Advances in Science and Technology Research Journal
Volume 12, Issue 1, March 2018, pages 89–98
DOI: 10.12913/22998624/81001

Research Article

ANALYSIS OF THE EFFECT OF WIRE ELECTRIC DISCHAGE MACHINING PROCESS PARAMETERS ON THE FORMATION OF HIGH SPEED STEEL FORM TOOL

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Received: 2017.05.24
Accepted: 2018.02.01
Published: 2018.03.01

ABSTRACT
The use of form tools is growing in industry, owing to their inherent advantage of improving productivity. However, the accurate formation of form tool profile is a really tedious task. In this research work, wire electric discharge machining (WEDM) process has been used for the generation of a form tool. Pulse on-time, pulse off-time, servo voltage, wire tension, flushing pressure have been considered as input parameters, whereas tool geometry (clearance angle, included angle), surface roughness and material removal rate are the selected responses. Response surface methodology (RSM) (Box Bhenken experimental design) technique has been used for design of experiments. Analysis of Variance (ANOVA) has shown that pulse on-time and pulse off-time are the two influential control factors for material removal rate (MRR), surface roughness (Ra), clearance angle and included angle. Contour plot analysis has been performed to find out the optimal ranges of the most influential control factors for each response characteristics.

Keywords: Wire electric discharge machining (WEDM), response surface methodology (RSM), ANOVA, Material removal rate (MRR), Surface roughness (Ra)

INTRODUCTION

Productivity has become quite an important consideration for industries for their survival in this competitive environment. Organizations are continuously striving to develop tools that help to enhance productivity. The development of different types of form tools is the consequence of this search. High speed steel (HSS) is commonly used to develop a form tool in industry, due to its improved ductility, higher fracture toughness and wear resistance [20]. The use of these form tools helps to reduce the manufacturing lead-time.

The accurate formation of the profile of these form tools is really an important ingredient to meet the tight tolerance requirement of industry. The dimensional accuracy of the machined part is directly dependent on the accuracy of the tool's profile. The required degree of accuracy in terms of dimensions and surface finish of HSS form tools cannot be achieved using conventional machining processes, such as milling, turning and grinding due to its properties of high hardness, toughness and abrasion resistance [16]. Therefore, non-conventional machining processes, such as electric discharge machining (EDM), ultrasonic machining, electrochemical machining and WEDM are used to form these tools because of their characteristics of processing hard to cut materials. Due to inherent advantages- processing too difficult to machine materials, easy machining of complex parts and formation of precision components out of hard to cut materials-over other non-conventional machining processes, WEDM is used in this study.

In WEDM process, metal removes due to the thermal energy created by controlled discharges. Dielectric fluid is used to flush away the debris. The process of WEDM is controlled by numerous control factors, such as pulse on-time, pulse-off time, servo voltage, open voltage, wire tension, wire feed, dielectric pressure etc. The cut quality of the machined part is mainly dependent on the appropriate choice of these control factors [3].

Researchers tried various combinations of these parameters for the evaluation of their impact on various response characteristics, such as MRR, surface roughness, corner deviation etc., while cutting variety of materials. Bobbili [1] evaluated the cutting performance of WEDM process for cutting high speed steel. The results showed that peak current, pulse on-time (Pon) and flushing pressure directly influenced the amount of material removed. Pulse on-time, wire feed, wire tension and flushing pressure were found to have a direct relationship with surface roughness (Ra). The effects of four WEDM parameters namely; pulse on-time (Pon), pulse off-time (Poff), peak current and wire tension were investigated by Dhobe [15] on surface roughness while cutting tool steel. It was found that wire tension and peak current were the two dominant control factors for Ra. Smaller values of wire tension and peak current were found to produces smaller surface roughness (Ra). Bobbili [1] reported that Pon, Poff and servo voltage were the significant factors for Ra and MRR for cutting armor tool steel. Shivade and Shinde [17] evaluated the cutting performance of WEDM for D3 tool steel. The results showed that MRR increases with the increase in Pon and peak current and decreases with the increase in Poff. Yang [22] investigated the effects of various WEDM input parameters on surface roughness (Ra) and material removal rate (MRR) while cutting tungsten. Results revealed that pulse on-time (Pon) and pulse off-time (Poff) were found to be the influential factors for MRR whereas Pon and flushing pressure were the major contributing parameters for Ra. Ikram [6] tried various combinations of seven input WEDM parameters namely; wire feed, flushing pressure, Pon, Poff, open gap voltage, wire tension and servo voltage for cutting of D2 die steel. Pon was found to be the most contributing factor for both MRR and Ra. Zhang [24] reported that Pon and Poff were the two most influential control factors for Ra, whereas for MRR, Pon and wire feed were found to be the major contributing factors during machining of SKD11 steel. Dhobe [5] studied the effects of different WEDM parameters on Ra while cutting Cryo-treated AISI D2 tool steel. Pon was found to be the significant factor for Ra, whereas Poff also affects Ra but at higher values. Pramanik [14] assessed the influence of Pon and wire tension on MRR and Ra for cutting Al 6061. MRR was found to be greatly influenced by Pon whereas the impact of wire tension was prominent for Ra. In another study, Tilekar [21] developed the optimal settings of WEDM parameters for cutting aluminum and mild steel using single response optimization technique. Peak current and Pon were proved to be the statistically significant control factors controlling Ra of cut specimen. Khan [7] evaluated the effect of different WEDM parameters on surface integrity and Ra while cutting low alloy steel. The results revealed that Pon, Poff and peak current were influential control factors for surface integrity and for Ra, Pon was found to be the most significant control factor.

Lin [12] investigated the effect of six WEDM input parameters namely; servo voltage, Pon, Poff, wire tension, wire feed and no load voltage on MRR during cutting of Fe-Al alloy. Pon was found to be the most influential control factor for MRR. In another research work, Yeh [23] tried various dielectric fluids for machining polycrystalline silicon. The use of pure water with sodium pyrophosphate powder as dielectric improved the surface roughness and cutting speed by 16% and 24% respectively. Mandal [13] evaluated the cutting performance of WEDM for machining Nimonic C-263 super alloy using multi-cut strategy. Their investigations revealed that Pon, servo voltage and feed rate were the significant factors for Ra. Parametric analysis of wire EDM on MRR was done by Singh and Garg [18] using hot H11 steel as work piece material. Spark on time, spark off time, gap voltage, peak current, feed of wire and wire tension were used as input parameters in this work. It was reported that Pon and peak current were the major contributing factors for MRR.

Research showed that improper combination of process parameters affects the response variables that ultimately leads to loss of productivity and dimensional accuracy in WEDM process [10]. Therefore, an optimization technique has become an essential tool in finding the exact combination of process parameters. Many researchers used various optimization techniques in order to optimize the process parameters of WEDM [6, 17, 21]. In addition to these, Kumar [8] used taguchi method while investigating the effects of cutting parameters on material removal rate for EN-42 using WEDM process. The same method was used by Tilekar [21] during the optimization of process parameters of WEDM process on aluminum and mild steel. Dabade [4] also used Taguchi method to optimize the response variables in WEDM process of Inconel 718 material. Singh and Pradhan [19] used taguchi and response surface methodologies for the optimization of WEDM process using AISI D2 steel.

The above literature highlights that limited work has been done on the parametric optimization of WEDM process in terms of quality of responses. Researchers paid attention mostly to surface roughness (Ra) and MRR as responses but in current study, along with these parameters, tool geometry (included angle, clearance angle) has also been investigated as it is an important function while analyzing the quality of machined components in tool and die making firms. It is evident from the above studies that most of the studies use taguchi method, grey relational analysis and RSM for optimization purpose. RSM-Box Behnken design- investigated the most significant method having capacity to provide the most significant process parameters and optimizes the responses using best combination of significant input parameters. Also, limited work has been reported on the optimization of process parameters in WEDM process using high speed steel (HSS) materials. Therefore, this research work aims to analyze the effect of process parameters on the formation of HSS form tools using wire electric discharge machining.

METHODS AND MATERIALS

High speed steel, which is commonly used cutting tool material, was selected for the formation of a form tool. The density of the material was 8.66·1000 kg/m^3. The Rockwell hardness of the work piece was HRC 62. The nominal composition of the work piece material is presented in Table 1.

Experimental Design

Response surface methodology, Box-Bhenken experimental design technique was used for performing series of experiments. Five WEDM parameters were selected as input parameters namely: pulse on (Pon), pulse off (Poff), wire tension, flushing pressure and gap voltage. The selection of these parameters and their levels were based on literature review and trials cutting. Design of experiments (process variables and their levels) are given in Table 2.

A total number of forty six experiments were performed as per Box-Bhenken experimental design technique. One of high speed steel form tool made by WEDM is shown in figure 1. Geometry of tool which includes clearance angle and included angle was measured by coordinate measuring machine (CMM). The resolution of machine was 0.001mm. Measurements are taken by a probe attached to the third moving axis of the machine. Surface roughness is measured by using surface texture machine.

Experimental Setup

The experimentation was performed on CNC WEDM (Model: G43S) shown in Figure 2. Machine comprises of a CNC pulse generator, machine tool, and dielectric liquid supply unit. The

Table 1. Chemical composition of high speed steel

Elements	C	Cr	W	V	Mn	Si
% age by wt.	1.2	3.8	17.2	1.1	0.35	0.3

Table 2. Process variables and their levels

Parameters	Gap voltage (G_v)	Pulse on time (P_{on})	Wire tension (W_t)	Flushing Pressure (F_p)	Pulse off time (P_{off})
Units	volt	μ-sec	G	Kgw/cm^2	μ-sec
Level 1	40.0	2.0	2.0	5.0	10.0
Level 2	45.0	3.0	8.0	8.5	15.0
Level 3	50.0	4.0	14.0	12.0	20.0

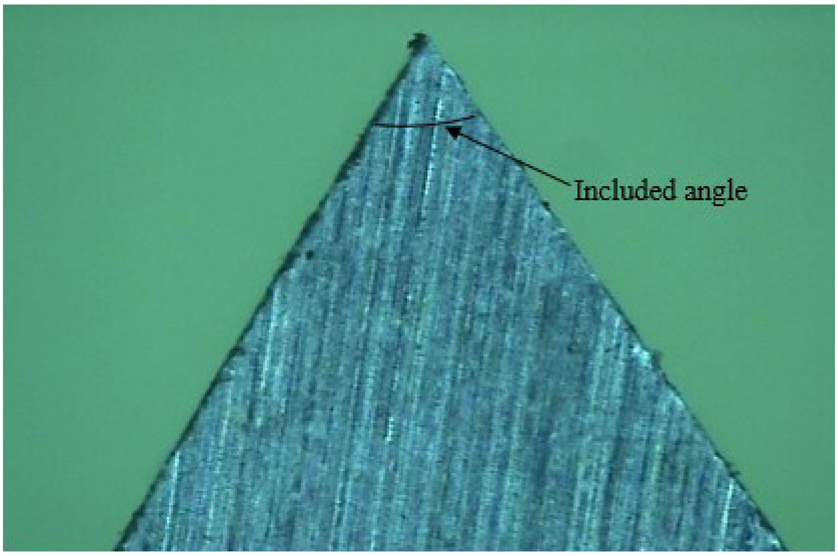

Fig. 1. HSS form tool profile

Fig. 2. Wire electric discharge machine

wire used in this experimentation was brass wire of diameter 0.25 mm having a tensile strength of 800–1000 MPa. Distilled water along with sodium zeolite was used as dielectric. In this process, spark generation occurs between constantly moving wire and part.

RESULTS AND DISCUSSION

Effects of input parameters (flushing pressure, wire tension, gap voltage, pulse on time and pulse off time) on responses (surface roughness, included angle, clearance angle and material removal rate) are presented in this section. For this purpose, the results of graphical trends, analysis of variance (ANOVA) and contour plots are described below. A total number of 46 experiments were performed as per RSM Box Bhenken experimental design technique shown in Table 3.

Graphical trends

The main effects plot analysis was carried out to figure out the trend of input parameters for surface roughness of the cut specimen. The graphical representation of these trends are shown in figure 3(a); which shows that Ra value decreases as there is increase in value of flushing pressure up to 8.5 kgw/cm^2. Beyond this, the value of surface roughness increases again. This is likely due to the reason that when flushing pressure increases beyond the threshold value, material tends to tear off due to high pressure. Similar kind of result was reported by Kuruvila [11] while cutting hot die steel. Wire tension behaves linearly with Ra and maximum value of Ra is obtained at maximum value of wire tension. Therefore, it is recommended to keep low value of wire tension. Ra value decreases as the value of gap voltage decreases and from 45V to onwards it does not affect the Ra value. Hence, it is recommended that value of gap voltage should be kept low to achieve good quality surface. Ra value increases as there is increase in value of pulse on time from 2 to 3μs. Due to large Pon current, the craters on surface are formed and good quality cannot be achieved. Similar increasing trend was achieved by Bobbili [2]. Ra value becomes high when Poff time increases from 10 to 15 μs. Hence poor surface is likely to be formed. For included angle in Figure 3(b), it was found that its value increases as there is an increase in the values of Pon, pulse off time and flushing pressure. While, its value decreases with the increase in wire tension and for the gap voltage, value of included

Table 3. Response surface methodology (Box-Bhenken sachem)

No. of trials	Flushing Pressure	Wire Tension	Gap voltage	Pulse on time	Pulse off time	Ra	Included angle	Clearance angle	MRR
1.	5.0	2	45	4	15	1.920	60.7000	12.2302	0.192
2.	12.0	8	45	2	15	2.060	60.6600	11.8925	0.167
3.	8.5	8	45	4	15	2.031	60.6940	11.7982	0.199
4.	5.0	8	45	4	10	1.900	60.5930	11.8511	0.209
5.	8.5	8	50	4	15	2.000	60.7170	11.8156	0.198
6.	8.5	2	45	2	15	1.820	60.7180	12.2302	0.166
7.	8.5	8	45	4	15	2.010	60.7950	11.7982	0.191
8.	8.5	8	50	4	15	1.992	60.7210	11.8156	0.209
9.	8.5	8	45	3	10	1.983	60.6970	11.7523	0.125
10.	8.5	2	45	3	15	2.000	60.7520	12.1315	0.276
11.	8.5	8	40	2	15	1.900	60.7090	11.9292	0.168
12.	8.5	8	45	4	15	2.050	60.7550	11.7982	0.213
13.	8.5	8	40	4	20	1.925	60.7730	11.9361	0.141
14.	8.5	14	45	4	20	1.935	60.6870	11.7844	0.154
15.	5.0	14	45	4	15	2.000	60.6730	11.7774	0.194
16.	5.0	8	45	2	15	1.860	60.6690	11.9947	0.170
17.	5.0	8	40	4	15	2.060	60.7750	11.9292	0.164
18.	8.5	2	45	4	20	1.932	60.7490	12.2371	0.147
19.	5.0	8	45	3	15	1.994	60.7410	11.8960	0.276
20.	8.5	2	40	4	15	2.006	60.7767	12.1647	0.192
21.	8.5	14	40	4	15	2.001	60.7109	11.8800	0.202
22.	12.0	14	45	4	15	2.100	60.6775	11.6760	0.197
23.	8.5	2	45	3	10	1.955	60.6279	12.1470	0.125
24.	8.5	14	50	4	15	2.000	60.6909	11.7370	0.197
25.	12.0	8	45	4	20	2.100	60.7680	11.9960	0.142
26.	8.5	14	45	3	10	1.920	60.5622	11.6520	0.125
27.	8.5	8	45	2	20	1.811	60.7296	12.0510	0.115
28.	12.0	8	45	2	15	2.008	60.7056	11.8470	0.155
29.	5.0	8	50	4	15	1.978	60.7382	11.8190	0.192
30.	5.0	14	45	3	15	2.091	60.6357	11.6560	0.275
31.	8.5	8	45	4	15	2.002	60.7213	11.9070	0.197
32.	12.0	8	50	4	15	2.060	60.7575	11.8100	0.209
33.	8.5	8	45	2	10	1.742	60.6128	11.9600	0.074
34.	12.0	8	40	4	15	2.100	60.7774	11.9320	0.188
35.	8.5	8	45	3	20	2.000	60.7341	11.8870	0.135
36.	5.0	8	45	4	20	1.900	60.7487	11.9490	0.146
37.	8.5	8	45	4	15	1.970	60.7213	11.7850	0.195
38.	8.5	2	50	4	15	1.895	60.7567	12.1520	0.201
39.	8.5	8	50	2	15	1.900	60.7191	11.8000	0.159
40.	8.5	8	40	4	10	1.914	60.6846	11.8120	0.177
41.	8.5	8	45	3	15	2.010	60.6988	12.0050	0.134
42.	12.0	2	45	4	15	2.000	60.7432	11.9350	0.197
43.	12.0	8	45	4	10	1.965	60.6512	11.7615	0.175
44.	8.5	14	45	2	15	1.930	60.6391	11.9810	0.167
45.	8.5	8	50	4	20	1.900	60.7814	12.0140	0.142
46.	8.5	8	40	3	15	2.035	60.7436	11.7880	0.276

angle decreases till 45v and then increases till 50v. Figure 3(c) shows that the value of clearance angle decreases with the increase in wire tension, gap voltage and Pon time (up to 2–3 μs: onward, it increases again); while reverse trend was found in case of Poff time. The effect of flushing pressure was found to be quite alike as that of Pon time. The graphical trends of various input parameters for MRR are shown in figure 3(d) which depicts that its value decreases with the decrease of flushing pressure up to 8.5 kgw/cm^2; after that it increases. Similarly, it decreases with increase in wire tension up to 8g and gap voltage up to 45 V. Similar trends were achieved by Singh and

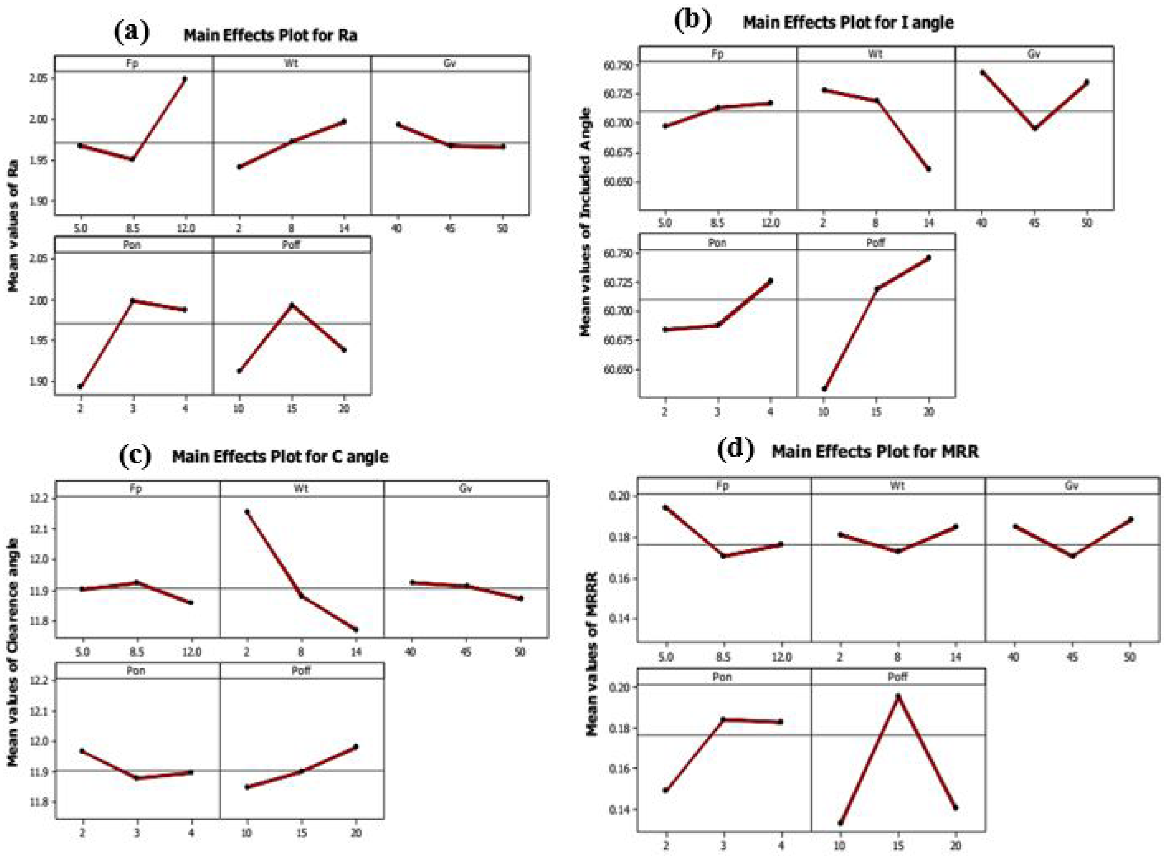

Fig. 3. Main effect plots (graphical trends) for; (a) surface roughness, (b) included angle, (c) clearance angle and (d) material removal rate

Garg [18]. Hence low values of Fp, Wt and Gv are recommended to achieve high MRR. In case of Pon time – from 2.0 to 3.0 µs – MRR increases, after that its value slightly decreases. Up to 15µs of Poff time; MRR was showing increasing trend; while, it decreases afterward. This is due to the reason that when Poff increases beyond the threshold value it tends to allow the re-solidification of the molten material in terms of recast layer that reduces MRR [18].

Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) was performed for testing the importance of input parameters on responses. It was investigated that variables will be vital for responses when F-ratio value is superior [23]. Such factors as flushing pressure, wire tension, pulse on and off time shows significant effect on Ra can be predicted from their p values in table 4, but gap voltage was an insignificant factor in case of surface roughness. Pramanik [14] had used same set of input variables, similar results were achieved that pulse on time had shown significant effect on SR. Furthermore, Pulse on and off time were most significant among all the factors because these factors contributed more towards surface roughness. Percentage contribution of these factors in terms of pi-chart is also shown in figure 4(a). In case of included angle, such parameters as wire tension, gap voltage, Pon and Poff time are significance. Flushing pressure does not have prominent effect on this response and it is a least significance parameter. Percentage contribution (figure 4b) of pulse on time and wire tension are more towards the response while flushing pressure is least contributor factor towards included angle. ANOVA for clearance angle shows that gap voltage does not have prominent effect on this angle so it is least significant parameter; while all other factors are significant in case of this response. Percentage contribution (pi-chart figure 4c) column shows that wire tension has very large contribution towards clearance angle and it affects prominently the clearance angle, while gap voltage parameter is a very low contributor towards response. P value in table 4 that pulse on and off time shows significant effect on MRR while all other factors are not significant. Pulse off time is most contributing factor among all the factors and wire tension is least contributor towards the MRR (figure 4d).

Table 4. ANOVA results of surface roughness, included angle, clearance angle and material removal rate

ANOVA results Surface roughness							
Source	D0F	Seq SS	Adj SS	Adj MS	F-value	P- value	Percentage Contribution
Flushing Pressure	2	0.060976	0.064422	0.032211	24.20	0.000	22
Wire Tension	2	0.012023	0.017196	0.008598	6.46	0.004	4
Gap Voltage	2	0.008244	0.004769	0.002384	1.79	0.182	3
Pulse on time	2	0.082255	0.109280	0.054640	41.06	0.000	30
Pulse off time	2	0.065154	0.065154	0.032577	24.48	0.000	24
Error	35	0.046579	0.046579	0.001331			17
Total 45	45	0.275231					
ANOVA results for included angle							
Source	D0F	Seq SS	Adj SS	Adj MS	F-value	P- value	Percentage Contribution
Flushing Pressure	2	0.002207	0.001841	0.000920	1.55	0.226	2
Wire Tension	2	0.024771	0.025294	0.012647	21.36	0.000	20
Gap Voltage	2	0.017292	0.005835	0.002918	4.93	0.013	14
Pulse on time	2	0.010595	0.009524	0.004762	8.04	0.001	9
Pulse off time	2	0.048580	0.048580	0.024290	41.02	0.000	39
Error	35	0.020724	0.020724	0.000592			17
Total 45	45	0.124170					
ANOVA results for clearance angle							
Source	D0F	Seq SS	Adj SS	Adj MS	F-value	P- value	Percentage Contribution
Flushing Pressure	2	0.027869	0.023999	0.012000	2.20	0.126	3
Wire Tension	2	0.656511	0.686813	0.343407	62.83	0.000	63
Gap Voltage	2	0.010961	0.013792	0.006896	1.26	0.296	1
Pulse on time	2	0.070544	0.071551	0.035776	6.55	0.004	7
Pulse off time	2	0.080109	0.080109	0.040055	7.33	0.002	8
Error	35	0.191296	0.191296	0.005466			18
Total 45	45	1.037290					
ANOVA results for material removal rate							
Source	D0F	Seq SS	Adj SS	Adj MS	F-value	P- value	Percentage Contribution
Flushing Pressure	2	0.0037642	0.0006652	0.0003326	1.45	0.249	7
Wire Tension	2	0.0012797	0.0000559	0.0000280	0.12	0.886	2
Gap Voltage	2	0.0047667	0.0000680	0.0000340	0.15	0.863	8
Pulse on time	2	0.0058522	0.0119840	0.0059920	26.09	0.000	10
Pulse off time	2	0.0334816	0.0334816	0.0167408	72.88	0.000	59
Error	35	0.0080396	0.0080396	0.0002297			14
Total 45	45	0.0571840					

Contour plots

After evaluating the significance of factors, contour plot for the two most significant parameters were developed to trace out the appropriate ranges of the two most contributing factors for optimal values of response feature i.e. Ra. In case of surface roughness, the most significant parameters were pulse on and off time. Based on contour plot analysis, it was found that appropriate range for Pon was 22–25 μs, whereas for Poff, the 10–16 μs was the optimal range to have batter surface finish. The optimal value of Ra can be obtained by using other parameters on their hold values shown in figure 5(a). The contour plots for included angle (figure 5b) depicts that the optimal value obtained is less than 60.63degree. This desired angle value is obtained when value of wire tension ranges between 12 to 14 g and value of pulse off time lies between 10 to 11 μs. Contour plot for clearance angle (figure 5c) shows that the most significant parameters were wire tension and pulse off time. This desired optimal value is obtained when value of wire tension ranges between 4–6 g while value

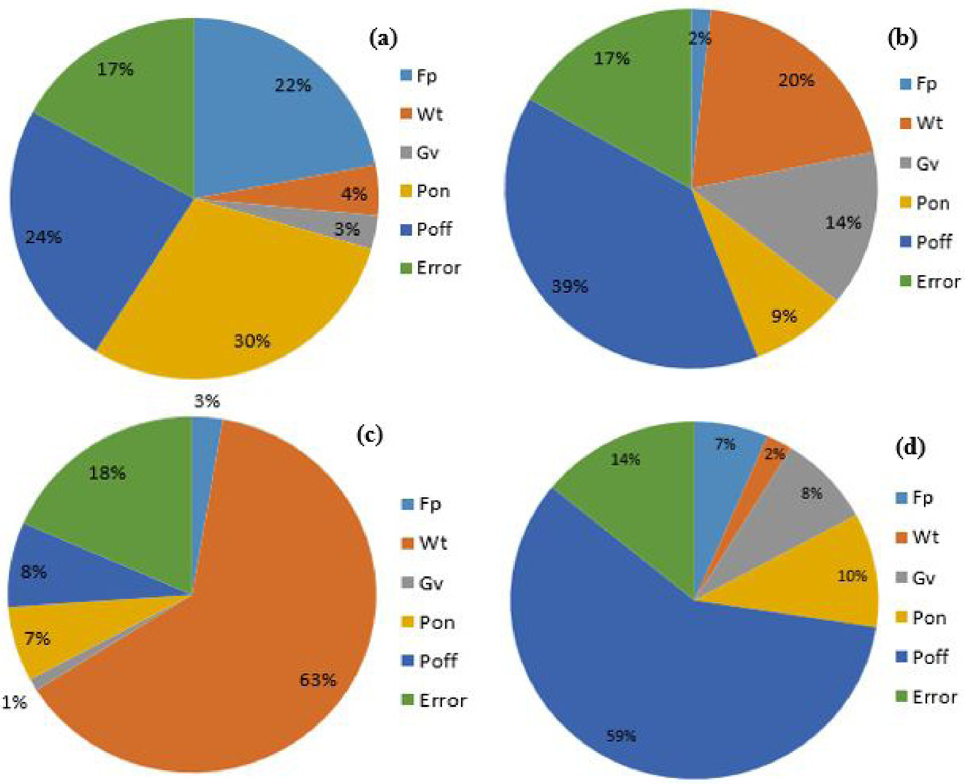

Fig. 4. Percentage contribution in term of Pi-charts for (a) surface roughness (Ra), (b) included angle, (c) clearance angle and (d) material removal rate (MRR)

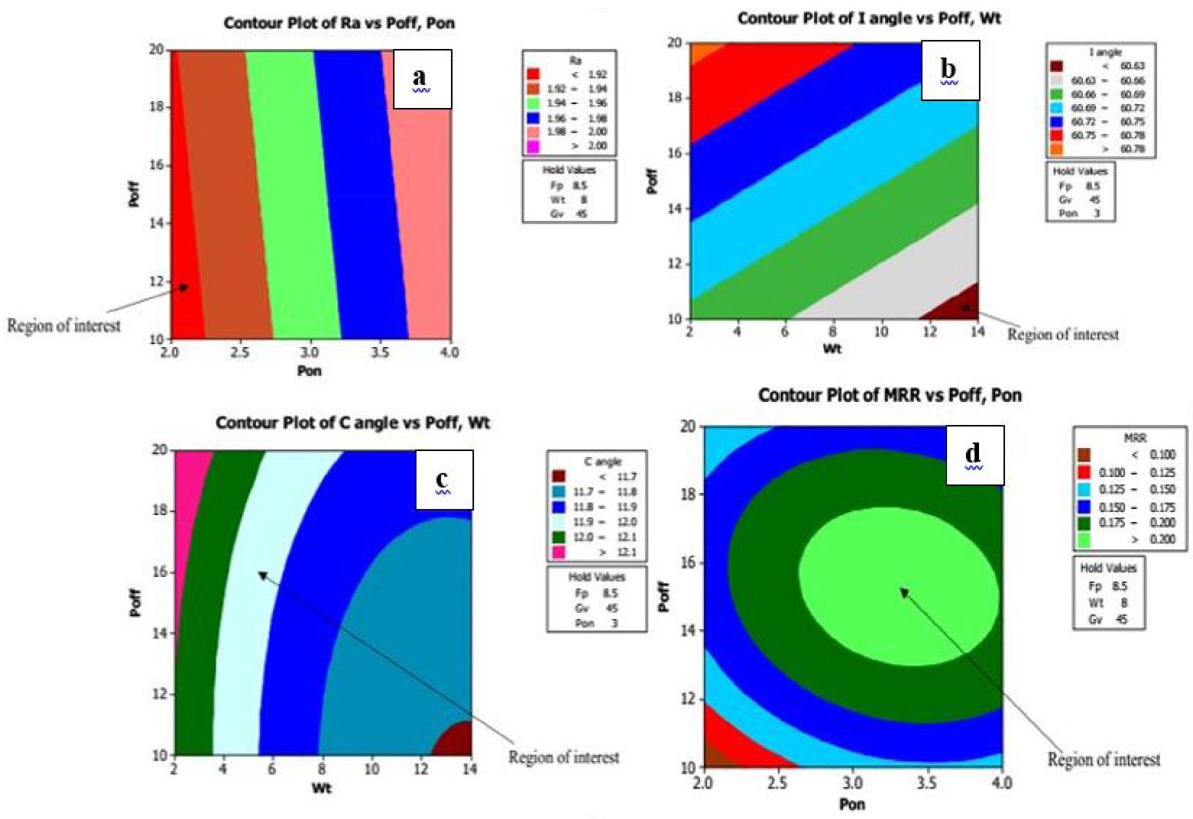

Fig. 5. Contour plots to select (a) Poff, Pon for required surface finish, (b) Poff, Wt for required included angle, (c) Poff, wt for required clearance angle and (d) Poff, Pon for required material removal rate

of pulse off time ranges between 10 and 16 μs. After identifying the significant parameters in case of MRR, the contour plots were drawn to achieve the desired optimal values (figure 5d). The maximum value for this response obtained at value of pulse on time ranges from 3 to 4 μs and pulse off time ranges from 14 to 16 μs.

CONCLUSIONS

The objective of this research work was to analyze the effect of process parameters on the formation of form tool using wire electric discharge machining. Furthermore, optimized values of WEDM input parameters were also found. High speed steel material was used for this purpose. The effects of gap voltage, pulse on time, wire tension, flushing pressure and pulse off time on surface roughness, included angle, clearance angle and material removal rate were modeled and analyzed using response surface methodology. Box-Behnken design was employed to perform the design of experiments. The results through experimentation concluded that pulse on time and pulse off time are the most significant input parameters for surface roughness, included angle, clearance angle and material removal rate. Flushing pressure does not effects significantly the clearance angle, included angle and material removal rate. Gap voltage is found insignificant for material removal rate and clearance angle. Other findings of this experimental work include the following:

- Improved surface quality of HSS form tool made by WEDM is obtained at the optimum value of pulse on time lies between 2 and 2.5 μs and pulse off time ranges between 10 and 16 μs.
- The maximum value of MRR is obtained at optimum value of pulse on time ranges from 3 to 4μs and pulse off time ranges from 14 to 16 μs.
- Improved accuracy in a form of tool geometry was found at optimum value of wire tension range between 12–14 g and pulse off time value range between 10–11 μs in case of included angle whereas for clearance angle, it was obtained at optimum value of wire tension ranges between 4–6 g and pulse off time lies between 10–16 μs.

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