Application of response surface methodology for evaluating material removal in rate die-sinking EDM roughing using copper electrode

Phan Nguyen Huu, Duc Nguyen Van, Bong Pham Van

***Abstract*—Die-sinking electrical discharge machining (EDM) is one of the most popular machining methods to manufacture dies and press tools because of its capability to produce complicated shapes and machine very hard materials. In this article, MRR study on die-sinking EDM in rough machinng of SKD11 die steel has been carried out. Response surface methodology (RSM) has been used to plan and analyze the experiments. Current (I), pulse on time (Ton) and voltage (U) were chosen as process parameters to study the die-sinking EDM performance in term of MRR. The results indicated that in order to obtain a high value of MRR within the work interval of this study, Ton should be fixed as low as possible, and conversely, the larger the selected I and U. And the optimal value of MRR was 139.126 mg/min at optimal process parameters I = 10 A, U = 90 V and Ton = 100 μs. The mathematical model for the MRR can be effectively employed for the optimal process parameters selection in die-sinking EDM for SKD11 die steel. Empirical tests show that the model can calculate quite accurately predicted by MRR (error ≈ 0.6%).**

***Index Terms*— Die-sinking EDM, MRR, RSM, SKD11.**

1 INTRODUCTION

Die-sinking EDM is one of the most widely used methods among the new techniques. It thus plays a major role in the machining of dies, tools, etc., made of tungsten carbides and hard steels. Researchers are actively engaged in experimentation related to Die-sinking EDM process. The areas of focus have been to select parameters for improving MRR, tool wear rate and surface quality work carried out by some researchers is briefly presented here. This study is trying to overcome this problem by studying the process inputs and outputs to reach the best machining conditions for this type of steel for higher productivity, less tool erosion and best surface qualities.

Die-sinking EDM process is very demanding but the mechanism of process is complex and far from being completely understood. Therefore, it is hard to establish a model that can accurately predict the response (productivity, surface quality, etc.) by correlating the process parameter, though several attempts have been made. Since it is a very costly process, optimal setting of the process parameters is the most important to reduce the machining time to enhance the productivity. The volume of material removed per discharge is typically in the range of 10^{-6} – 10^{-4} mm^3 [1] and the MRR is usually between 0.1 to 400 mm^3/min depending on specific application [2]. A mathematical model of die-sinking EDM has been formulated by applying RSM in order to estimate the machining characteristics such as MRR. Analysis of variance (ANOVA) was applied to investigate the influence of process parameters and their interactions viz., Ip, Ton, V and Toff on MRR. The objective was to identify the significant process parameters that affect the output characteristics [3-7]. It has been concluded that the proposed mathematical models in this study would fit and predict values of the performance characteristics, which would be close to the readings recorded in experiment with a 95 % confidence level. The effect of machining parameters, such as pulse on time, pulse off time and discharge current on the MRR of AISI D2 tool steel was determined [8-9]. The experiments

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signified that the parameters of pulse on time, pulse off time and current, have a direct impact on MRR, and with their increase, MRR increases as well. The development of a comprehensive mathematical model for correlating the interactive and higher order influences of various die-sinking EDM parameters through RSM, utilizing the relevant experimental data as obtained through the experimentation of SR [10-11]. The prime advantage of employing RSM is the reduced number of experimental runs required to generate sufficient information about a statistically adequate result. Improving the MRR and surface quality are still challenging problems that restrict the expanded application of the technology. For the prediction of the die-sinking EDM responses, the empirical models and multi regression models are usually applied. Their interest is, however, the correlation of the quality indicators with the machining conditions and optimizing the die-sinking EDM.

An experimental investigation is presented to explore MRR in the die-sinking EDM. Parametric analysis has been carried out by conducting a set of experiments using SKD11 workpiece with copper electrode. The investigating factors were I, Ton, and U. The effect of the machining parameters on MRR is studied and investigated. Designing and planning of experimental investigation, mathematical model have been developed using response surface methodology. ANOVA is used to check the validity of the models.

2 EXPERIMENTAL SETUP

The experiments have been conducted on the Die-sinking EDM model CM323C of CHMER EDM, Ching Hung machinery & Electric industrial. Co. LTD available at Ha Noi University of industry, Foxconn center for technical tranining. SKD11 die steel is used as workpiece material in this experiment. The workpiece was ground and milled to dimension of 120×45×20 mm (Fig. 1), and the surface of workpiece has ground on the surface grinder to remove the scaling. The tool material used in Die-sinking EDM can be of a variety of metals like copper, brass, aluminium alloys, silver alloys etc. The material used in this experiment is copper. The tool electrode is in the shape of a cylinder having a diameter of 20 mm, Fig. 1. Positive polarity of the electrode is selected to conduct experiments.

Figure 1. Electrodes and workpieces used

The MRR of the workpiece was measured by dividing the weight of workpiece before and after machining (found by weighing method using balance) againts the machining time that was achieved. Precision balance was used to measure the weight of the workpiece before and after the machining process (model vibra AJ-203 shinko max 200g /d=0.001g, Japan).

The experimental trials of die-sinking EDM in rough machining of SKD11 die steel involved three factors which were varied at two levels; high and low levels. The three factors were voltage, current and pulse on time. They are labeled X_1, X_2 and X_3 respectively. The details of the factors for the EDM of SKD11 die steel are given in Table 1. The Central Composite Design was used to conduct the experiments with three variables, having eight cube, three central points, in total of 11 runs in three blocks [Minitab16]. Table 2 presents run order, point type, block, the various combination of input parameters and the response MRR obtained from these experimentations.

Table 1. Input variables used in the experiment and their levels

Variable	Factor	Unites	Set-up		
			-1	0	+1
Voltage (U)	X_1	V	60	75	90
Current (I)	X_2	A	6	8	10
Pulse on time (Ton)	X_3	μs	100	150	200

Table 2. Experimental strategy with obtained response

No exper.	X_1	X_2	X_3	U (V)	I (A)	Ton (μs)	MRR (g/min)
1	-1	-1	-1	60	6	100	38.333
2	0	0	0	75	8	150	67.333
3	1	1	1	90	10	200	121.500
4	1	-1	1	90	6	200	34.666
5	-1	1	1	60	10	200	101.000
6	-1	-1	1	60	6	200	23.666
7	1	-1	-1	90	6	100	44.333
8	-1	1	-1	60	10	100	128.000
9	0	0	0	75	8	150	67.666
10	0	0	0	75	8	150	67.000
11	1	1	-1	90	10	100	140.000

3 RESPONE SURFACE METHODOLOGY

Response surface methodology (RSM) is a collection of statistical and mathematical techniques which is useful for developing, improving and optimizing processes. In this work, RSM has been applied for developing the mathematical models in the form of multiple regression equations for the quality characteristic in die-sinking EDM. In applying the RSM, the dependent variable is viewed as a surface to which a mathematical model is fitted. For the development of regression equations related to various quality characteristics of die-sinking EDM, the second order response surface has been assumed as:

$$Y=b_0+\sum_{i=1}^{k}b_i x_i+\sum_{i=1}^{k}b_{ii}x_i^2+\sum_{i,j=1,\, i\neq j}^{k}b_{ij}x_i x_j \quad (1)$$

Where Y is the corresponding response (MRR produced by the various process variables of die-sinking EDM), x_i (1, 2, …, k) is the input variables (x_i are coded levels of k quantitative process variables), x_i^2 and $x_i x_j$ are the squares and interaction terms, respectively, of these input variables. The unknown regression coefficients are b_0, b_1, b_2, ..., b_{ij}. In order to estimate the regression coefficients, a number of experimental design techniques are available.

4 RESULT AND DISCUSSION

The analysis of variance (ANOVA) of MRR: The effect of the machining parameters (I, Ton and U) on the response variable MRR was evaluated by conducting experiments. Minitab software was used to find out the relationship between the input factors and the response MRR. And the full quadratic model is considered for further analysis in this study. Table 3 represents the regression coefficients in coded units and its significance in the model. The columns in the table correspond to the terms, the value of the coefficients (Coef.), and the standard error of the coefficient (SE Coef), t-statistic and p-value to decide whether to reject or fail to reject the null hypothesis. To test the adequacy of the model, with a confidence level of 95%, the p-value of the statistically significant term should be less than 0.05. The values of R^2 and R^2_{adj} are 99.99% and 99.96%, respectively, exhibiting significance of relationship between the response and the variables and the terms of the adequate model are U, I, Ton, U^2, U*Ton, U*Ton and I*Ton.

Table 3. Estimated Regression Coefficients for MRR

Term	Coef	SE Coef	T	P
Constant	67.333	0.4413	152.565	0.000
U	6.187	0.2703	22.894	0.002
I	43.688	0.2703	161.648	0.000
Ton	-8.729	0.2703	-32.299	0.000
U*U	11.604	0.5175	22.423	0.000
U*I	1.938	0.2703	7.169	0.006
U*Ton	1.687	0.2703	6.244	0.008
I*Ton	-2.646	0.2703	-9.789	0.002
S = 0.764423	R^2 = 99.99% R^2_{adj} = 99.96%			

ANOVA is used to check the sufficiency of the second-order model, which includes test for significance of the regression model, model coefficients and test for lack-of-fit. Table 4 summaries the ANOVA of the model that comprises of two sources of variation, namely, regression and residual error. The variation due to the terms in the model is the sum of linear and square terms whereas the lack of fit and pure error contribute to residual error. The table depicts the sources of variation, degree of freedom (DF), sequential sum square eror (Seq SS), adjusted sum square error (Adj SS), adjusted mean square error (Adj MS), F statistic and the p-values in columns. The p-value of lack of fit is 0.065, which is ≥ 0.05, and certainly indicate that there is statistically insignificant “lack of fit” at 95% confidence level. However, the p-value of regression model and its all linear and square terms have p-value 0.000, hence they are statistically significant at 95% confidence and thus the model adequately represent the experimental data. In this research, U, I, Ton, U^2, U*I, U*Ton and I*Ton are signiicant model terms. The other model terms are said to be nonsigniicant. The model F value of 4055.22 implied that the model is significant for MRR. There is only a 0.01% chance that a “model F value” this large could occur due to noise. The lack of it F value of 0.0652 implies that it is not signiicant relative to the pure error.

Multi-regression analysis was performed to the data to obtain a quadratic response surface model (Table 5) and the equation thus obtained in uncoded unit is (2):

$$\mathbf{MRR = 210.2520 - 8.1778{*}U + 20.9688{*}I - 0.1316{*}Ton + 0.0515{*}U^2 + 0.0645{*}U{*}I + 0.0022{*}U{*}Ton - 0.0264{*}I{*}Ton} \quad (2)$$

Table 4. Analysis of Variance for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	16587.4	16587.4	2369.6	4055.22	0.0001
U	1	306.3	306.3	306.3	524.15	0.0001
I	1	15269.0	15269.0	15269.0	26130.14	0.0001
Ton	1	609.6	609.6	609.6	1043.22	0.0001
U*U	1	293.8	293.8	293.8	502.79	0.0032
U*I	1	30.0	30.0	30.0	51.39	0.0064
U*Ton	1	22.8	22.8	22.8	38.99	0.0081
I*Ton	1	56.0	56.0	56.0	95.83	0.0022
Residual Error	3	1.8	1.8	0.6	-	-
Lack-of-Fit	1	1.5	1.5	1.5	13.81	0.0652
Pure Error	2	0.2	0.2	0.1	-	-
Total	10	16589.2	-	-	-	-

Table 5. Estimated Regression Coefficients for MRR using data in uncoded units

Term	Constant	U	I	Ton	U*U	U*I	U*Ton	I*Ton
Coef	210.2520	-8.1778	20.9688	-0.1316	0.0515	0.0645	0.0022	-0.0264

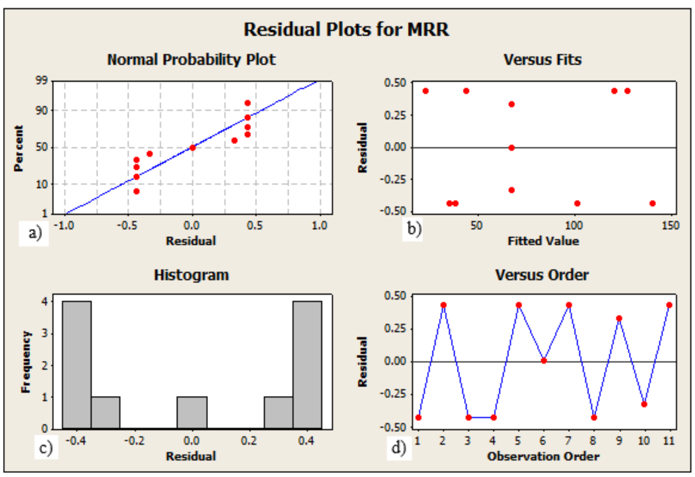

Figure 2. Graphs balance for MRR

a) Normal plot of residuals for MRR b) Histogram plot of residuals for MRR

c) Plot of standardised residuals vs. fitted value for MRR d) Versus order of residuals for MRR

Effect of process parameters on MRR:

The normal probability plot is a graphical technique for evaluating whether a data set is approximately normally distributed. The standardised residuals are plotted on a normal probability plot (Fig. 2a) to check the departure of the data from normality. It can be seen that the residuals are almost falling on a straight line, which indicates that Ra are normally distributed and the normality assumption is valid. The plots show that the residuals are distributed normally on a straight line. Fig. 2b depicts the histogram plot of non-standardised residue for all the observations. The distance between the two bars indicates the outliers present in the results. In addition, the plot of MRR verse run order illustrates that there is no noticeable pattern or unusual structure present in the data as depicted in Fig. 2c. MRR, which lies in the range of -0.4375 to 0.4375 μm are scattered randomly about zero, i.e., the errors have a constant variance. Residual plots are an important accompaniment to the model calculations and may be plotted against the fitted values to offer a visual check on the model assumptions. Fig. 2d shows the distribution of all the data and indicates that the error is not random. The results showed that the predicted values were distributed across the entire value surveys within a small error.

Fig. 3 depicts the plots of main effects on MRR, those can be used to graphically assess the effects of the factors on the response. It indicates that U, I and Ton have significant effect on MRR, which is supported by results in Table 5. However, I is the most influencing parameter showing a sharp increase in MRR of 32.038 mg when I increases from 6 A to 8 A and then the increases in Ra by 55.292 mg, when I increases from 8 A to 10 A. This implies that I has a more dominant effect on the MRR. In addition, MRR decreases by 20.333 mg, and then slightly increases by 2.875 mg with Ton increases from 100 μs to 150 μs, and 150 μs to 200 μs respectively. Furthermore, for U the trend is analogous, MRR decreases by 5.416 mg and then increase by 17.791 mg with increases of U from 60 V to 75 V and 75 V to 90 V, respecively. Nevertheless, Ton is also an important factor which influences the MRR after I. This can be evident from Table 5 and I has a more dominant effect on MRR than that of Ton.

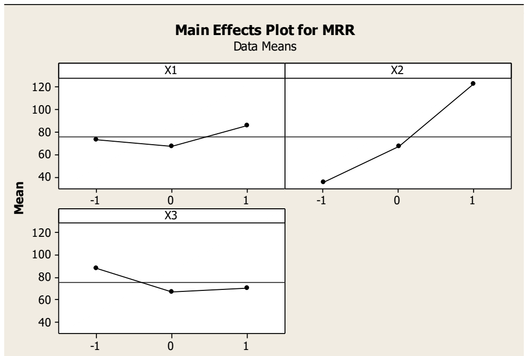

Figure 3. Effect of factors on MRR

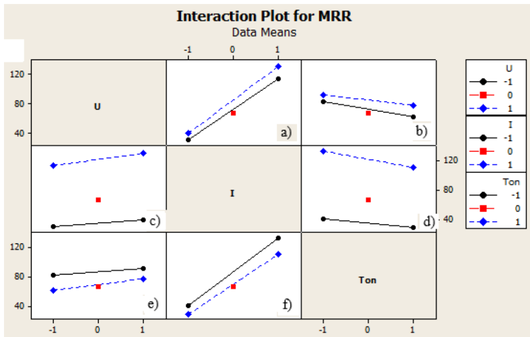

Figure 4. Interaction effect of factors on MRR

Fig. 4 contains two interaction plots for various two-factor interactions between I, U and Ton. Each pair of the factor is plotted keeping the other factors constant at the mean level. In each plot, the factors of interest are varied in three levels, low, medium and high levels. If the lines are nonparallel, an interaction exists between the factors. The greater the degree of departure from parallelism, the stronger is the interaction effect. It can be seen in the figure that the most important interaction effect is produced between I and Ton.

Fig. 5 and 6 response surface for MRR in relation to the machining parameters of U and I. From the figures, it is unambiguous that MRR value is more with higher I and U. The value MRR tends to increase significantly with the increase in I for any value of U. Hence, maximum MRR is obtained at high current (10 A) and U (90 V). Fig. 7 and 8 response surface for MRR in relation to the machining parameters of I and Ton. From the figures, it is unambiguous that MRR value is more with higher I and shorter Ton, the value MRR tends to increase significantly with the increase in I for any value of Ton. Maximum MRR is obtained at low pulse on- time (100 μs) and high current (10

A). Figure 9 and 10 shows that U*Ton interaction has affected MRR, its influence is much smaller than the effect of U*I and I*Ton. Maximum MRR is obtained at low pulse on- time (100 µs) and high voltage (90 V). From these observations, it can be concluded that I and Ton are directly proportional to the MRR as compared to U, and for U*Ton and U*I the effect is less as compared to the I*Ton.

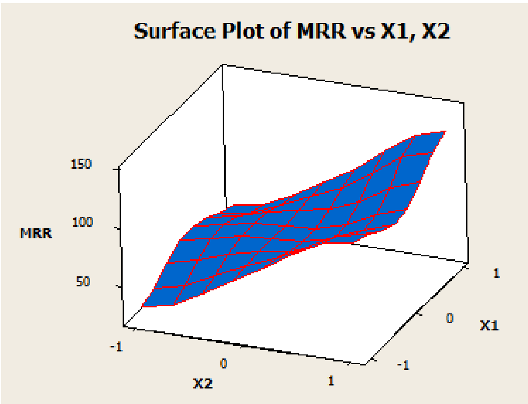

Figure 5. Response surface of MRR vs, U and I

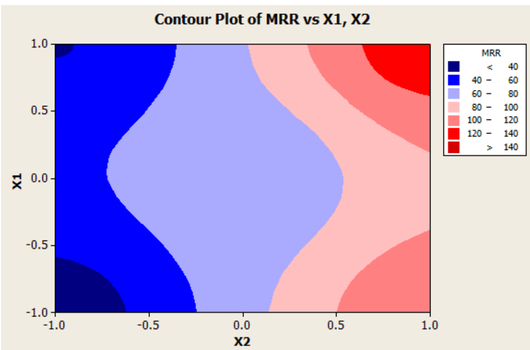

Figure 6. Two dimensional plot for effect of U and I on MRR

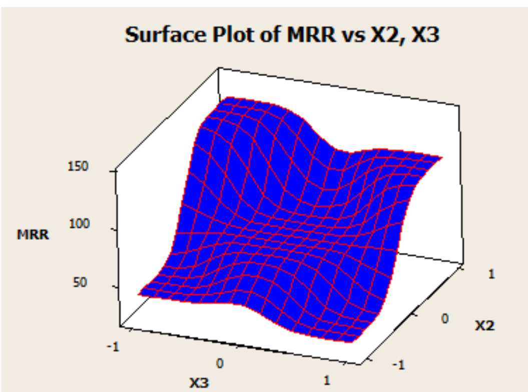

Figure 7. Response surface of MRR vs, I and Ton

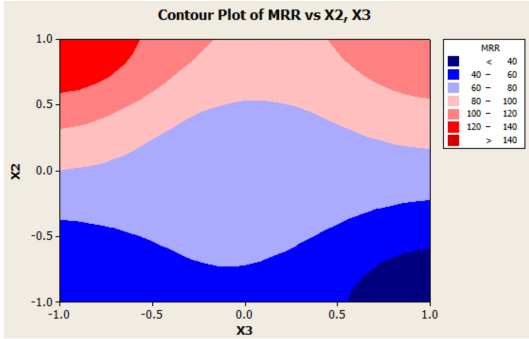

Figure 8. Two dimensional plot for effect of I and Ton on MRR

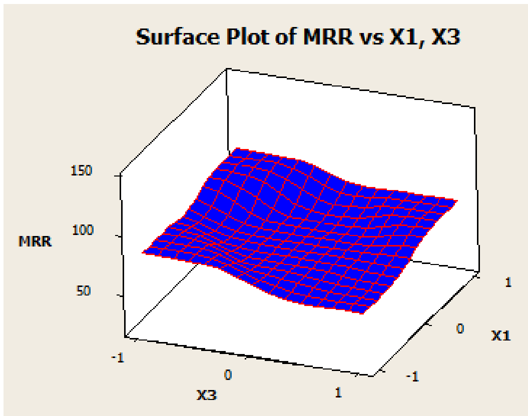

Figure 9. Response surface of MRR vs, U and Ton

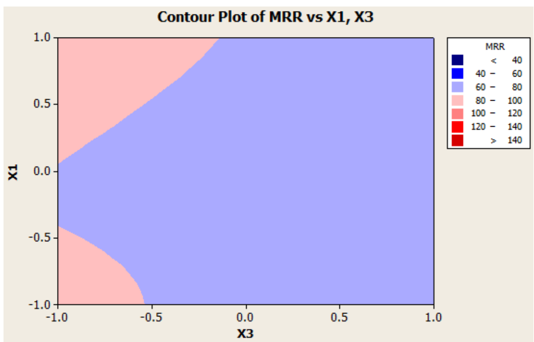

Figure 10. Two dimensional plot for effect of U and Ton on MRR

Confirmation Experiments: The estimated value of the MRR under optimal conditions: U = 90 V, I = 10 A and Ton = 100 µs. After the selection of optimal level of the process parameters, the last step is to predict and verify the improvement of the response using the optimal level of the machining parameters. Confirmation experiments were carried out using the optimal process parameters as current: 10 A, voltage: 90 V, and pulse on time: 100 µs. Table 6 shows the percentage of error present for experimental validation of the developed model for the responses with optimal parametric setting. Where MRR are the difference between the experimentally observed data and the model predictions.

Table 6. Experimental validation of developed model with optimal parameter setting

Level	MRR at optimal parameters (mg/min)		
	Predicted value	Experimental value	% difference
U = 90V, I=10A, Ton= 100µs	139.126	140.000	0.6%

5 CONCLUSSION

In this study, the influence of the most significant factors on MRR has been studied for SKD11 die steel in die-sinking EDM in rough machining. RSM design was used to conduct the experiment with I, Ton, and U as input parameters. The ranges of these parameters were chosen which are widely used by machinists to control die-sinking EDM machine. The input factors that significantly influenced the output responses were I, Ton, U, square of U, interaction between I and Ton, interaction between I and Ton, and interaction between U and Ton with a confidence level of 95%. The result reveals that in order to obtain a high value of MRR within the work interval of this study, Ton should be fixed as low as possible, and conversely, the larger the selected U and I. However, the developed mathematical model for the MRR can be effectively employed for the optimal selection of the die-sinking EDM process parameters in rough machining of SKD11 die steel workpiece to achieve maximum MRR (2). The error between experimental and predicted values at the optimal combinations of parameters setting for MRR is 0.6%. This confirms proper reproducibility of experimental conclusion.

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Ứng dụng phương pháp bề mặt phản hồi để đánh giá năng suất gia công thô trong xung định hình với điện cực đồng

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***Tóm tắt*–Phương pháp xung định hình là phương pháp gia công phi truyền thống được sử dụng rộng rãi để gia công các loại khuôn mẫu và dụng cụ. Phương pháp này gia công được các loại vật liệu có độ bền và độ cứng bất kỳ với hình dạng bề mặt phức tạp. Trong bài báo này, MRR trong gia công thô của thép khuôn SKD11 bằng xung định hình đã được thực hiện. Phương pháp bề mặt phản hồi (RSM) đã được sử dụng để thiết kế thí nghiệm và phân tích các kết quả. Cường độ dòng điện (I), thời gian phát xung (Ton) và điện áp (U) được chọn làm tham số nghiên cứu. Các kết quả chỉ ra rằng: MRR tăng khi Ton giảm, ngược lại I và U lại tăng. Giá trị tối ưu của MRR = 139.126 mg/phút với I = 10 A, U = 90 V và Ton = 100 µs. Mô hình toán học của MRR có thể sử dụng để tối ưu các tham số trong quá trình xung định hình khi gia công thép SKD11. Các kết quả thực nghiệm cho thấy mô hình này có thể tính toán chính xác MRR (sai số 0,6%).**

***Từ khóa*–Xung định hình, MRR, RSM, SKD11.**