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ORIGINAL ARTICLE

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Modeling and analysis of white layer depth in a wire-cut EDM process through response surface methodology

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Abstract A white layer is considered a major flaw on a workpiece surface machined with wire-cut electrical discharge machining (WEDM). In this paper, an attempt has been made to model the white layer depth through response surface methodology (RSM) in a WEDM process comprising a rough cut followed by a trim cut. An experimental plan for rotatable central composite design of second order involving four variables with five levels has been employed to carry out the experimental investigation and subsequently to establish the mathematical model correlating the input process parameters with the response. Pulse on time during rough cutting, pulse on time, wire tool offset, and constant cutting speed during trim cutting are considered the dominant input process parameters whilst the white layer depth is the response. An insignificant "lack of fit" term indicated a curve with a good fit. Also, an extensive analysis of the influences of all the individual input parameters on the response has been carried out and presented in this research study.

Keywords RSM · Trim cutting · WEDM · White layer depth

1 Introduction

Wire-cut electrical discharge machining (WEDM) has been found to be the most potential electro-thermal process among the other nontraditional machining processes. This is due to its capability to meet the requirements of the present-day product manufacturing industries for machining any kind of electrically conductive work, irrespective of its mechanical properties with the scope of achieving required shape and size with enhanced productivity, better surface finish characteristics, and better dimensional accuracy features at comparatively reduced costs. WEDM is a special form of the traditional electrical discharge machining (EDM) process in which the electrode is a continuously moving electrically conductive wire. The movement of the wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece. The mechanism of material removal in WEDM process involves the complex erosion effect by rapid, repetitive and discrete spark discharges between the wire tool and job immersed in a liquid dielectric medium. A DC power supply is used to generate very high frequency pulses. These electrical discharges melt and vaporize minute amounts of work material, which are ejected and flushed away by the dielectric, leaving small craters on the work piece.

In WEDM, the material removal rate (MRR) and the surface topography of the machined job are mainly influenced by the sparking frequency and the crater size determined by the electrical discharge energy contained in a pulse. The work piece material, which gets melted, is not completely expelled during the process. The residual material resolidifies on the machined surface to form a hard skin on the work piece. Thus, an extreme fast heating, melting and vaporization is followed by a fast cooling of the work piece material in the sparking zone during the process of material removal produce a huge change in both of the surface topography as well as in the surface metallurgy of the work piece. Surface metallurgy of a wire-cut electro-discharge machined job is concerned with the number of effects the process has beneath the outermost layer of the machined job. The subsurface characteristics occur in various layers or zones, which are usually termed as altered material zones (AMZ). These alterations, caused by the thermal energy of spark discharges, are generally in the form of microcracks, spalling, change in hardness, residual stresses, metallurgical transformations and, of course, heat affected zones (HAZ). Thermal spalling is mechanical failure of the material without melting due to the generated internal stresses, which overcome the bond strength of the material.

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However, a multi-layered heat affected zone is formed at the machined surface of the work piece while machining it with WEDM. The upper recast layer of this zone is called the "white layer". It has a high hardness and it contains a lot of microcracks. Like the other layers of the heat-affected zone, the white layer also has different microstructural and metallographic characteristics than the base material. But, the white layer gets the most significant attention compared to other layers in the heat affected zone because, often, the other layers can not be clearly defined. They differ only very little from each other and sometimes they can not even be properly distinguished. Besides, it is the only white layer that is in direct contact with the environment and the micro cracks, if any, are mostly restricted to this layer only. It is also well understood that the white layer at the surface of the work piece machined by WEDM is extremely undesirable as the surface becomes susceptible to fatigue failure.

An attempt to study the surface characteristic behavior of the eroded surface in electrical discharge machining was made by Kahng and Rajukar [1]. The experimental results confirmed that the increase in pulse duration resulted in an increase in surface roughness, depth of surface microcracks and depth of heat affected zones. It was reported that the application of fine cutting condition along with a lower pulse duration resulted in a better surface geometry. But, a higher discharge duration should always be considered for removal of white layer and heat affected zone including cracks, as was suggested in their research study. A detailed exhaustive metallographic study to acquire profound knowledge of white layers in die sinking EDM has been conducted by Kruth et al. [2]. Three workpiece specimens, such as mould steel, ordinary carbon steel (C35) and pure iron, were the subject of the tests using two types of dielectrics as oil and deionized water. The electrode materials were electrolytic copper, aluminum and graphite. It was reported that the microcracks were found to be perpendicular to the machined surface and the dendrites were oriented in the direction of the maximum cooling gradient and were also perpendicular to the machined surface. It was reported that the white layers of samples machined in an oil dielectric consisted of dendritic structures formed by the rapid solidification of the molten pool and contained more carbon than the base material while samples machined in a water dielectric contained less carbon than the base material. The excess carbon in the white layer came from the oil dielectric and formed iron carbide. However, it was not clear whether the high hardness of the white layer was caused by the metallographic structure of it or by the presence of carbide. The molten pool could possibly freeze into a martensite or amorphous structure to give rise to a very high hardness as well. Spedding and Wang [3] made an attempt to model the wire electrical discharge machining process through response surface methodology and artificial neural networks considering pulse on time, pulse off time, wire tension and wire feed speed as the input parameters and the cutting speed, surface roughness and the surface waviness as the output parameters or responses. It was shown in a part of their research study that a pulse on time of $1.2\,\mu s$ resulted in a thicker ($\approx 15\,\mu m$) and discontinuous recast layer with an irregular surface. A pulse on time of $0.8\,\mu s$, however, resulted in a thinner ($\approx 8\,\mu m$) and continuous recast layer with a smoother surface. Huang and Liao [4, 5] studied on the determination of the number of finish cutting operations and process parametric setting in wire electrical discharge machining utilizing the concept of Taguchi quality design. Six different machining parameters were chosen as the control factors whereas the machining performances of the finish cutting process were gap width, surface roughness, white layer depth and finish cutting area ratio. It was shown that the pulse on time and the distance between the wire periphery and the workpiece surface (D_{ww}) in finish cutting were the two dominant factors influencing the machining performances. It was also established that a negative and medium D_{ww} was appropriate in order to obtain a smaller surface roughness whereas a larger D_{ww} should be chosen for smaller white layer depth. Rebelo et al. [6] carried out an experimental analysis to characterize the surface integrity of steels in an electrical discharge machining process. A stochastic process was highlighted with the use of the data collected through optical and scanning electron microscopy. The dimensions of the random overlapping surface craters, the density and penetration depth of the cracks in the recast layer were reported to increase with the increase in pulse energy in machining and network crack formation was observed with the development of high tensile stresses.

Therefore, it is evident that although several attempts were made to thoroughly understand the mechanism of formation and properties of the white layer, little research has been carried out where the modeling of the process has been regarded as a problem of correlating the dominant input parameters of the WEDM process with the white layer depth as the machining performance or criterion. It has been felt that modeling the white layer depth is also of ardent necessity for the better understanding of the correlation of the WEDM input process parameters with the magnitude of the depth of white layer. Hence, the present research attempts to develop a mathematical model of white layer depth and to carry out an extensive analysis of the influences of the dominant input process parameters on the same in wire-cut EDM process. Response surface methodology (RSM) has been effectively used for this purpose.

2 Planning and designing the experimental study

It is a well-known fact that a high MRR and a very good surface finish can never be achieved simultaneously in a WEDM process. This is an age-long problem and continuous efforts are being made by different researchers all over the world to fulfill such an objective. A rough cut followed by one or two trim cuts is considered a probable solution to the above problem depending upon customer requirements. The trim cutting method associated with the WEDM process has been described in Appendix A. In an extremely complicated machining process like wire-cut EDM, which is governed by as many as ten control factors, it is a really difficult task to find the dominant input process parameters that effect the various important machining performances. Furthermore, the number of process parameters increases to twenty when a machining process comprises a rough cut followed by a trim cut.

On the other hand, although a polynomial response surface in RSM has great advantages, it has a few disadvantages, too. One such disadvantage is that the polynomials are untrustworthy when extrapolated beyond the experimental region. Another important disadvantage of using second order polynomial in RSM is that the size of experiments becomes too large and analysis becomes too complicated with more than three X variables or with more than three levels. However, a well-designed experimental plan can substantially reduce the total number of experiments. Central composite designs (CCD) are one of those means. Proceeding a step ahead, central composite rotatable designs of second order have been found to be the most efficient tool in RSM to establish the mathematical relation of the response surface using the smallest possible number of experiments without loosing its accuracy. For example, the size of the experiment is 31 for four X variables. The design is subdivided into three parts as shown below [7].

1. The points constituting a 2^k factorial design, i.e., 16 points; k is the number of input variables.
2. The extra points are included to form a CCD with α. The figure formed by these points is called a star. The value of α must be $2^{k/4}$ in order to make the design rotatable. The number of star points is 8 for four X variables, and
3. The extra seven points are added at the center to give roughly equal precision for Y_u within a circle of radius 1. Y_u is the uth response in the experimentation.

However, Puri et al. [8] have conducted an extensive experimental investigation to find the main factors influencing the average cutting speed (V_c), surface finish characteristic in terms of CLA values (R_a) and the geometrical inaccuracy due to wire lag (g) in a WEDM process comprising a rough cut followed by a trim cut. The other surface finish characteristics like R_t (peak to valley measures) and R_z (ten point averaged heights of irregularities) were not taken into consideration because their trends of variation are almost similar as with R_a in wire EDM process [9]. It has been established that pulse on time, pulse off time, pulse peak current during rough cutting, and pulse on time and constant cutting speed during trim cutting are the most significant factors for the average cutting speed. Pulse peak current during rough cutting, and pulse on time, pulse peak voltage, servo spark gap set voltage, dielectric flow rate, wire tool offset and constant cutting speed during trim cutting, were the significant factors for surface roughness values (R_a). The pulse on time, pulse off time and pulse peak current during rough cutting, and pulse peak voltage, wire tension, servo spark gap set voltage, wire tool offset and constant cutting speed during trim cutting were the significant factors for geometrical inaccuracy due to wire lag.

Keeping the above aspects in view, the WEDM process in the present study is designed to comprise a rough cut followed by a trim cut. It is felt that four independent process parameters, such as pulse on time for rough cutting (RT_{on}), and pulse on time (TT_{on}), wire tool offset (Offset) and constant cutting speed (C. speed) for trim cutting would effectively represent a mathematical relationship with white layer depth as the response required for general engineering purposes.

Hence, in the present research study, the above four process parameters were considered as X variables for a rotatable CCD of second order. According to this experimental plan, five levels of the variables with 31 total treatment combinations are to be studied. Each of the X variables takes different coded values by coding each X scale so that the upper level of X is considered to be $+2$ and the lower level of X is taken as -2 for designing the experimental plan. The relationship between the coded and actual scale for the different X variables were considered as follows.

$$X_1 = (RT_{\text{on}} - 1.10)/0.05; \quad X_2 = (TT_{\text{on}} - 0.6)/0.1$$
$$X_3 = (135 - \text{Offset})/10; \quad X_4 = (\text{C. speed} - 3.0)/1.0 \qquad (1)$$

The actual values of these process variables with their coded values are shown in Table 1. The rough cutting conditions and the trim cutting conditions in the machining operation are found in Tables 2 and 3, respectively. The constant values of the various parameters in Tables 2 and 3 have been determined based on the earlier machining experience. The detailed experimental design for the rotatable CCD of second order used in the present research study is illustrated in Table 4. The data for

Table 1. Actual values and coded values of factors for the machining operation

Process parameters	Level/Code					Unit
	-2	-1	0	+1	+2	
X_1: Pulse on time during first cut (RT_{on})	1	1.05	1.1	1.15	1.2	μs
X_2: Pulse on time during trim cut (TT_{on})	0.4	0.5	0.6	0.7	0.8	μs
X_3: Offset during trim cut : (Offset)	155	145	135	125	115	μm
X_4: Constant cutting speed during trim cut (C. speed)	1	2	3	4	5	mm/min

Table 2. Rough cutting conditions

Pulse off time, $T_{\text{off}} = 15$ μs	Wire tension, $W_T = 8.83$ N
Pulse peak current, $I_p = 200$ A	Wire tool offset (left) = 175 μm
Pulse peak voltage, $V_p = 100$ V	Dielectric flow rate, $FR = 9$ L/min
Dielectric pressure, $W_p = 14.7$ bar	Actual gap voltage, $V_g = 12/14$
Wire feed rate, $W_F = 6$ m/min	Servo spark gap set voltage, $SV = 3$

Table 3. Trim cutting conditions

Pulse off time, $T_{\text{off}} = 5.5$ μs	Wire feed rate, $W_F = 6$ m/min
Pulse peak current, $I_p = 80$ A	Wire tension, $W_T = 10$ N
Pulse peak voltage, $V_p = 100$ V	Dielectric flow rate, $FR = 3$ L/min
Dielectric pressure, $W_p = 4.9$ bar	Servo spark gap set voltage, $SV = 10$

Table 4. The layout of experimental plan for rotatable CCD of second order

Exp. No	Coded variables				Response	Exp. No	Coded variables				Response
	X_1	X_2	X_3	X_4	Y_u, (μm)		X_1	X_2	X_3	X_4	Y_u, (μm)
1.	−1	−1	−1	−1	17.47	17.	−2	0	0	0	6.03
2.	1	−1	−1	−1	14.11	18.	2	0	0	0	4.45
3.	−1	−1	−1	−1	6.9	19.	0	−2	0	0	6.81
4.	1	−1	−1	−1	10.36	20.	0	2	0	0	4.45
5.	−1	1	1	−1	5.72	21.	0	0	−2	0	8.29
6.	1	1	1	−1	4.53	22.	0	0	2	0	6.02
7.	−1	1	1	−1	6.21	23.	0	0	0	−2	8.98
8.	1	1	1	−1	7.99	24.	0	0	0	2	8.98
9.	−1	−1	−1	1	4.15	25.	0	0	0	0	5.52
10.	1	−1	−1	1	6.9	26.	0	0	0	0	7.89
11.	−1	−1	−1	1	8.58	27.	0	0	0	0	4.73
12.	1	−1	−1	1	4.94	28.	0	0	0	0	5.52
13.	−1	1	1	1	9.57	29.	0	0	0	0	6.31
14.	1	1	1	1	6.9	30.	0	0	0	0	7.10
15.	−1	1	1	1	5.32	31.	0	0	0	0	5.52
16.	1	1	1	1	2.57						

white layer depth are collected using scanning electron microscopy (SEM).

3 Experimentation and observations

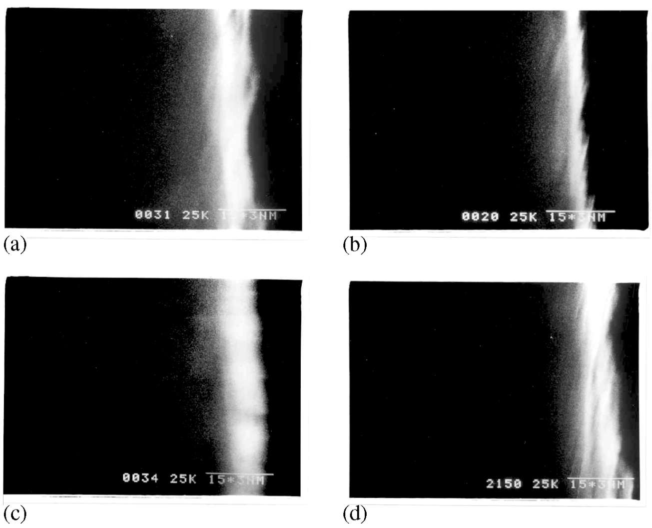
A wire-cut EDM machine, supercut-734, manufactured by Electronica, India, was used for the experiments with a typical die steel (M2-hardened and annealed: 0.85% C, 4% Cr, 6.25% W, 5% Mo, 2% V) plate of 28 mm thickness, as the work piece (anode). A brass wire of 250 μm diameter was used as the tool electrode (cathode). The machining operation consisted of a rough cut followed by a trim cut with the respective machining conditions as stated earlier. Rectangular jobs of sizes 12 mm × 12 mm × 28 mm were cut out from the die steel plate as test specimens.

The cut out specimens, after machining, were washed and cleaned with a 1:10 (by volume) dilute phosphoric acid solutions. The specimens were transversely cut to the length of 10 mm, which is the maximum accommodating job length for the scanning electron microscope used in this study. Polishing is performed to have mirror finish on the transverse section and subsequently these faces are etched with 2% nital solution for 20 to 25 s. After this, these samples were seen with the help of a scanning electron microscope. SEM micrographs of the samples were taken for all the experimental runs. The white layers from the photographs are easily identified. However, for ease of measurement, the samples were viewed with 2000 times magnification (2000×). The depths of white layers were measured carefully from the micrographs and an average of nine readings were taken for each experimental run. The magnitudes of white layer depths in the experimentation are presented in Table 4 along with the experimental design. A few micrographs are shown in Fig. 1. It was observed from the micrographs that no microcracks developed on the machined surfaces. However, pock marks and small pockets were observed in many cases. The white layer depths as measured for various experimental runs were found to vary within a range of 2.57–17.47 μm.

4 Results and discussion

4.1 Mathematical model for white layer depth in WEDM process

The mathematical model for correlating the white layer depth (Y) in WEDM with various machining process parameters, such as pulse on time for rough cutting, and pulse on time, wire tool offset and constant cutting speed during trim cutting, have been developed based on RSM. Based on the test results obtained through the design of experimental plan as already discussed, the mathematical model obtained is as



(a) (b) (c) (d)

Fig. 1a–d. SEM micrographs of white layer beneath the surface machined with WEDM process.
a $RT_{on} = 1.05$ μs; $TT_{on} = 0.7$ μs; Offset = 125 μm; C. Speed = 2 mm/min
b $RT_{on} = 1.15$ μs ; $TT_{on} = 0.7$ μs; Offset = 125 μm; C. Speed = 4 mm/min
c $RT_{on} = 1.1$ μs ; $TT_{on} = 0.6$ μs; Offset = 135 μm; C. Speed = 3 mm/min
d $RT_{on} = 1.1$ μs; $TT_{on} = 0.6$ μs; Offset = 135 μm; C. Speed = 1 mm/min

follows:

$$
\begin{aligned}
Y = 6.084 + 0.556X_1 - 0.883X_2 - 1.222X_3 - 1.015X_4 \\
- 0.07X_1^2 + 0.027X_2^2 + 0.42X_3^2 + 0.914X_4^2 \\
+ 0.207X_1X_2 - 0.252X_1X_3 - 0.434X_1X_4 \\
+ 0.451X_2X_3 + 0.266X_2X_4 + 1.511X_3X_4 \,. \qquad (2)
\end{aligned}
$$

4.2 Adequacy test for the developed mathematical model

It is an indispensable part of RSM to check the adequacy of the developed model based on the mathematical formulation of the analysis of variance (ANOVA). The test results for ANOVA are listed in Table 5. For a particular source of variation to be significant at a certain confidence level, the calculated F-value must be higher than the tabulated value at that confidence level. Hence, the lack of fit term should be insignificant in order to confirm the adequacy of a mathematical model and the F-value should be less than that of corresponding tabulated value. The lack of fit was found to be less than $F_{.01}$ (10,6) in the present research study and, hence, the developed model may be accepted. Interestingly, the second order terms were found to be insignificant whereas the linear terms are significant.

4.3 Analysis of the parametric influences on white layer depth

The influences of process parameters like the pulse on time during first cutting (RT_{on}), and the pulse on time (TT_{on}), offset and cutting speed during trim cutting in WEDM process have been analyzed based on the developed mathematical model. The plots of pulse on time during the first cut versus the white layer depth for varying combinations of other process parameters have been prepared and are presented in Figs. 2 to 4 to illustrate the trend of variation of the white layer depth with various machine control parameters mentioned above.

Figure 2 illustrates that the white layer depth goes on increasing nonlinearly with the increase of pulse on time during first cut (RT_{on}). Also, the white layer depth is found to decrease with the increase of pulse on time during trim cutting (TT_{on}) for any value of pulse on time during first cut within the range of study. It should be noticed that the measured white layer depths are the resultant ones. To be more specific, the trim cut removes a thin layer of material from the white layer generated by the first cut. This thin layer removed in trim cutting, goes on increasing with the increase of pulse on time during trim cut and consequently, the white layer depth becomes smaller and smaller with the increase of pulse on time during trim cut.

Table 5. ANOVA test results for the developed white layer depth model

Source of variation	Sum of squares	Degree of freedom	Mean square	F-Value
First order terms	86.715	4	21.678	18.25
Second order terms	75.87	10	7.587	6.4 *
Experimental error	7.13	6	1.188	—
Total	256.70	30	—	—
Lack of fit	86.99	10	8.7	7.32*

$F_{.01}(10, 6) = 7.87$; *Not significant

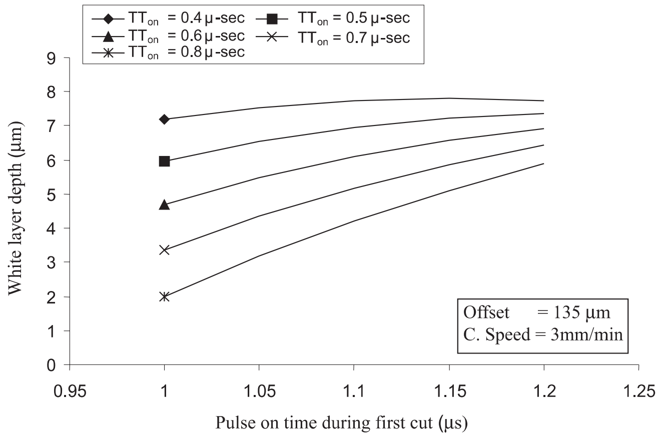


Fig. 2. Variation of the white layer depth with pulse on time during the first cut with varying pulse on time during trim cut

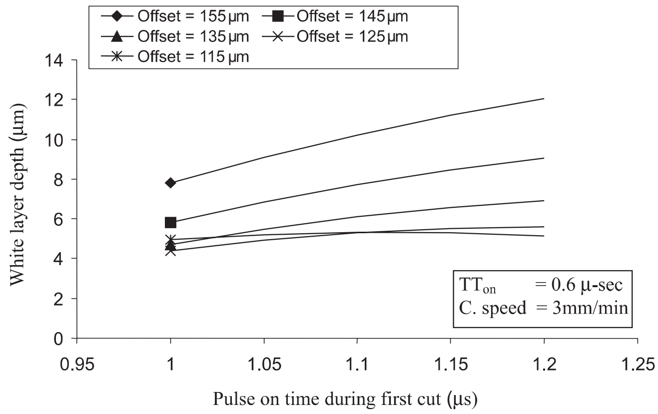


Fig. 3. Variation of the white layer depth with pulse on time during the first cut with varying offset during trim cut

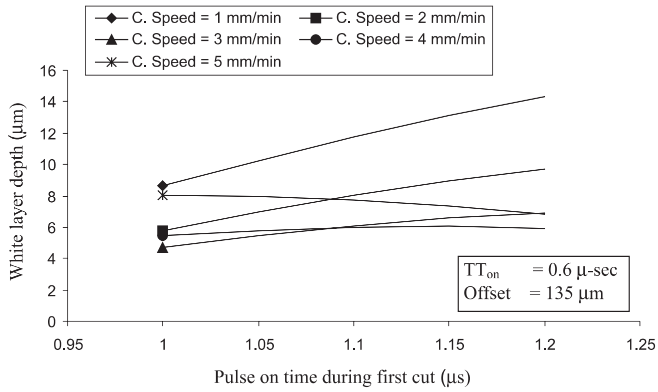


Fig. 4. Variation of the white layer depth with pulse on time during the first cut with varying constant cutting speed during trim cutting

The influence of offset during trim cutting on white layer depth has been shown in Fig. 3. It is seen that the white layer depth reduces with the decrease of offset during trim cutting. This is because the layer removed from the workpiece surface with a smaller offset is thicker. This is in agreement with the earlier research conducted by Huang et al. [4, 5]. Interestingly, it is found that an offset value lesser than the radius of the wire tool not only removes the white layer generated in the first cut completely, but also produces a fresh white layer thicker than that obtained with an offset equal to the wire tool radius. However, this is seen up to a pulse duration of 1.1 µs for rough cutting.

The influence of cutting speed during trim cutting on white layer depth is shown in Fig. 4, which shows that the white layer depth first reduces and then starts increasing with increasing trim cutting speed. With a lower cutting speed during trim cutting, the pulses have more time to strike on a particular area of the workpiece causing a thicker layer removal from the white layer generated in the first cut. As cutting speed increases, the pulses have less time to remove the white layer generated in the first cut, enabling a thinner layer to be removed from the layer generated in the first cut. It is clearly observed that the minimum white layer depth is achieved for a particular trim cutting speed. This optimum trim cutting speed is 3 mm/min for this set of experiments. However, Figs. 3 and 4 depict that the plots of white layer depths, when drawn versus RT_{on}, are almost linear for various offsets and cutting speeds in trim cutting.

5 Conclusions

Mathematical modeling of white layer depth has been carried out to correlate the dominant input parameters of the WEDM process, comprising of a rough cut followed by a trim cut. An experimental plan of rotatable central composite design in RSM consisting of four input variables, such as the pulse on time during rough cutting (RT_{on}), and pulse on time (TT_{on}), offset and cutting speed during trim cutting have been employed to carry out the experimental study. The individual influences of all process parameters on white layer depth have been analyzed based on the developed mathematical model to yield the following conclusions.

1. The white layer depth increases with increasing pulse on time during the first cut.
2. The white layer depth decreases with increasing pulse on time during trim cutting.
3. The white layer depth reduces with decreasing wire tool offset during trim cutting. However, in no case should the offset be chosen to be below the diameter of the wire itself.
4. With increasing cutting speed in trim cutting, the white layer depth first reduces and then starts increasing. This break-even trim cutting speed has been found to be 3 mm/min in the present research study.

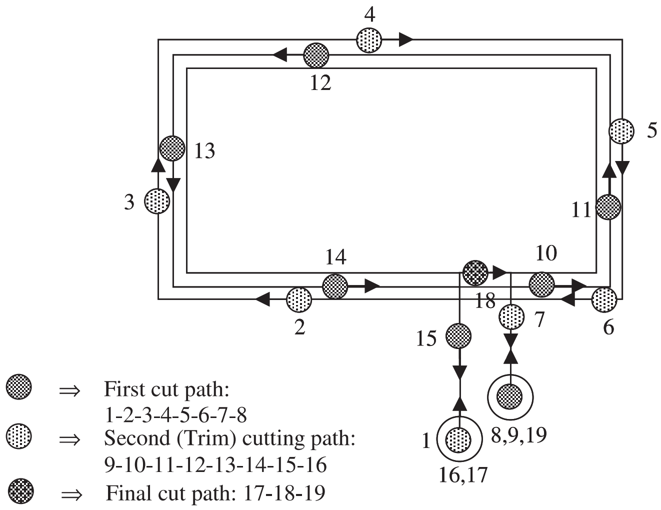


Fig. 5. Trim cutting feature in the WEDM process

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Appendix: Trim cutting features in WEDM

The trim cut (also called skim cut) is an operation where the wire electrode traces back over the same path after the first cut is made. Multi-pass cutting of jobs might be required for two or three cuts depending on the specific requirement. While trim cutting, very low energy pulses are applied so that only very little material is removed in order to achieve better job accuracy and to achieve an improved surface finish. The modern WEDM systems are provided with the arrangement for trim cutting as shown in Fig. 5. For multi-pass cutting of a punch, for example, it is necessary to hold the punch in place for each cutting pass. Usually, it is done by leaving a path of length 2 to 5 mm at the end of the profile while cutting. This uncut length of the profile holds the job in place and subsequent trim cut(s) can be made. After completing the trim cutting, the remaining path length is cut in a single cut with the appropriate wire offset.

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