Multi-objective optimization of SKD61 steel WEDM to improve cutting velocity and reduce surface roughness

Tối ưu hóa đa mục tiêu quá trình cắt dây thép SKD61 để nâng cao vận tốc cắt và giảm độ nhám bề mặt

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Abstract

This studywork systematically investigated the effects of technological parameters on the technological responses, including the cutting velocity (*CV*) and surface roughness (*SR*) in the WEDM of SKD61 material. Technological parameters consist of current *I*, pulse on time T_{on}, pulse of time T_{off}, and wire speed *S*. A WEDM machine was adopted in conjunction with the Box-Behnken matrix to conduct experimental trails. The nonlinear relationships between process parameters and responses were developed using response surface method (RSM). Subsequently, an optimization technique entitled multiple objective particle swarm optimization (MOPSO) was used to solve the trade-off analysis between responses considered and find the optimal parameters. The measured improvements using optimal parameters of the *CV* and *SR* are approximately 12.32 % and 53.08 % in comparison with initial settings. A hybrid approach comprising RSM and MOPSO can be considered as an effective method for parameter optimization and observation of reliable values in WEDM processes.

Keywords:

WEDM, SKD61, Cutting velocity, Surface roughness, Technological Parameters, MOPSO.

Tóm tắt

Nghiên cứu này khảo sát ảnh hưởng của các thông số công nghệ đến vận tốc cắt và độ nhám bề mặt khi gia công cắt dây thép SKD61. Các thông số công nghệ bao gồm cường độ dòng điện *I*, độ kéo dài xung t_{on}, khoảng cách xung t_{off}, và vận tốc dây *S*. Quá trình thực nghiệm được tiến hành trên máy cắt dây CNC theo ma trận quy hoạch Box-Behnken. Phương pháp bề mặt đáp ứng được sử dụng để thiết lập phương trình hồi quy. Thuật toán bầy đàn đa mục tiêu được dùng để xác định thông số tối ưu. Kết quả nghiên cứu chỉ ra rằng vận tốc cắt tăng lên khoảng 12.32% và độ nhám giảm 53.08% so với giá trị chưa tối ưu. Sự kết hợp giữa phương pháp đáp ứng bề mặt và thuật toán bầy đàn có thể coi như một phương phương hiệu quả trong việc mô hình hóa và tối ưu quá trình cắt dây.

Từ khóa:

Cắt dây, SKD61, Vận tốc cắt, Độ nhám bề mặt, Thông số công nghệ, Thuật toán bầy đàn.

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1. INTRODUCTION

WEDM is an effectively precise process which was widely used on the mold, instrument, and manufacturing industries. The primary advantages of this process are less wasted material, complex shapes produced, high degree of precision. In processing time, the discharge energy was used to cut the material by melting and vaporization. The wire was guided in order to generate the cutting path desired. The WEDM was efficiently applied to cut electrically conductive materials, such as metals, carbides, alloys, graphite, and composites. Therefore, improving the technical outputs of WEDM is still an effective contribution and important research area.

Enhancing technological responses of the WEDM processes using optimum factors has been widely investigated in previous works. Former researchers attempted to enhance machining performances, including the metal removal rate and surface finish [1-7]. A Taguchi design was used to propose a multi-response optimization method considering the metal removal rate, surface roughness, and wire wear ratio [8]. Tosun [9] used a regression analysis to investigate the effect of cutting parameters on wire crater. Yang et al. [10] proposed an hybrid approach using response surface methodology and back propagation neural networks to optimize the metal removal rate, surface roughness, and corner deviation. However, the aforementioned works in the WEDM processes have still the following deficiencies:

Machining parameter optimization for improving the WEDM performances, including the *CV* and *SR* of the SKD61 material has not performed, resulting in a deficient WEDM optimization.

Most of previous researchers attempted to minimize *SR* of the machined surface. Practically, it is unnecessary to observe the minimum *SR* due to increased machining costs and time. Furthermore, the *SR* is predefined as a technical requirement before machining.

To fulfill the mentioned research gaps, a multi-objective optimization in the WEDM process of SKD61 material has considered in this paper for improving the cutting velocity with the predefined *SR*. A hybrid approach combining RSM model and MOPSO is used to develop the predictive models as well as identify the globally optimal solution. This paper is expected as a significant contribution to exhibit the impacts of process parameters on the cutting velocity and surface roughness as well as help the WEDM operators to select the appropriate conditions.

2. METHODS

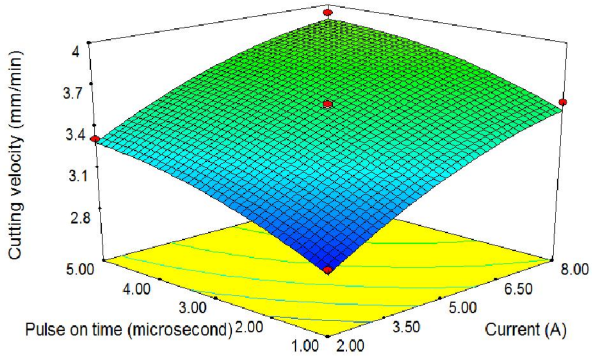
The systematic procedure for the SKD61 WEDM and process parameter optimization is depicted in Fig. 1. The Box-Behnken method was adopted in order to avoid costly full experiment and guarantee the modeling accuracy. Four key process parameters are the current I, pulse on time $T_{on,}$ pulse of time T_{off}, wire speed S, and their levels were listed in Table 1. The parameter ranges were determined based on the recommendations of previous literatures, machine characteristics, and material properties. The output models considered of *CR* and *SR* were developed with the aid of RSM and experimental data. An ANOVA analysis was performed to investigate the adequacy of the models proposed and parameter significances. An optimizing technique entitled MOPSO was used in order to find the best optimal values.

Table 1. Control factors and their ranges

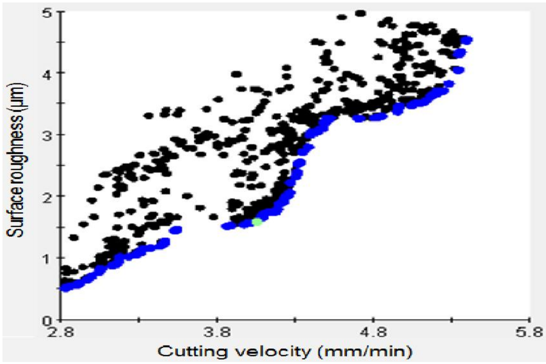
Symbol	Parameters	level-1	level 0	level +1
I	Current (A)	2	5	8
T_{on}	Pulse on time (μs)	1	3	5
T_{off}	Pulse of time (μs)	4	8	12
S	Wire speed (m/min)	4	6	8

(a) WEDM experiment

(b) Surface roughness measurement



(c) Modeling and analyzing



(d) Optimization results

Fig. 1. Optimization procedure

CNC WEDM namely MTL-SFL70 was used to perform the experimental runs as depicted in Fig. 1a. The workpiece was prepared with the dimensions of 230 mm× 90 mm×8 mm and the molybdenum wire diameter of 0.18 mm was used as tool material for erosion process. The cutting velocity (mm/min) was calculated as the following:

$$CV = \frac{60 \times L}{t} \tag{1}$$

where L (mm) and t (s) are the cutting length and time, respectively.

The SR values were measured using roughness tester Mitutoyo SJ-301, as shown in Fig. 1b. The average response values were observed from repeated five times at different positions.

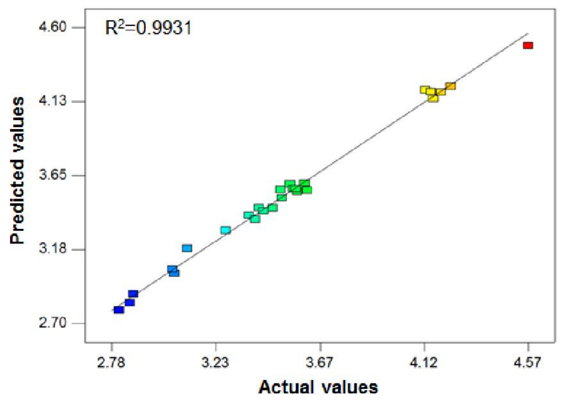
3. RESULTS AND DISCUSSION

The DOE matrix and experimental results of the WEDM trials are exhibited in Table 2. The accuracy of the predictive models is assessed by the R^2-value. The R^2-values of the CV and SR model are 0.9931 and 0.9916, respectively. Additionally, the data points lie on the straight lines and did not show any particular trend, as exhibited in Fig. 2. It can be stated that there is a good agreement between predicted and measured values. Therefore, the accuracy of the RSM models proposed for two WEDM performances is acceptable.

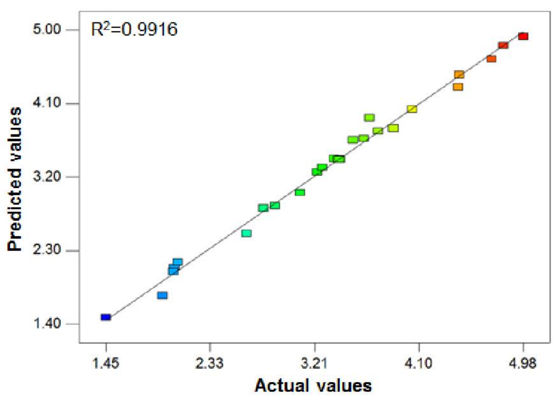
The significance and percentage contributions of WEDM parameters on the responses were analyzed using ANOVA. The factors with p-value less than 0.05 are considered as significant factors.

Table 2. DOE table and experimental results

No.	I	T_{on}	T_{off}	S	CR	SR	No.	I	T_{on}	T_{off}	S	CR	SR
1	5	5	8	8	4.25	4.43	14	2	1	8	6	2.86	2.03
2	5	3	4	4	3.81	3.38	15	2	3	12	6	2.82	2.88
3	5	3	12	4	3.05	1.93	16	5	5	12	6	3.10	3.54
4	5	3	8	6	3.56	3.41	17	2	3	8	4	2.88	2.02
5	5	1	4	6	3.57	3.09	18	2	3	4	6	3.71	3.88
6	5	3	12	8	3.67	3.75	19	5	3	8	6	3.57	3.42
7	8	3	4	6	4.23	4.98	20	5	5	8	4	3.21	2.78
8	2	5	8	6	3.31	3.63	21	8	3	12	6	3.45	4.04
9	8	5	8	6	3.93	4.81	22	2	3	8	8	3.47	3.43
10	5	3	4	8	4.59	3.68	23	5	1	8	8	3.63	2.64
11	5	5	4	6	4.47	4.71	24	8	3	8	8	4.26	4.44
12	5	1	12	6	3.11	2.06	25	8	3	8	4	3.48	3.28
13	8	1	8	6	3.58	3.24	26	5	1	8	4	3.04	1.45



(a) For cutting velocity model



(b) For surface roughness model

Fig. 2. Investigation of model accuracy

As shown in Table 3, the I, T_{on}, T_{off}, S, I^2, T_{on}^2, T_{off}^2, S^2, T_{on} T_{off}, and T_{on} S are significant terms for the CV model. The pulse off time is the most affected factor due to the highest contribution (37.07%) with regard to the single term, followed by S (26.83), I (20.70), and T_{on} (8.45%). All the interaction terms are considered as insignificant factors due to p values higher than 0.05. The T_{off}^2 account for the highest percentage contribution with respect to quadratic terms (0.75%); this followed by I^2 (0.68%), T_{on}^2 (0.54), and S^2 (0.39).

Table 3. ANOVA results for the CV

Source	Sum of Squares	Mean Square	F-Value	p-value	Remark	Contri.
Model	6.15714	0.43980	111.36918	< 0.0001	Significant	
I	1.25027	1.25027	316.60478	< 0.0001	Significant	20.70
T_{on}	0.51003	0.51003	129.15582	< 0.0001	Significant	8.45

T_{off}	2.23867	2.23867	566.89704	< 0.0001	Significant	37.07
S	1.62038	1.62038	410.32711	< 0.0001	Significant	26.83
IT_{on}	0.00252	0.00252	0.63833	0.4412	Insignificant	0.04
IT_{off}	0.00350	0.00350	0.88533	0.3670	Insignificant	0.06
IS	0.00870	0.00870	2.20415	0.1657	Significant	0.14
$T_{on}\,T_{off}$	0.20380	0.20380	51.60755	< 0.0001	Significant	3.37
$T_{on}\,S$	0.05209	0.05209	13.19093	0.0039	Significant	0.86
$T_{off}\,S$	0.00678	0.00678	1.71573	0.2169	Insignificant	0.11
I^2	0.04120	0.04120	10.43195	0.0080	Significant	0.68
$T_{on}^{\;2}$	0.03239	0.03239	8.20287	0.0154	Significant	0.54
$T_{off}^{\;2}$	0.04503	0.04503	11.40201	0.0062	Significant	0.75
S^2	0.02348	0.02348	5.94638	0.0329	Significant	0.39

Table 4. ANOVA results for the *SR*

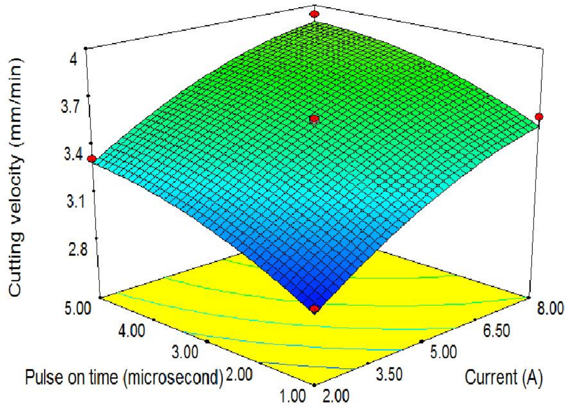
Source	Sum of Squares	Mean Square	F-Value	p-value	Remark	Contri.
Model	21.89875	1.56420	92.88492	< 0.0001	Significant	
I	3.99053	3.99053	236.96541	< 0.0001	Significant	17.91
T_{on}	7.34768	7.34768	436.31882	< 0.0001	Significant	32.98
T_{off}	2.53920	2.53920	150.78249	< 0.0001	Significant	11.40
S	4.72508	4.72508	280.58388	< 0.0001	Significant	21.21
IT_{on}	0.00023	0.00023	0.01336	0.9101	Insignificant	0.00
IT_{off}	0.00090	0.00090	0.05344	0.8214	Insignificant	0.00
IS	0.01563	0.01563	0.92784	0.3561	Insignificant	0.07
$T_{on}\,T_{off}$	0.00490	0.00490	0.29097	0.6003	Insignificant	0.02
$T_{on}\,S$	0.05290	0.05290	3.14130	0.1040	Insignificant	0.24
$T_{off}\,S$	0.57760	0.57760	34.29898	0.0001	Significant	2.59
I^2	0.36068	0.36068	21.41797	0.0007	Significant	1.62
$T_{on}^{\;2}$	0.25926	0.25926	15.39543	0.0024	Significant	1.16
$T_{off}^{\;2}$	0.16593	0.16593	9.85307	0.0094	Significant	0.74
S^2	0.67653	0.67653	40.17387	< 0.0001	Significant	3.04

The ANOVA results of the *SR* model are presented in Table 4. For this model, the single terms (I, T_{on}, T_{off}, S), interaction term ($T_{off}\,S$), and quadratic terms (I^2, $T_{on}^{\;2}$, $T_{off}^{\;2}$, S^2) are considered as the significant terms. Especially, T_{on} is the most effective parameter due to the highest contribution (32.98%), followed by S (21.21). The percentages of I and T_{off} are 17.91% and 11.40%, respectively.

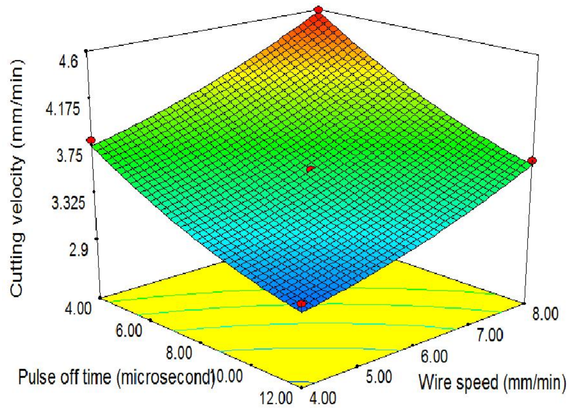
The predictive models of WEDM responses were developed with regard to process parameters using RSM and experimental data. The regression coefficients of insignificant terms were eliminated based on ANOVA results. Consequently, the regression response surface models showing the *CV* and *SR* are expressed as follows:

$$CV = 2.94084 + 0.16175I + 0.30778T_{on} - 0.10637T_{off} - 0.11964S + 0.028529T_{on}S - 0.005144T_{off}S - 0.010796I^2 - 0.02154T_{on}{}^2 + 0.0063487T_{off}{}^2 + 0.018339S^2 \quad (2)$$

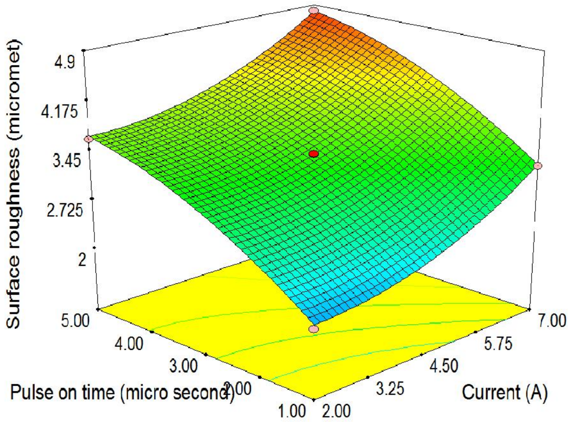
$$SR = 0.21531 - 0.070972I + 0.62562T_{on} - 0.58812T_{off} + 1.08083S + 0.047500T_{off}S + 0.031944I^2 - 0.060937T_{on}{}^2 + 0.012187T_{off}{}^2 - 0.098438S^2 \quad (3)$$



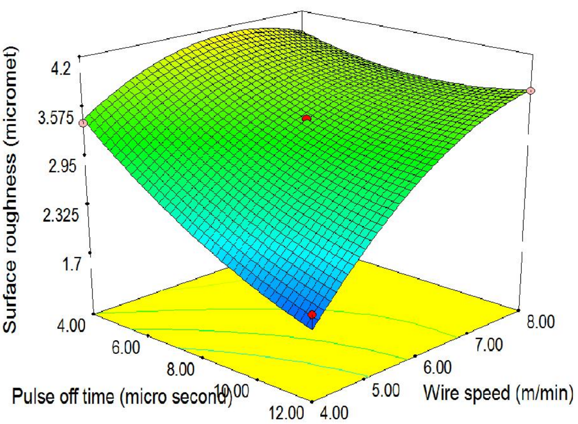
(a) Cutting velocity vs current and pulse on time



(b) Cutting velocity vs speed and pulse off time



(c) Surface roughness vs current and pulse on time



(d) Surface roughness vs speed and pulse off time

Fig. 3. Parameter effects on the WEDM responses

The main effects of each processing parameter and their interactions on the WEDM responses are shown in Fig. 3. As shown in Fig. 3a, an increase in the T_{on} and I produces longer spark duration of discharge energy. Because of this, large amount of material evaporates on the surface and improve the *CV*. A higher wire speed increases the detachment of debris material from the surface, leading to an improved *CV*. In constrast, an increased T_{off} results in a low discharge energy and material evaporated.

Fig. 3b indicated that the high discharge energy using a increased T_{on} or I results in deeper and wider size craters, thereby increasing roughness value. The higher drum speed leads to large size voids and pits, resulting higher roughness values. Increasing the T_{off} results in less number of craters and melt material, leading to less *SR*.

The objective of this paper is to improve the *CV* and decrease *SR* using process parameter optimization. The optimizing problem can be defined as follows:

Find $X = [I, T_{on}, T_{off}, S]$

Maximize cutting velocity.

Minimize surface roughness.

Constraints: $2 \leq I \leq 7$ (A), $1 \leq T_{on} \leq 5$ (µs), $4 \leq T_{off} \leq 12$ (µs), $4 \leq S \leq 8$ (m/min).

The developed equations showing the relationship between process parameters and responses are used to find optimal parameters with the aid of MOPSO. The Pareto font was shown in Fig. 4 in which blue points are the feasible solutions. The optimal parameters and responses can be found in the Table 5 which was depicted as blue point. The improvements of the *CV* and *SR* are 12.32% and 53.08%, respectively, compared to initial values.

Table 5. Optimization results

Optimization parameters				**Responses**	
I **(A)**	T_{on} **(µs)**	T_{off} **(µs)**	***S*** **(m/min)**	***CV*** **(mm/min)**	***SR*** **(µm)**
2.6	5.0	11.94	4.0	4.06	1.60
5.00	3.00	8.00	6.00	3.56	3.41
Improvement (%)				12.32	53.08

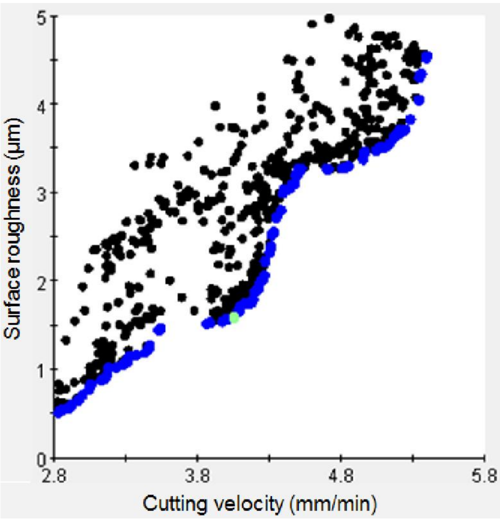


Fig. 4. Pareto generated by MOPSO

Practically, it is unnecessary to simultaneous minimizing two objectives and *SR* is common predefined as the technical requirement. Furthermore, it can be stated that it is hard to determine the optimal machining parameters for different technological outputs based on practical experience or operating guide. As a result, the global relations among the technological responses shown in Figs. 4 can be used to determine the maximum *CV* and optimal machining parameters with the predefined *SR*. These points are the industrial and academic contribution to the milling process. Therefore, the proposed approach in this paper is multi-purpose and can be applied in all cases of WEDM processes with different materials.

4. CONCLUSIONS

This work presented a multi-responses optimization of processing parameters in the WEDM process to improve the *CV* and decrease the *SR*. The RSM models were used in conjunction with MOPSO to render the nonlinear relations between inputs and technological outputs as well as determine the optimal values. The main conclusions from the research results of this work can be drawn as follows within parameters considered:

1. The highest levels of current, pulse on time, and wire speed were recommended in order to maximize the cutting velocity. Additionally, the lowest value of pulse off time should be used to observe the maximum processing efficiency.

2. The lowest levels of current, pulse on time, and wire speed have effective contributions to minimizing the surface roughness. Additionally, the highest value of pulse off time was recommended to improve the surface characteristic.

3. Solving multi-objective optimization issue using MOPSO ensured the reliable optimizing values. The proposed approach for improving the cutting velocity with predefined surface roughness is versatile and realistic in the WEDM processes, compared to single objective or simultaneous two response optimization.

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