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PRODUCTION ENGINEERING ARCHIVES 2021, 27(2), 112-118

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

An investigation of wire offset and surface morphology of Die Steel D-3 on Wire EDM by using RSM-CCD

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Article history
Received 03.03.2021
Accepted 26.04.2021
Available online 14.06.2021

Keywords
Wire Offset
Surface Morphology
SEM
Wire EDM
RSM

Abstract
The work investigated the effect on wire offset and surface morphology, with input process parameters as peak current, pulse on time, wire tension over Die Steel D3. Some of experiments were performed by using response surface methodology (RSM) as the design of experiment with central composite design (CCD) technique for the analysis. The ANOVA results annotate that the model is significant. Wire Tension and peak current are observed to have major impact on wire offset during machining operation and surface morphology. The scanning electron microscope (SEM) images confirmed that the thermal stresses produced during the machining of the workpiece resulted in the development of microcracks, craters and spherical module. Due to higher thermal gradient i.e., higher peak current and pulse on-time larger cracks and melted deposits were observed.

DOI: 10.30657/pea.2021.27.14 JEL: L69, M11

1. Introduction

For the machining of conductive material with intricate shapes and profile Wire Electric Discharge Machining (WEDM) is used. Wire EDM is a non-conventional process for the machining of mould, dies, punch, tool, and automotive industries. In this machining process, a thin brass wire of diameter 0.25mm travels continuously along the workpiece by achieving precise and accurate shapes in Die Steel D3. The brass wire moves continuously in tension in the presence of dielectric fluid as water. The spark is generated between the tool and the workpiece. The spark generated during electro-discharge machining causes the erosion of material. In the present research, the key objective is to study the different process parameters during machining of Die Steel D3, such as peak current (Ip), pulse on time (Ton) and wire tension (WT) on wire offset and surface morphology. Wire Offset or dimensional shift arises due to the force between brass wire and workpiece in the presence of dielectric fluid during the machining operation. Moreover, surface morphology has been studied using SEM for crater, cracks, gas deposits developed on the machined surface. Several researchers have tried to improve the performance characteristics of material mainly on Wire Offset, Surface Morphology, Material Removal Rate, Surface Roughness, kerf width, and spark gap but still because of its complex nature, more variables involved, there is some work required to be done on wire offset and surface morphology.

Mahapatra et al.,2006; an effort was made to independently specify the significant machining parameters in the WEDM process for performance measurements such as MRR, SF, and kerf distance. The experimental design approach of Taguchi is used to achieve the optimal combination of parameters for maximization of MRR, SF and kerf minimization. As higher MRR, SF and low kerf are equally important targets in WEDM implementation, this analysis measures the output metrics with equal consideration to weighting factors. Using multiple work materials and hybrid optimization approaches, the analysis can be applied in the future. Bhangoria et al.,2010; using the DOE L32 (21 X 44) mixed orthogonal array Taguchi method, statistical and regression analysis of kerf width was used. Experimental studies have shown that both methods can successfully refine machining parameters (gap voltage, pulse on time, pulse off time, wire feed and dielectric flushing pressure), taking the response kerf width into account. Shandilya et al.,2011; to model and evaluate surface roughness in SiCp/6061 Al MMC, an experiment was performed using response surface methodology in WEDC. In WEDC servo voltage, pulse on time, pulse-off time and wire feed rate parameters were varied to investigate the impact of SiCp/6061 aluminium MMC on cut efficiency using surface roughness as the response parameter. To calculate the value of surface roughness mathematically, the mathematical relationship between WEDC input process parameters and surface roughness was defined. Analysis of variance (ANOVA) was used to define the important variables for the WEDC process. Shanmuga Prakash et al.,2017; regarding the multiple input variables, output value measurement, novel optimization methods, etc., the wire EDM method was checked. They also addressed the importance of optimizing wire EDM efficiency to satisfy the machining industry's requirements. Shinde et al.,2014; by using Taguchi's L9 orthogonal array by adjusting the pulse on time, pulse off time, peak current and wire speed, AISI D3 tool steel was considered for experimentation. Finally, the desired criteria for machining have been obtained. Sivakumar et al., 2017; the tool steel (AISI D3) workpiece was experimentally machined and the influence of pulse on time, peak current and voltage on the removal rate of material and surface roughness was tested. To achieve a better material removal rate and surface finish, they concluded the optimized parameter for machining the D3 steel. Sarkar et al.,2005; optimized WEDM's trim cutting process of γ- TiAl alloy by desirability function approach and Pareto- optimization algorithm and superior efficiency compared to desirability function approach for a given machining condition. A prediction model of surface roughness for machining mild steel was developed using Response Surface Methodology (RSM). Ashok Kumar Srivastava et al.,2013; investigated the effect of WEDM on wire offset. It was analysed that higher wire offset is obtained by increasing the pulse on-time, lower wire offset is obtained by an increasing pulse off-time, wire feed has small effects in small wire offset. Ikram et al.,2013; to optimize the surface roughness, kerf and MRR for tool steel D2, the Taguchi model of the experiment was used. The input parameters include wire feed velocity, pulse on-time, pulse off-time, dielectric strength, open voltage, servo voltage, and wire voltage. They discovered that the most critical aspect was pulse on time and open voltage for surface roughness. The important considerations for kerf are pulse on-time, wire stress and open voltage. Mishra et al.,2017; found that Due to internal stresses induced by heating and rapid cooling of the surface, cracks are found on machined surfaces. Rizvi et al., 2016; to determine the cracks and residual stress, offered an approach and concluded that cracks often occur on the machined surface. Increasing the pulse length increases the opening of the crack. They also concluded that higher residual pressures result from higher peak current and length pulse values.

2. Experimental Procedures

In the present study for experimentation work, Die Steel D3 has been used as a working material. The tool selected for machining operation is 0.25mm brass wire. Plane water is used as a dielectric fluid medium for spark generation. All experiments were performed on Maxicut Electronica Wire EDM as shown in Fig.1. For the validation of the experiment, three input process parameters were selected viz. peak current, pulse on time, and wire tension to develop influence on Wire Offset and Surface Morphology for induced cracks. The machining of the workpiece and specimen is shown in Fig. 1(b).

(a)

(b)

Fig. 1. (a) Experimental setup of Maxicut Electronica Wire EDM **(b)** Wire EDM Machining process.

2.1. Wire offset

Wire offset developed during machining operation is the result of the force created by electro-discharge between the brass wire and dielectric fluid during machining which tends to deviate the wire electrode through a small distance. Due to this force, the variance induces a dimensional shift in the profile to be produced. The scanning electron microscope (SEM) images as shown in Fig. 3(a), 3(b), 3(c) is used to calculate the width of the actual work profile W_a.

Wire offset or Dimensional Shift (DS) is for rough cutting. It is the distance between the actual machined job profile and the programmed job profile. The Mathematical formula for the calculation of wire offset is

$$DS = 0.5\,(W_p - W_a) \tag{1}$$

where,
DS = Dimensional shift
W_p = Programmed width
W_a = Actual width

2.2. Design of experiment

During machining operation, the required input parameter variables like peak current (Ip), pulse on time (Ton), wire tension (WT), as given in Table 1, is related to the wire offset with Response Surface Methodology (RSM) as the design of experiment using Central Composite Design (CCD). A Response Surface Design is a series of advanced design of experiment (DOE) techniques that allow to understand the response better and to optimize it.

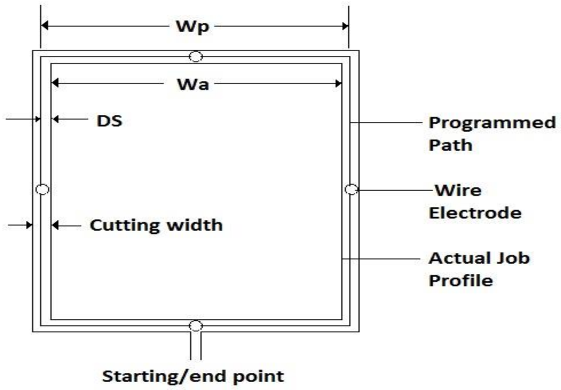


Fig. 2. Wire offset in wire EDM.

The methodology of response surface design is also used to refine models after the use of factorial designs has defined important variables for modelling and analysis of the problem. RSM is a collection of mathematical and statistical procedures where the main objective is to optimize the response. Based on the number of input variables and levels, 20 trial experiments were conducted, the combination of variable is shown in Table 2.

Table 1. Selected levels of input parameters on WEDM

Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Peak Current	I_p	A	2	4	6
Pulse on Time	T_{on}	μsec	3	6	9
Wire Tension	WT	Kgf	400	700	1000

Table 2. Wire EDM RSM-CCD

Exp. No	Peak Current (Ip)	Pulse on Time (Ton)	Wire Tension (WT)	Machining Time (min.)	Weight Loss (gm)	Machined Size (mm)	Programmed size (mm)	Wire Offset
1	2	3	400	18.57	0.949948	4.774	5	0.1130
2	6	3	400	21.02	1.065352	4.696	5	0.1520
3	2	9	400	15.53	0.850048	4.815	5	0.0925
4	6	9	400	17.45	0.992220	4.789	5	0.1055
5	2	3	1000	20.88	0.850056	4.815	5	0.0925
6	6	3	1000	23.13	1.396012	4.792	5	0.1040
7	2	9	1000	26.3	1.006963	4.909	5	0.0455
8	6	9	1000	18.95	1.098241	4.883	5	0.0585
9	2	6	700	23.88	0.987977	4.903	5	0.0485
10	6	6	700	22.68	1.414010	4.733	5	0.1335
11	4	3	700	20.63	0.962296	4.903	5	0.0485
12	4	9	700	18.42	0.945029	4.876	5	0.0620
13	4	6	400	17.57	0.938340	4.876	5	0.0620
14	4	6	1000	18.02	0.891748	4.964	5	0.0180
15	4	6	700	12.93	0.698271	4.913	5	0.0435
16	4	6	700	13.03	0.647476	4.934	5	0.0330
17	4	6	700	12.98	0.697804	4.928	5	0.0360
18	4	6	700	13.08	0.697004	4.920	5	0.0400
19	4	6	700	12.87	0.698677	4.908	5	0.0460
20	4	6	700	12.95	0.698128	4.922	5	0.0390

3. Results and discussion

3.1. Wire Offset

The investigation is carried out to examine the effect of Wire EDM parameters using brass wire electrodes on wire offset produced in Die Steel D3. The model was analyzed using the Design Expert 13 software. The Sequential Model Sum of Square and Lack of Fit test is shown in Table 3 and 4, a quadratic model is suggested for wire offset. ANOVA test was performed as shown in Table 5. The model F-value of 8.12 inferred that the present model is significant and there is only a 0.15% chance that this F-value could occur due to noise. Thus, the present model represents the data within the required value of a 95% confidence interval. From the test, peak current (A), Pulse on time (B), Wire Tension (C), Peak Current-Peak current(A^2) are significant model terms as their p-value is less than 0.0500.

Table 3. Sequential model sum of the square for Wire Offset

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F-VALUE	P-VALUE	
Mean vs Total	0.0943	1	0.0943			
Linear vs Mean	0.0090	3	0.0030	2.80	0.073	
2FI vs Linear	0.0003	3	0.0001	0.0643	0.9778	
Quadratic vs 2FI	0.0138	3	0.0046	14.57	0.0006	**Suggested**
Cubic vs Quadratic	0.0030	4	0.0007	25.88	0.0006	**Aliased**
Residual	0.0002	6	0.0000			
Total	0.1205	20	0.0060			

Table 4. Lack of fit test of Wire Offset

SUM OF SQUARE	DF	MEAN SQUARE	F-VALUE	P-VALUE	
0.0170	11	0.0015	68.40	0.0001	
0.0168	8	0.0021	92.66	<0.0001	
0.0030	5	0.0006	26.80	0.0013	**Suggested**
0.0001	1	0.0001	2.61	0.01669	**Aliased**
0.0001	5	0.0000			

Table 5. ANOVA results for Wire Offset

SOURCE	SUM OF SQUARE	DF	MEAN VALUE	F-VALUE	P-VALUE	
MODEL	0.0230	9	0.0026	8.12	0.0015	**Significant**
A-PEAK CURRENT(Ip)	0.0026	1	0.0026	8.29	0.0164	
B-PULSE ON TIME(Ton)	0.0021	1	0.0021	6.77	0.0264	
C-WIRE TENSION(WT)	0.0043	1	0.0043	13.55	0.0042	
AB	0.0001	1	0.0001	0.2384	0.6359	
AC	0.0001	1	0.0001	0.3004	0.5957	
BC	0.0001	1	0.0001	0.2583	0.6223	
A^2	0.0061	1	0.0061	19.45	0.0013	
B^2	0.0004	1	0.0004	1.14	0.3103	
C^2	0.0000	1	0.0000	0.1274	0.7286	
RESIDUAL	0.0031	10	0.0003			
LACK OF FIT	0.0030	5	0.0006	26.80	0.0013	**Significant**
PURE ERROR	0.0001	5	0.0000			
COR TOTAL	0.0262	19				

Wire tension with a P-value equaling to 0.0042 is the most dominating factor for wire offset for the present model followed by peak current. Earlier researchers have only focused on Pulse on time and current but wire tension, too influenced wire offset which is in good agreement with earlier researches. Pulse on time factor was the least influencing among the selected set of parameters for wire offset.

The 3D surface plot in Fig. 4(a) shows the interaction effect of pulse on-time and peak current on wire offset, it was observed that with the increase in peak current wire offset first decreases and then increases gradually with least effect on the pulse on time. Fig. 4(b) shows the interaction effect of Wire Tension and Peak Current on wire offset. It was observed that with the increase in peak current at minimum wire tension, wire offset initially decreases and then increases drastically. However, it was observed that when maximum wire tension occurs, then wire offset decreases gradually with an increase in peak current. Fig. 4(c) shows the interaction effect of Wire Tension and pulse on time on wire offset. It was observed that wire offset initially increases slightly at lower wire tension, and then decreases significantly with the increase in pulse on time, wire offset initially increases slightly with higher wire tension, and then decreases enormously, as the pulse on-time increases.

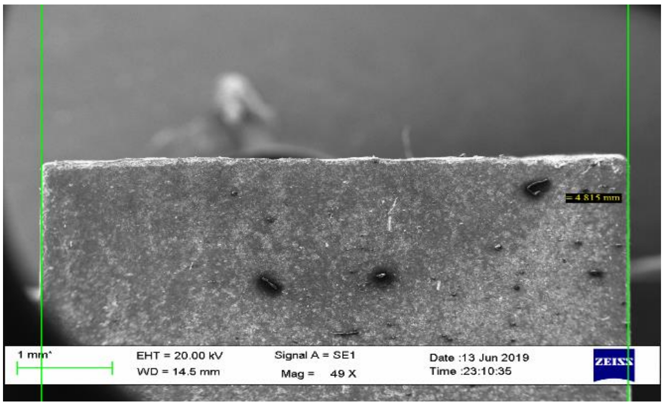


Fig. 3. (a) SEM images of wire offset work piece of sample 1

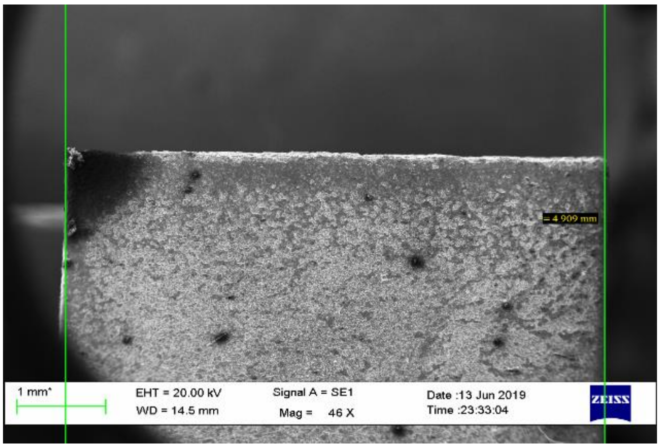


Fig. 3. (b) SEM images of wire offset work piece of sample 10

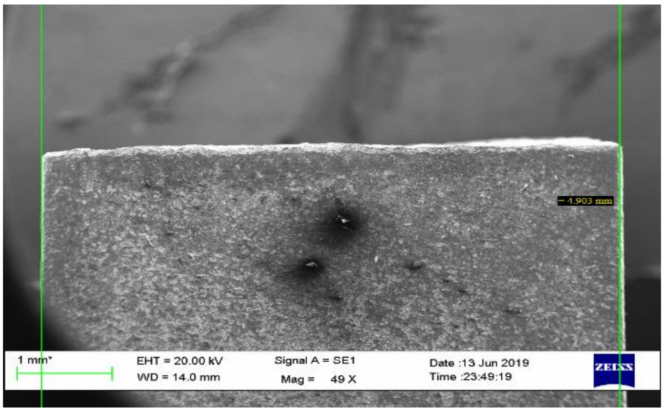


Fig. 3. (c) SEM images of wire offset work piece of sample 20.

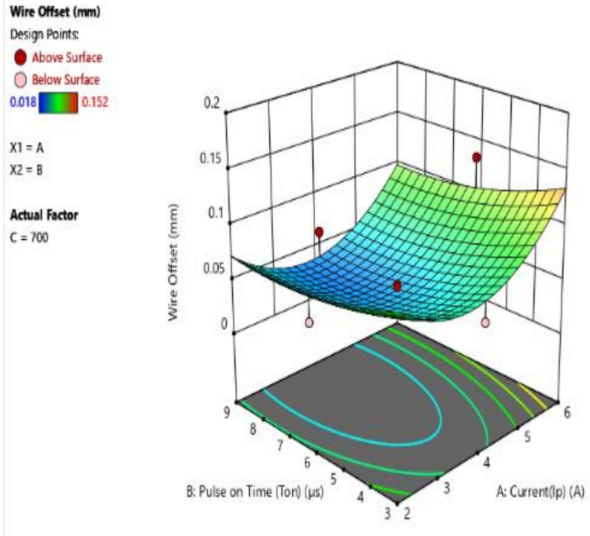


Fig. 4. (a) Interaction effect of pulse on time and peak current

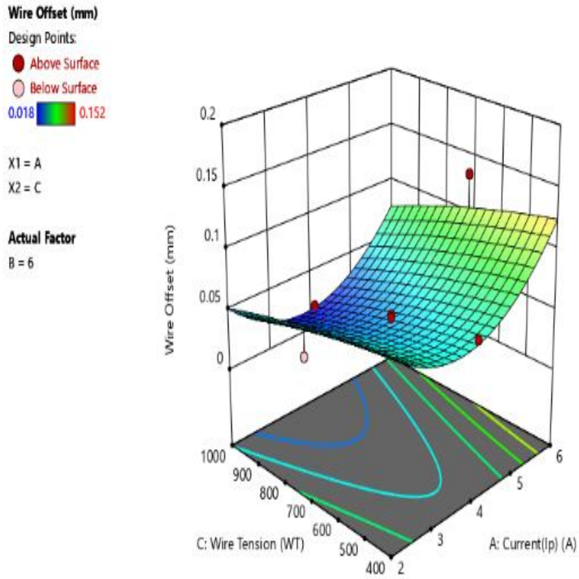


Fig. 4. (b) Interaction effect of wire tension and peak current

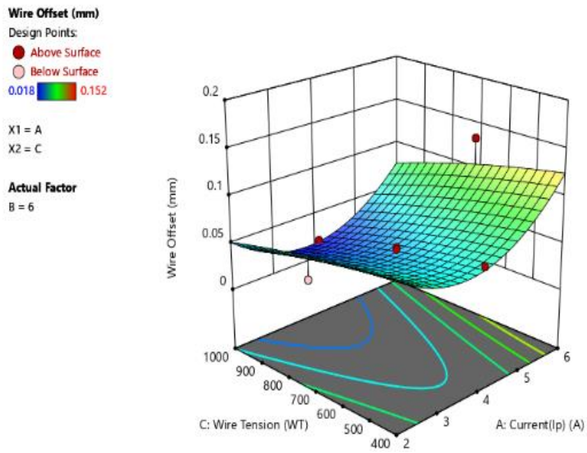
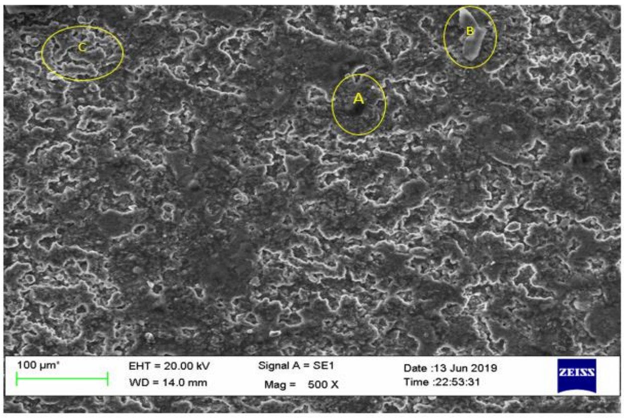


Fig. 4. (c) Interaction effect of wire tension and pulse on time

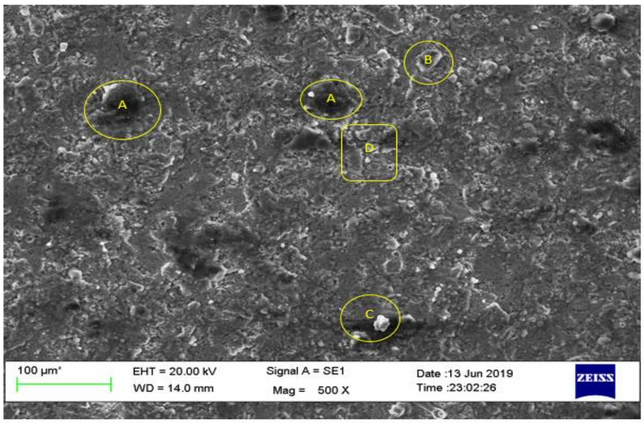
3.2. Results of Surface Morphology

The need for an SEM micrograph is to observe the surface integrity and surface characteristics. During the machining process input parameters such as Peak Current, pulse on time and wire tension is used to perform the experiment. The machined surface of die steel D3 was examined on SEM micrographs as shown in Fig. 5(a). Various types of the crater, micro-cracks, small gas hole etc. developed on the surface of Die Steel D3 specimen during machining operation on Wire EDM is seen. The major cause of various defects developed on the surface of the specimen is due to oxidation or decomposition reaction, internal stresses developed due to uneven temperature distribution created at the time of machining during sparking. The appearance of craters, micro-cracks, spherical module is generated due to high thermal energy (10,000ºC – 14,000ºC) during the sparking of Wire EDM. The porous structure on the machined surface is developed due to a gas hole. Moreover, the spark generated due to the discharge of current between the brass wire and dielectric fluid had great emphasis on the crater and crack initiation. As can be seen from SEM images in Fig. 5(a). At lower peak current and pulse on-time small wear out material and crater are seen in micrograph along with some trapped gas hole is seen. These cracks and craters are dispersed all over the machined surface which is due to the spark generated between tool and dielectric fluid and due to the uneven temperature distribution. At larger current and pulse on-time, more wear out material takes place, and more roughness is generated which results in the larger crater and more melted deposits are seen in Fig. 5(b) these are developed due to high internal stresses thermal energy and oxidation or reduction reaction. In Fig. 5(c) a large amount of gas deposits and the spherical module is seen which results in the development of a rough machined surface. This type of deposits takes place due to the high current and pulse on time in a dielectric fluid medium.



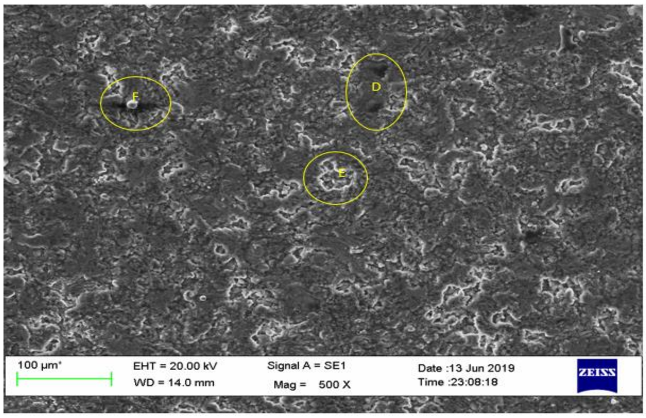
A= CRATERS B= WIRE WEAR OUT MATERIAL C= SMALL GAS HOLE

(a)



A= CRATERS B= WIRE WEAR OUT MATERIAL C= MELTED DEPOSITES D= MICRO CRACKS

(b)



D = SMALL SHALLOW CRATER E = SMALL GAS DEPOSITES F = SPHERICAL MODULE

(c)

Fig. 5. (a) SEM image of the machined surface of Sample 1 **(b)** SEM image of the machined surface of Sample 10 **(c)** SEM image of the machined surface of Sample 20.

4. Summary and conclusion

In the present work of machining of Die steel D3 using brass wire as an electrode. The various input process parameters selected like peak current, pulse on time, wire tension on the response characteristics of wire offset and surface morphology was investigated by response surface methodology with central composite design. The conclusions drawn from the present work are as follows:

1. Wire tension is the most dominating factor followed by peak current, moreover, pulse on time has the least effect on wire offset.
2. It can be observed that with the increase in peak current wire offset firstly decreases and then increases gradually with least effect on the pulse on-time with the increase in peak current at minimum wire tension wire offset initially decreases and then increases drastically, for maximum wire tension wire offset decreases gradually with increase in peak current.
3. The analysis shows that wire offset initially increases a little at lower wire tension and then decreases by a large amount with the increase in pulse on time, wire offset initially increases little with higher wire tension, and then decreases enormously as the pulse on-time increases.

4. The major cause of crater and microcrack development is the presence of high thermal energy during the machining process, moreover due to internal stresses created during sparking in presence of dielectric fluid also has a great impact on the initiation of cracks and crater.
5. At the higher level of peak current and pulse on-time large amount of wear out material and melted deposits are developed on workpiece specimen during machining due to higher thermal gradient.
6. The uneven temperature distribution results in the evolution of the gas deposit and spherical module on the surface of the specimen during machining.

Acknowledgement

The authors gratefully acknowledge Research and Development cell, Integral University, Lucknow for providing manuscript communication number IU/R&D/2021-MCN0001094 and kind support.

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利用 RSM-CCD 研究 D-3 钢在电火花线切割机上的线偏移和表面形态

關鍵詞
线偏移
表面形态
扫描电镜
电火花线切割
RSM

摘要

这项工作使用 Die Steel D3 上的输入工艺参数（例如峰值电流，脉冲接通时间，线张力）研究了对线偏移和表面形态的影响。通过使用响应面方法（RSM）作为实验设计进行了一些实验，并使用了中央复合设计（CCD）技术进行了分析。方差分析结果说明该模型很重要。观察到线张力和峰值电流对机加工操作和表面形态期间的线偏移有重大影响。扫描电子显微镜（SEM）图像证实，在加工工件期间产生的热应力导致了微裂纹，弹坑和球形组件的发展。由于较高的热梯度，即较高的峰值电流和脉冲导通时间，观察到较大的裂纹和熔化的沉积物。