controlled variables in the experiment. In this experiment, there were four controlled variables investigated including pulse-on time (ON), pulse-off time (OFF), pulse-peak current (IP), and wire tension (WT). Two levels of each factor were selected for the 2^k experiment as follows: pulse-on times at 2 and 5 ms; pulse-off times at 5 and 15 ms; pulse-peak currents at 16 and 17 A; wire tensions at 7 and 15 $\mathrm{kg_f/mm^2}$. These machining conditions were chosen based on typical operating conditions of the machine recommended for cutting tool steels. Each machining condition had three replications; therefore, the total number of experimental trials was 48. Replication of experiment has two important characteristics. First, it allows the experimenter to obtain an estimate of the experimental error. This estimate of error becomes a basic unit of measurement for determining whether observed differences in the data are really statistically different. Second, if the sample mean is used to estimate the effect of a factor in the experiment, then replication permits the experimenter to obtain a more precise estimate of this effect. In this experiment, both the allocation of the experimental material and the order in which the individual trials of the experiment are to be performed are randomly determined because ANOVA requires that the observations or errors be independently distributed random variables. Randomization usually makes this assumption valid. By properly randomizing the experiment, the effects of extraneous factors or confounding variables that may be present are averaged out. Confidence level of 95% ($\alpha = 0.05$) was used throughout analyses of the experiment. In addition, high-order interactions were neglected in this screening experiment. Only main effects and second-order interactions were included in the analysis.

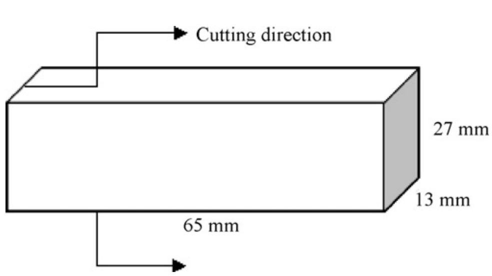

Fig. 1. Specimen dimensions and cutting path.

General mathematical model of ANOVA for full factorial design in this experiment can be expressed as Eq. (1).

$$y_{ijklm} = \mu + \tau_i + \beta_j + \gamma_k + \lambda_l + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\tau\lambda)_{il} + (\beta\gamma)_{jk} + (\beta\lambda)_{jl} + (\gamma\lambda)_{kl} + \varepsilon_{ijklm} \quad (1)$$

where y_{ijklm} is the observed response when factor A is at the ith level ($i = 1, 2, \ldots$), factor B at the jth level ($j = 1, 2, \ldots$), factor C at the kth level ($k = 1, 2, \ldots$), factor D at the lth level ($l = 1, 2, \ldots$) for the mth replicate ($m = 1, 2, \ldots$), μ the overall mean effect, τ_i the effect of the ith level of factor A, β_j the effect of the jth level of factor B, γ_k the effect of the kth level of factor C, λ_l the effect of the lth level of factor D, $(\tau\beta)_{ij}$ the effect of the interaction between τ_i and β_j, $(\tau\gamma)_{ik}$ the effect of the interaction between τ_i and γ_k, $(\tau\lambda)_{il}$ the effect of the interaction between τ_i and λ_l, $(\beta\gamma)_{jk}$ the effect of the interaction between β_j and γ_k, $(\beta\lambda)_{jl}$ the effect of the interaction between β_j and λ_l, $(\gamma\lambda)_{kl}$ the effect of the interaction between γ_k and λ_l, and ε_{ijklm} is a random error or residual component.

Although analysis of variance has been widely used in metal machining research, assumptions of this analytical technique are not much mentioned [11–16]. In applying ANOVA technique, certain assumptions must be checked through analysis of residuals before interpreting and concluding the results. Only interpreting the results from p-values of the ANOVA table without carefully checking its assumptions is very uncertain and unreliable, and it is easy to obtain misleading results. From statistical point of view, it is highly recommended to examine these residuals for normality, independence, and constant variance when using ANOVA.

A typical check for normality assumption could be made by constructing a normal probability plot of the residuals. Each residual is plotted against its expected value under normality. If the residual distribution is normal, this plot will be a straight line. In visualizing the plot, the central values of the plot should be more emphasized than on the extremes. However, if linearity of the normal plot is doubtful by visual observation, in this case, Looney and Gulledge [17] recommended further analysis using coefficient of correlation of the plot. If the correlation coefficient is greater than its corresponding critical value, the normality assumption of residuals is assured.

Plotting the residuals in time order of data collection is helpful in checking independence assumption on the residuals. The residual plot should be structureless; that is, they should contain no obvious patterns. This technique is the traditional checking technique for independence assumption. However, it is quite subjective to determine the pattern of the plot. In this study, Durbin–Watson test was used to check independence assumption on the residuals. If the Durbin–Watson test statistic is greater than its corresponding upper bound value, residuals are independent.

The assumption of constant variance is typically checked by plotting residuals versus predicted values. If the assumption is satisfied, the residual plot should be structureless. However, this checking method is also subjective. In this paper, Brown–Forsythe test (also known as modified Levene's test) was employed to check constancy of residual variance. If the Brown–Forsythe test statistic is equal to or less than its corresponding critical value, the residuals have constant variance. Details on Durbin–Watson test and Brown–Forsythe test will not be mentioned here. They can be found in most advanced statistics textbooks.

3. Results and discussion

Analysis of variance for surface roughness was performed to study influences of the wire-EDM machining variables. Before looking at the results from ANOVA for this study, assumptions of normality, independence, and constant variance of residuals of Eq. (1) were examined. Quantitative test methods as explained above were used in this paper. Normality of residuals was first checked using a normal probability plot. The normal probability plot of the residuals for this experiment is shown in Fig. 2. Linearity of this normal plot was suspicious. Further analysis using coefficient of correlation of the plot was then performed. According to Looney and Gulledge [17], at 95% confidence level, when the number of residuals is 48, the critical value of coefficient of correlation between residuals and its expected value under normality is 0.977. From Fig. 2, the correlation coefficient of the plot was 0.988, which is greater than its critical value. This indicates that the normal distribution of residuals was satisfied.

Fig. 3 shows plotting of the residuals in time order of data collection. This method is helpful in checking independence assumption on the residuals. It is desired that the residual plot should contain no obvious patterns. However, it is noticeable from Fig. 3 that determination of the pattern is subjective to the experimenter's experience, and could be biased. Thus, in this paper, Durbin–Watson test was employed to check independence assumption on the residuals. At 95% confidence level, when the number of experimental variables is 4 and the number of residuals is 48, the upper bound value of Durbin–Watson test is 1.72. Durbin–Watson test statistic for this experiment was 2.37, which is larger than the upper bound value. Therefore, independence assumption on the residuals was fulfilled for this experiment.

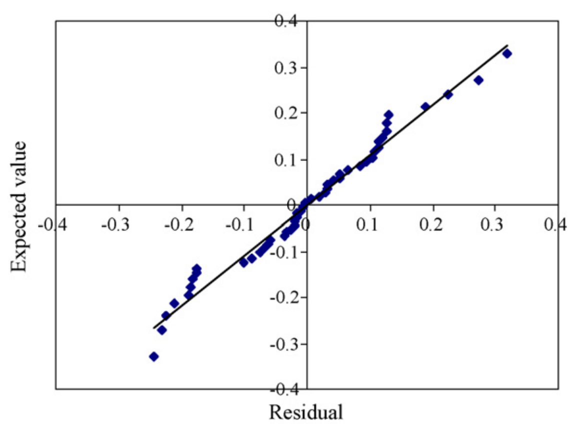

Fig. 2. Normal probability of residuals.

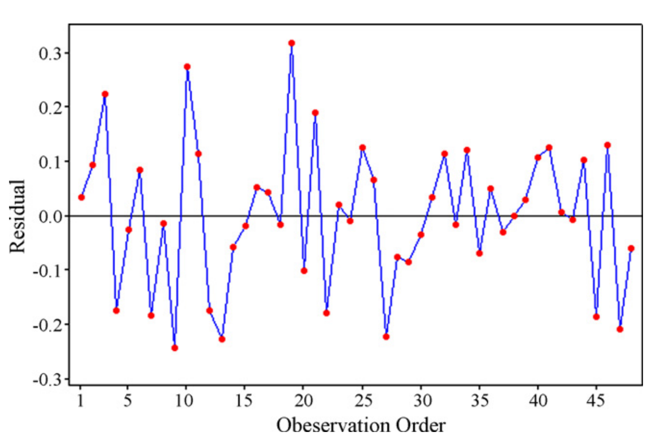

Fig. 3. Residuals in time order.

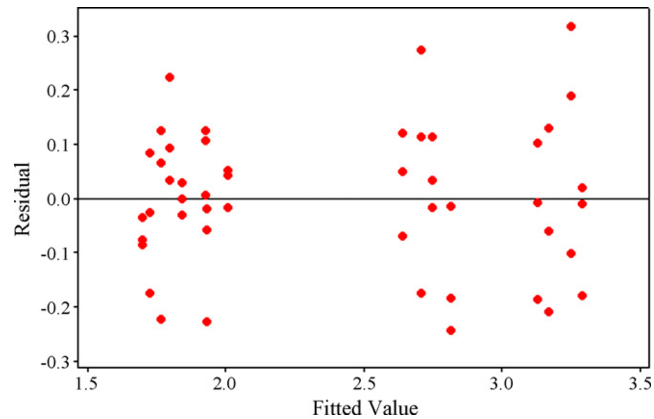

Fig. 4. Residual plot vs. predicted value.

Shown in Fig. 4 is plot of residuals versus predicted values. This plot is the typical testing for the assumption of constant variance. If the assumption is satisfied, the residual plot should be structureless. It is obvious that it is subjective and difficult to determine whether the plot is structured. To get rid of this ambiguity, in this paper, the assumption of constant variance was checked by Brown–Forsythe test. At 95% confidence level, when the number of residuals is 48, the critical value of Brown–Forsythe test is 2.013. In this study, Brown–Forsythe test statistic was 1.693. With the smaller value of the test statistic than its critical value, it can be concluded that the assumption of constant variance of residuals was satisfied.

After the validity of the assumptions was carefully checked, no assumption was violated. Therefore, the ANOVA of this screening experiment was sufficiently reliable. From the statistical analysis, effects of the four main variables and second-order interactions on surface roughness of the EDMed DC 53 die steel are shown in Table 1. Based on the evidence, at 95% confidence level ($\alpha = 0.05$), pulse-on time and pulse-peak current had significant effect on surface roughness of the EDMed surface (p-value <0.05) whereas pulse-off time, and wire tension did not affect the surface roughness (p-value >0.05). Among interactions, only interaction between ON and IP showed significant effect on the surface roughness (p-value <0.05). Other interactions were not statistically significant to the surface quality of the specimen.

From Fig. 5, plots of main effects, when ON and IP are increased, surface roughness of the machined surface is increased. This is because the discharge energy becomes more intense with increasing pulse-on time and pulse-peak current. The higher discharge energy, the more powerful explosion and

Table 1
ANOVA table for the screening experiment

Source	Sum of squares	d.f.	Mean square	*F*-ratio	*p*-Value
Main effects					
A: ON	1.3200	1	1.3200	59.9190	0.0001
B: OFF	0.0705	1	0.0705	3.2002	0.0817
C: IP	15.3907	1	15.3907	698.6332	0.0001
D: WT	0.0024	1	0.0024	0.1089	0.7428
Interactions					
AB	0.0091	1	0.0091	0.4131	0.5249
AC	0.2760	1	0.2760	12.5285	0.0011
AD	0.0675	1	0.0675	3.0640	0.0883
BC	0.0040	1	0.0040	0.1816	0.6712
BD	3.00E−05	1	3.00E−05	0.0014	0.9692
CD	0.0044	1	0.0044	0.1997	0.6572
Residual	0.8151	37	0.0220		
Total (corrected)	17.9598	47			

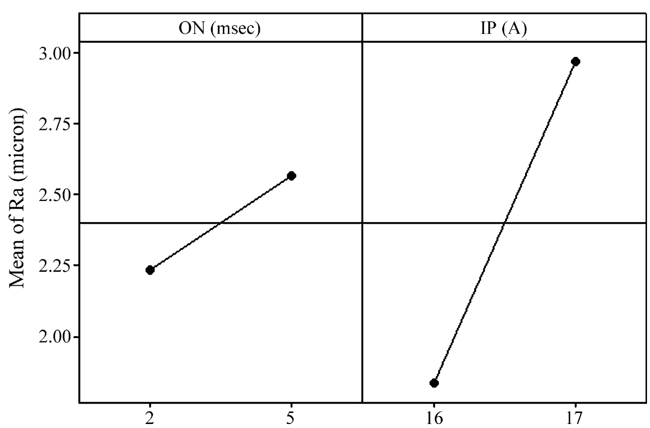

Fig. 5. Plots of significant main effects.

the deeper crater created on the machined surface resulting rougher surface. Hence, to obtain a good surface finish of a wire-EDMed workpiece, pulse-on time and pulse-peak current should be set as low as possible. However, machining a workpiece at low levels of these two variables causes a lengthy machining time. Fig. 6 illustrates interaction plot between ON and IP. It reveals that pulse-peak current has a larger effect on the surface roughness at high pulse-on time than at low pulse-on time.

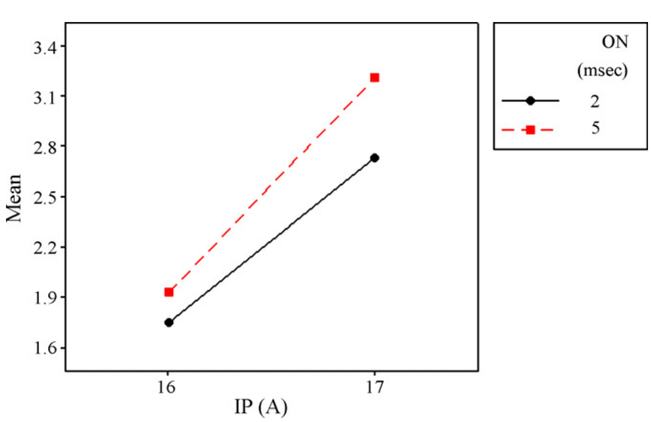

Fig. 6. Plot of significant interaction.

Results from this study were in agreement with findings in literature in that surface roughness of EDMed surface depended on pulse-on time and pulse-peak current [18–23]. Although those research efforts performed on different materials other than DC 53, the outcomes were in accordance. Surface roughness of EDMed surface was increased when pulse-on time and pulse-peak current increased. This indicates that surface roughness of EDMed workpiece is determined by the same machining variables, pulse-on time and pulse-peak current, regardless of the material type being machined.

Lastly, a mathematical model was developed using multiple regression technique to formulate the pulse-on time and pulse-peak current to the surface roughness. Pulse-off time and wire tension were dropped from the consideration because, based on the statistical analysis, they did not show significant effects on the surface roughness.

In general, the units of process variables differ from each other. Even if some of the variables have the same units, not all of these variables will be tested over the same range. Since variables pulse-on time and pulse-peak current have different units and different ranges in the experimental data set, regression analysis should not be performed on the raw or natural variables themselves. Instead, they must be normalized before performing a regression analysis. The normalized variables are called coded variables. Each of the coded variables is forced to range from -1 to 1, so that they all affect the response more evenly, and so the units of the variables are irrelevant. Coded value of -1 corresponds to the minimum value of the natural variable while the value of 1 matches up the maximum value of the natural variable. In this study, coded variables of pulse-on time and pulse-peak current are used as the independent variables in the regression analysis. A coded variable must be defined for each of the actual variables. Regression analysis is then performed on the response variable as a function of coded variables. The general model to predict the surface roughness over the experimental region can be expressed as Eq. (2).

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_1 x_2 \quad (2)$$

Table 2
ANOVA table for model fitting

Source	Sum of squares	d.f.	Mean square	F-ratio	p-Value
Model	16.9867	3	5.6622	256.0385	<0.0001
Residual	0.9731	44	0.0221		
Total (corrected)	17.9598	47			

Table 3
ANOVA table for regression coefficients

Source	Sum of squares	d.f.	Mean square	F-ratio	p-Value
x_1	1.3200	1	1.3200	59.6900	<0.0001
x_2	15.3907	1	15.3907	695.9466	<0.0001
$x_1 \times x_2$	0.2760	1	0.2760	12.4818	0.0010
Residual	0.9731	44	0.0221		
Total (corrected)	17.9598	47			

where x_1 and x_2 are coded variables for pulse-on time and pulse-peak current, respectively, and the $\hat{\beta}$s are regression coefficients. Using multiple linear regression technique with the collected data, the prediction equation for the surface roughness can be written as Eq. (3).

$$\hat{y} = 2.4021 + 0.1658x_1 + 0.5663x_2 + 0.0758x_1x_2 \quad (3)$$

From Eq. (3), the variables x_1 and x_2 have an additive effect on the surface roughness. Note that because $\hat{\beta}_2 > \hat{\beta}_1$, it is concluded that x_2 (pulse-peak current) has stronger effect on surface roughness than x_1 (pulse-on time). This result is in agreement with graphical results in Fig. 6. Although the operating range of pulse-peak current was intentionally selected to be narrow, from Fig. 6, it is clear that pulse-peak current has stronger effect on surface roughness than pulse-on time. Furthermore, because $\hat{\beta}_3$ is positive, interaction between pulse-on time and pulse-peak current also has an additive effect on the surface roughness, but its effect is much less than those of the main effects.

Analysis of residuals of the model shown in Eq. (3) was performed to test assumptions of normality, independence, and constant variance of residuals. The quantitative test methods mentioned earlier were employed again, and none of the assumptions was violated. Table 2 summarizes the results of fitting a general linear statistical model relating surface roughness to two predictive factors. Since the p-value in Table 2 is less than 0.05, there is a statistically significant relationship between surface roughness and the predictor variables at the 95% confidence level. The calculated R^2 statistic for this regression model was 0.9458. This number indicates that the model as fitted explains 94.58% of the variability in surface roughness. These analyses showed that the prediction model sufficiently explains the relationship between surface roughness and the independent variables.

Table 3 is the ANOVA table for surface roughness that tests the statistical significance of the regression coefficient of each factor as it was entered into the model. Since all p-values in Table 3 are less than 0.05, all parameter coefficients included in the model are statistically significant at the 95% confidence level. Therefore, the developed model was sufficiently reliable.

The prediction model was then validated with another set of data that was not previously used to develop the model. The collected data and predicted surface roughness was shown in Table 4. In Table 4, process variables are shown in terms of natural variables and their corresponding coded variables. In order to evaluate the accuracy of the prediction model, percentage error and average percentage error were used. Percentage of prediction errors is shown in the last column of Table 4. The maximum prediction error was 6.76%, and the average percentage error of this model validation was about 2.84%. As a result, the prediction accuracy of the model appeared satisfactory.

Table 4
Prediction values and errors

Natural variables		Coded variables		Predicted values (μm)	Experimental values (μm)	Prediction error (%)
ON (ms)	IP (A)	x_1	x_2			
2	16	−1	−1	1.75	1.68	4.17
3	16	−0.33	−1	1.81	1.74	4.02
4	16	0.33	−1	1.87	1.93	3.11
5	16	1	−1	1.93	2.07	6.76
2	17	−1	1	2.73	2.77	1.44
3	17	−0.33	1	2.89	2.89	0.00
4	17	0.33	1	3.05	3.00	1.67
5	17	1	1	3.21	3.26	1.53

4. Conclusion

Influences of wire-EDM machining variables on surface roughness of newly developed DC 53 die steel were investigated in this paper. The machining variables included pulse-on time, pulse-off time, pulse-peak current, and wire tension. The variables affecting the surface roughness were identified using ANOVA technique. Assumptions of ANOVA were tested using residual analysis. Quantitative testing methods were employed in place of the typical qualitative testing techniques. After careful testing, none of the assumptions was violated. Results showed that pulse-on time and pulse-peak current were significant variables to the surface roughness of wire-EDMed DC53 die steel. The surface roughness of the test specimen became larger when these two variables were increased. Finally, a mathematical model was developed using multiple regression method to formulate the pulse-on time and pulse-peak current to the surface roughness. The developed model showed high prediction accuracy within the experimental region. The maximum prediction error of the model was less than 7%, and the average percentage error of prediction was less than 3%. Future research will be performed on optimization of wire-EDM machining variables for DC 53 tool steel.

Acknowledgments

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