Manjaiah et al. International Journal of Mechanical and Materials Engineering (2016) 11:7
DOI 10.1186/s40712-016-0060-4

International Journal of Mechanical and Materials Engineering

SHORT COMMUNICATION

Open Access

Parametric optimization of MRR and surface roughness in wire electro discharge machining (WEDM) of D2 steel using Taguchi-based utility approach

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Abstract

Background: This paper reports the effect of process parameters on material removal rate (MRR) and surface roughness (Ra) in wire electro discharge machining of AISI D2 steel.

Findings: The wire electro discharge machining characteristics of AISI D2 steel have been investigated using an orthogonal array of design. The pulse on time and servo voltage are the most significant parameter affecting MRR and surface roughness during WEDM process. The simultaneous performance characteristics MRR and surface roughness was optimized by Taguchi based utility approach. The machined surface hardness is higher than the bulk material hardness due to the repetitive quenching effect and contained various oxides in the surface recast layer.

Methods: The experiments were performed by different cutting conditions of pulse on time (T_{on}), pulse off time (T_{off}), servo voltage (SV) and wire feed (WF) by keeping work piece thickness constant. Taguchi L_{27} orthogonal array of experimental design is employed to conduct the experiments. Multi-objective optimization was performed using Taguchi based utility approach to optimize MRR and Ra.

Results: Analysis of means and variance on to signal to noise ratio was performed for determining the optimal parameters. It reveals that the combination of Ton3, Toff1, SV1, WF2 parameter levels is beneficial for maximizing the MRR and minimizing the Ra simultaneously. The results indicated that the pulse on time is the most significant parameter affects the MRR and Ra.

Conclusions: The melted droplets, solidified debris around the craters, cracks and blow holes were observed on the machined surface for a higher pulse on time and lower servo voltage. Recast layer thickness increased with an increase in pulse on time duration. The machined surface hardness of D2 steel is increased due to the repetitive quenching effect and formation oxides on the machined surface.

Keywords: WEDM, D2 steel, MRR, Surface roughness, Utility approach, Recast layer and XRD

Background

Introduction

Tool steel, D2, is an important material for die-making industries. There is remarkable demand for hardened steel in cold-forming molds, press tool, and die-making industries due to their excellent wear resistance, high compressive strength, greater dimensional stability, and high hardness (Novotny & M 2001). However, the high carbon and chromium contents of these alloys which increase the mechanical strength and hardness of the material due to the formation of ultra hard and abrasive carbides result in high cutting temperature, larger stresses causing greater tool wear, and cutting tool failure in conventional machining of D2 steel. Leading to poor machinability and surface integrity, hence, it is considered as difficult material to cut (Jomaa et al. 2011). Nevertheless, industry, extremely the press tool sector, dies, molds are currently under pressure to compete on price and lead times. Manufacturers have therefore unavoidably needed to adopt enhanced technologies to achieve better surface quality, dimensional accuracy

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and lower cost of production (Coldwell et al. 2003). This resulting development of new processes for machining hard-to-cut materials is required. Therefore, wire electro discharge machining (WEDM) is a thermo-electric process to machine hard to cut material of electrically conductive and gained popularity in machining complex shapes with desired accuracy and dimensions (Dhobe et al. 2013). Several researchers (Beri et al. 2010; Dhobe et al. 2014) have attempted to improve the performance characteristics such as material removal rate (MRR), surface roughness, and surface and subsurface properties. But with full potential utilization, this process still not completely solved due to its complexity, stochastic nature, and number of process variables involved in this process. In order to optimize the process parameters during WEDM of D3 steel Lodhi and Agarwal (2014) performed L_9 orthogonal array of experiments. Single objective optimization was performed by the Taguchi-based signal to noise (S/N) ratio approach. The discharge current and pulse on time is the most significant factors affecting the surface roughness. Singh and Pradhan (2014) investigated the effect of process parameters such as pulse on time, pulse off time, servo voltage, and wire feed on MRR and surface roughness during machining of AISI D2 steel using brass wire. The second order regression model has been developed to correlate the input parameters with the output responses. The authors concluded that pulse on time and pulse off time are significantly affecting the MRR and pulse on time and servo voltage is significantly affecting the surface roughness. Ugrasen et al. (2014) made a comparison of machining performances between the multiple regression model and group method data handling technique in WEDM AISI 402 steel using molybdenum wire. It was reported that the group method data handles the technique for prediction than multiple regression analysis. The EDM process parameters were optimized using a gray relation approach during machining of M2 steel. The electrode rotational speed majorly affects the MRR, electrode wear rate, and overcut followed by voltage and spark time (Purohit et al. 2015). Lin et al. (Lin et al. 2006) analyzed the material removal and surface roughness on the process parameters during WEDM of SKD11 steel. The process parameters were optimized using back propagation neural network (BPNN)—genetic algorithm (GA) method, and the predicted accuracy BPNN has close relation with the significance of optimum results. The optimal results can be achieved by nonlinear optimization of GA. Lin et al. (Lin et al. 2006) studied the effect of process parameters in EDM on the machining characteristics of SKH 57 high-speed steel by the L_{18} orthogonal array of Taguchi design. It is reported that the MRR increased with peak current and pulse on time duration as it increased up to 100 μs after it falls down. Surface roughness increased with peak current but dropped as the pulse duration increased. From the analysis of variance (ANVOA) machining polarity, peak current affects the MRR and electrode wear, but only peak current significantly affected the surface roughness. Recently, increased in the production of micro/miniature parts based on the replication technologies are hot embossing, microinjection molding, and bulk forming technology. The forming tool yields sufficient tool life and integrated microstructural characteristics and high load bearing capacities, which due to the requirements, the hardened steels are used. Mechanical properties of these materials are limited to structuring technologies which are in use. Due to this, WEDM offers an alternative technology to obtain structural and dimensional accuracies in the miniature die- and mold-making applications (Uhlmann et al. 2005). Since, WEDM technologies apply to micromanufacturing technological applications (Löwe & Ehrfeld 1999). This is especially due to thermal material removal mechanism, allowing an almost all stress/force-free machining independently from the mechanical properties of machined material. In combination with the geometry and accuracy, the WEDM can process materials like hardened steel, silicon, cemented carbide, die steels, and electrically conductive ceramics with submicron precision. Hence, WEDM can be economically used to machine microparts, microdie, and mold especially in single and batch production mode (Dario et al. 1999; Receveur et al. 2007). In this paper, wire electro discharge machining characteristics of D2 steel were studied and determined the optimum process parameters for maximizing MRR and minimizing surface roughness using utility approach.

Experimental methodology

Work piece material and electrode

Experiments were performed on AISI D2 steel as work piece material; the general chemical composition is given in Table 1. The electrode material is zinc-coated brass wire of 0.25-mm diameter. The experiments were conducted on Electronica ECOCUT Wire EDM under power pulse mode (discharge current 12A) using de-ionized water as dielectric fluid with pressure of 12 kg/mm^2.

Experimental details

In the current research work, four process parameters such as pulse on time (T_{on}), pulse off time (T_{off}), servo voltage (SV), and wire feed (WF) were selected for conducting the experiments. The range of experiments was determined from the previous experiments by the author. Each process parameter was investigated at three levels to study the nonlinearity effect of parameters. The

Table 1 Chemical composition of AISI D2 steel

Composition	Wt (%)	Composition	Wt (%)
C	1.51	Ni	0.43
Cr	11.87	Mo	0.67

Table 2 Process parameters and their levels

Process parameters	Level 1	Level 2	Level 3
Pulse on time (μs)	110	120	130
Pulse off time (μs)	30	36	42
Servo voltage (V)	20	40	60
Wire feed (m/min)	2	4	6

selected process parameters and their levels are given in Table 2. Each trial of experiments was conducted three times as per the L_{27} orthogonal array of experiments, and their mean response are listed in Table 3.

Measurement

The MRR and surface roughness were selected as output responses. The tool wear is not important in WEDM, once the wire passes through the work piece; it is scrap, not reusable, and hence not considered in the present study. The initial weights of work were weighed using an electronic balance (0.0001 g accuracy). The wire electrode and work were connected to negative and positive terminals of power supply, respectively. Towards the end of each trial, the work was removed and weighed on a digital weighing machine. The machining time was determined using stopwatch. The MRR is computed as:

$$\mathrm{MRR} = \frac{\mathrm{WRW}}{\rho * t} \tag{1}$$

where WRW is the work piece removal weight, ρ is the density of the work piece, t is the machining time.

The surface roughness of the machined samples were measured by using a Hommel surface profilometer (HOMMEL-ETAMIC T8000). The center line average surface roughness of the specimen were measured with 0.8-mm cutoff length. The roughness values were measured

Table 3 Experimental plan with mean responses, corresponding S/N ratios and multi-response S/N ratio values

Trial no.	Process parameters				Mean responses		S/N ratio		
	T_{on} (μs)	T_{off} (μs)	SV (V)	WF (m/min)	MRR (mm^3/min)	Ra (μm)	η_1	η_2	η
1	110	30	20	2	2.6325	1.31	8.4074	−2.3454	3.0309
2	110	30	40	4	1.701	1.5	4.6141	−3.5218	0.5461
3	110	30	60	6	0.7695	1.4	−2.2758	−2.9225	−2.5991
4	110	36	20	4	2.592	1.31	8.2727	−2.3454	2.9636
5	110	36	40	6	1.531	1.41	3.6995	−2.9843	0.3575
6	110	36	60	2	0.6885	1.28	−3.2419	−2.1442	−2.6930
7	110	42	20	6	1.863	1.36	5.4043	−2.6707	1.3667
8	110	42	40	2	1.2555	1.43	1.9763	−3.1067	−0.5651
9	110	42	60	4	0.6075	1.33	−4.3291	−2.4770	−3.4030
10	120	30	20	4	6.561	2.2	16.3394	−6.8484	4.7454
11	120	30	40	6	4.1148	1.85	12.2870	−5.3434	3.4717
12	120	30	60	2	1.9035	1.52	5.5911	−3.6368	0.9770
13	120	36	20	6	5.913	2.3	15.4362	−7.2345	4.1008
14	120	36	40	2	3.8475	1.7	11.7036	−4.6089	3.5472
15	120	36	60	4	1.782	1.54	5.0182	−3.7504	0.63387
16	120	42	20	2	5.2245	2.3	14.3609	−7.2345	3.5631
17	120	42	40	4	3.1995	1.97	10.1016	−5.8893	2.1061
18	120	42	60	6	1.377	1.59	2.7787	−4.0279	−0.6246
19	130	30	20	6	8.505	2.85	18.5935	−9.0969	4.7482
20	130	30	40	2	8.0595	2.46	18.1262	−7.8187	5.15373
21	130	30	60	4	3.7665	1.9	11.5188	−5.5750	2.9718
22	130	36	20	2	9.396	3.05	19.4589	−9.686	4.8864
23	130	36	40	4	6.966	2.7	16.8597	−8.6272	4.1161
24	130	36	60	6	3.1995	2.1	10.1016	−6.4443	1.8286
25	130	42	20	4	8.343	2.85	18.4264	−9.0969	4.6647
26	130	42	40	6	5.7105	2.6	15.1335	−8.2994	3.4170
27	130	42	60	2	2.7135	1.97	8.6706	−5.8893	1.3906

at five different locations of the work piece across the machined surface in the transverse direction of cutting, and the average of five roughness values was taken as an arithmetic surface roughness (Ra). The measured values of surface roughness and computed MRR are listed in Table 3.

The cross-sectioned machined surface morphologies were observed and measured using scanning electron microscopy (SEM, VEGA3 TESCAN). The micro-hardness of machined surface is measured using CLEMEX microhardness tester under a condition of 25-g load and 15-s dwell time. For each sample, average hardness value was taken from at least five test readings.

Results and discussion

Effect on MRR

The S/N ratios of the experimental responses are given in Table 3, and the average values of the MRR for each process parameter and the respective levels are plotted in Fig. 1. The main effect plot shows the effect of process parameters on the response of MRR. It is observed from the figure that the MRR is increased linearly with increase in pulse on time. This is due to the increase in pulse on time duration that causes more discharge energy onto the work piece which leads to melting the most amount of material and evaporation. The increase in discharge energy and enhancement in pulse on time leads to faster in cutting speed which causes higher MRR. As the pulse of time increases from 30 to 42 μs which is of smaller range, the MRR decreases with a lesser amplitude of variations. This is because the number of discharges within the desired period of time becomes smaller due to the time between the two pulses increases (pulse off time) which leads to lower cutting speed. Also, there may be due to the reduction in melting rate and spark ignition ratio in the plasma channel which causes lower MRR. Similarly, with the increase in servo voltage, decreased MRR was attained. This is due to the reduced spark intensity caused by the discharge gap. The increase in servo voltage leading to an increased discharge gap causes the reduction of the spark intensity. This reduces the intensity of spark impinging on work piece surface which helps less melting and evaporation. The increase in the wire feed rate is from 2 to 6 m/min; there is not much difference in MRR observed. This may be due to the spark generation from the surface of zinc-coated wire which is of similar manner for smallest deviation in the wire feed rate. It may increase for larger deviation of wire feed rate movement due to higher cutting speed and faster number spark generation from the new surface of the wire.

Effect of process parameters on Ra Figure 2 shows the effect of process parameters on Ra. The increase in surface roughness was observed with increased pulse on time. This is because of increased pulse on time which produces larger discharge energy between electrode and the work piece. It ceases to melt more amounts of material which helps to create a larger and deeper crater. This influences the increase in surface roughness (Manjaiah et al. 2015; Kuruvila and V 2011). In the increase in pulse on time from 110 to 130 μs, drastic increase surface roughness was observed as seen in Fig. 2. At higher pulse on time, the pulse energy in the plasma channel is more and time to impinges on machined surface is more. The large number of sparks and high-intensity spark creates deeper craters and more melted droplets surrounded by globule of debris compared to lower pulse on time as observed from the SEM micrographs in Fig. 3.

As the increase in pulse off time, there were no changes in the surface roughness during machining of D2 steel. This is due to the time between the pulse width which is inconsequentially increased and which is not

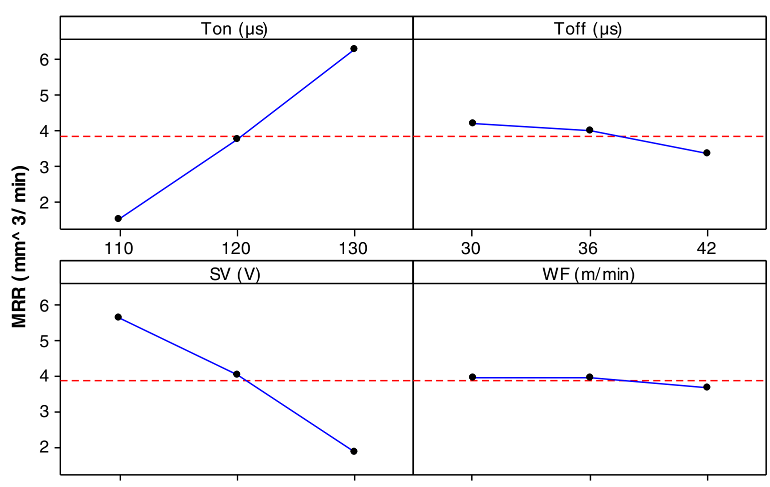

Fig. 1 Effect of process parameters on MRR of D2 steel

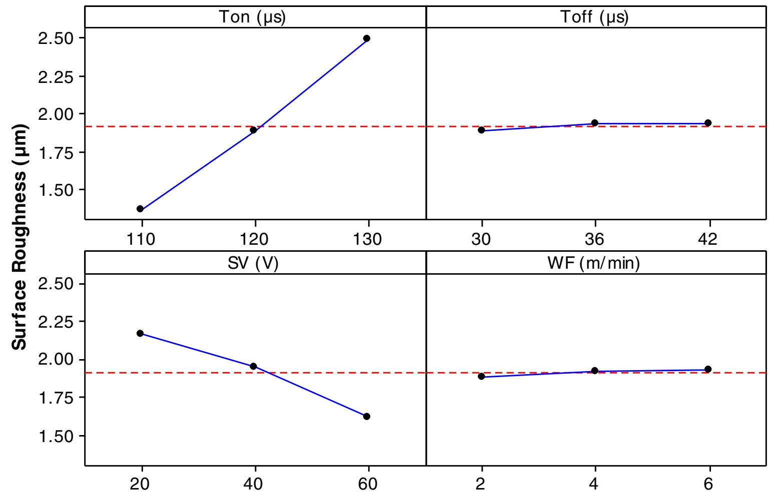

Fig. 2 Effect of process parameters on surface roughness of D2 steel

much affecting the ratio of pulse energy in the plasma channel between the electrode and work piece surface. It is observed that the surface roughness increases with increase of pulse on time and decreases with the increase of servo voltage. With increase in servo voltage, the average discharge gap gets widened resulting into better surface accuracy due to stable machining. During the increase in servo voltage, the discharge gap widens means the intensity of the spark impinges on the machined surface is low and causes for smaller craters leading to lower surface roughness (Shahali et al. 2012). At lower servo voltage, the discharge gap was reduced causes higher intensity of spark penetrates into the material, melts more amount of material, forms deeper crater on the machined surface, and causes worsening of the surface leads to higher surface roughness. Effect of wire feed on surface roughness is similar to MRR. A minor change in the surface roughness with respect to wire feed is observed. This may be due to the no changes in cutting speed caused by the increase in wire feed which leads to melting and evaporation of material.

ANOM and ANOVA Analysis of means was performed to signal to noise ratio values to determining the optimum process parameter levels. In this paper, the Taguchi design with a utility approach concept (Manjaiah et al. 2014) is proposed for optimizing the multiple responses such as MRR and Ra. Here, MRR is to be maximized, and Ra is to be minimized. Hence, larger the better signal to noise ratio characteristic is selected, and for Ra, smaller the better signal to noise ratio is

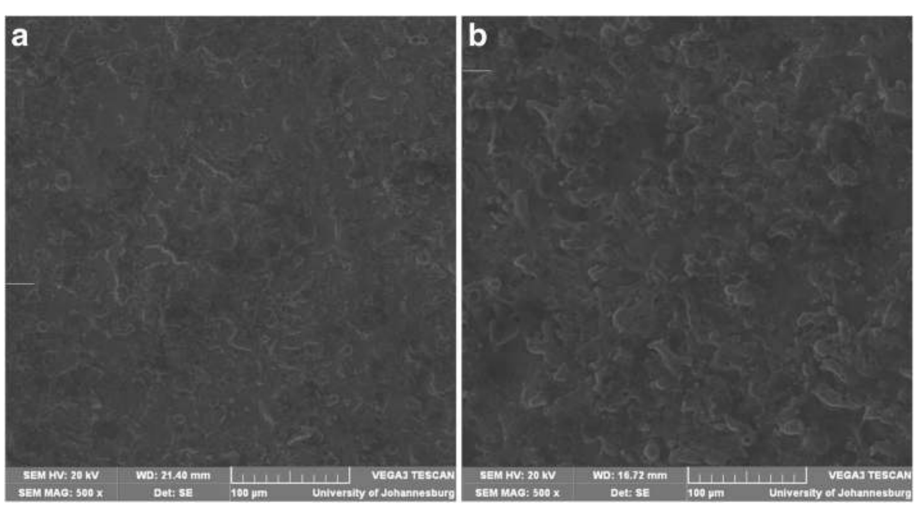

Fig. 3 SEM micrographs of D2 machined steel. **a** Pulse on time—110 µs. **b** Pulse on time—130 µs

selected. The S/N ratios associated with responses are depicted in the following Eqs. (2) and (3).

$$\eta_1 = -10\log\left[\frac{1}{\mathrm{MRR}^2}\right] \tag{2}$$

$$\eta_2 = -10\ \log {R_a}^2 \tag{3}$$

In the utility concept, the multi-response S/N ratio is given by Manjaiah et al. (Manjaiah et al. 2014; Chalisgaonkar & Kumar 2013) as follows:

$$\eta = w_1\eta_1 + w_2\eta_2 \tag{4}$$

where w_1 and w_2 are the weighting factors associated with S/N ratio for each of the machining characteristics, MRR and Ra, respectively. In the present study, weighting factor of 0.5 for each of the machining response characteristics is considered, which gives equal priorities to both MRR and Ra for simultaneous optimization (Chalisgaonkar and Kumar 2013). The calculated values of the S/N ratio for each characteristic and the multi-response S/N ratio for each trial in the orthogonal array are listed in Table 3. Analysis of means (ANOM) is used to predict the optimum level of process parameters, and the results of optimum values are listed in Table 4. In the simultaneous optimization of MRR and Ra, the combination of process parameters is $T_{\mathrm{on}3}$, $T_{\mathrm{off}1}$, SV_1, and WF_2, which is beneficial for maximizing the MRR and minimizing the Ra simultaneous.

The relative significance of individual process parameters was investigated through the analysis of variance (ANOVA). Table 5 lists the summary of the ANOVA of multi-response S/N ratio values. It is found that the pulse on time has the highest contribution (63.86 %) followed by servo voltage (33 %). However, pulse off time and wire feed have least effect on optimizing the multi-objective response in WED-machining of D2 steel. It is revealed that the major influencing factor is pulse on time and servo voltage on both MRR and surface roughness. This means that the larger pulse on time leading greater discharge and intense spark removes lumps of material from the work piece surface leading to form a larger deeper crater causes greater MRR and surface roughness. The dominant parameters are duty cycle (pulse on time and pulse off time) and servo voltage (discharge gap). Causing a lower pulse off time and servo voltage, the larger number with high-intensity spark discharge leads to faster removal of material in a given time (Garg et al. 2012; Nourbakhsh et al. 2013).

Table 4 ANOM based on S/N ratio values

Parameter	Level 1	Level 2	Level 3	Optimum
T_{on}	−0.1106	2.5023	3.6864	3
T_{off}	2.5607	2.1935	1.324	1
SV	3.7856	2.4612	−0.1687	1
WF	2.1435	2.1494	1.7852	2

Table 5 Analysis of variance based on S/N ratio values

Source	Degrees of freedom	Sum of square	Mean square	*F*	*P*	% contribution
T_{on}	2	406.583	203.292	407.33	0.000	63.86
T_{off}	2	8.25	4.125	8.27	0.003	1.141
SV	2	210.603	105.301	210.99	0.000	33.00
WF	2	0.674	0.337	0.68	0.522	–
Error	18	8.984	0.499			3.14
Total	26	635.094	24.426			100

S = 0.7065, R-Sq = 98.6 %, R-Sq(adj) = 98.0 %

Confirmation experiment The optimum process parameters (combination of collective optimization of MRR and surface roughness) have been determined by S/N ratio analysis using utility approach. The S/N ratio analysis of utility values was performed using MINITAB 16 statistical software. Taguchi approach for predicting the mean response characteristics and determination of confidence intervals for the predicted mean has been applied. Three trials of confirmation experiments for each response have been performed at optimal setting process parameters, and average values have been reported. The average values of confirmation experiments have been reported in Table 6. It is found that the prediction error is within the 95 % confidence interval (CI). For calculating the CI, the following equations has been used (Gaitonde et al. 2008):

$$\mathrm{CI} = \sqrt{F_{(1,\nu_e)}\ V_e\left(\frac{1}{n_{\mathrm{eff}}}+\frac{1}{n_{\mathrm{ver}}}\right)} \tag{5}$$

where $\mathrm{V_e}$ is the degrees of freedom for error = 8, $F_{(1,\mathrm{Ve})}$ is the F value for 95 % CI = 4.4138, $\mathrm{V_e}$ is the variance of error = 0.499, $n_{\mathrm{eff}} = \frac{N}{1+\nu}$, N is the total trial number = 27, V is the degrees of freedom of p process parameters = 8, and η_{ver} is the validation test trial number = 3.

In the current study, the prediction error that is the difference between the η_{opt} and η_{obt} is 0.1405 dB, which is within the CI value of ±1.033 dB and, hence, justifies that the adequacy of additivity of the model.

Recast layer thickness Figure 4 shows the microstructure and the cross-sectioned machined surfaces. The recast layer was observed after the etching with Nital

Table 6 Confirmation experiments

Optimum values	Predicted S/N ratio	Experimental S/N ratio	Error	CI
$T_{\mathrm{on}3}$, $T_{\mathrm{off}1}$, SV_1, WF_2	16.1717 dB	16.0312 dB	0.1405 dB	1.033 dB

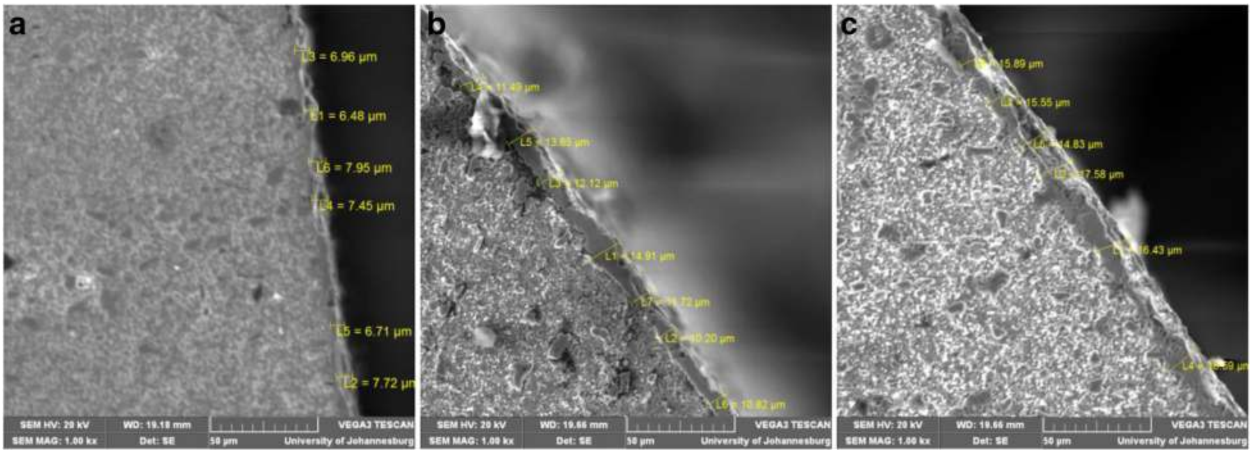

Fig. 4 Recast layer thickness of WED-machined D2 steel **a** trial 6, **b** trial 17, and **c** trial 27

2 %. The cross-sectioned surface shows deposition of a recast layer on the machined surface. This EDM characteristic shows the superimposition of craters due to metal evaporation during machining particles of different size melted and re-solidified on the surface which affects the surface properties of the component. The recast layer was measured for a varying pulse on time. It shows that the recast layer melting and deposition rate is increasing with an increase pulse on time duration. From Fig. 4a–c, the layer deposition is of the average of 7.2, 12.15, and 16.16 μm, respectively. Indeed, the damage of surface consists of recast layer zone and heat-affected zone which was found to be limited in its thickness and could not recognize easily. Hence, the depth of damaged zone measured from the extreme surface to the end of the recast zone. The recast layer zone increased with increase in pulse on time. This is due to the high discharge energy melting more material which is not flushed away from the surface caused by the less thermal conductivity of D2 steel at lower heat transfer rate. The conclusion is made to reduce the recast layer zone by machining at lower pulse on time (110 μs) and higher servo voltage (60 V). It is found that wire feed does not have significant effect on the recast layer thickness. The outcome of the study is in agreement with the Hascalyk and Cayda (Ahmet Hasçalýk 2004) who pointed out the recast layer deposition related to EDM parameters.

Microhardness The microhardness of the machined surface measured for varying depth from the surface. It shows that the surface hardness increased due to repetitive heating and cooling. The thermal impact produced on the surface is accompanied by rapid quenching effect. The transient thermal waves produce a recast layer on the machined surface with heat-affected zone causes for increased hardness values. As seen from Fig. 5, the surface hardness increased from the bulk hardness because of over tempered martensite (Ahmet Hasçalýk 2004) produced by heating and cooling during machining. This

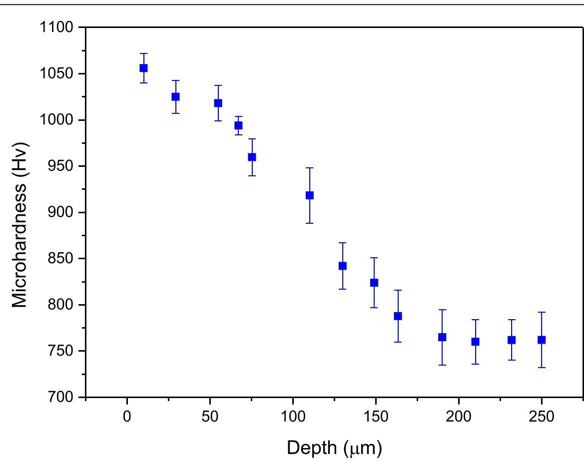

Fig. 5 Microhardness versus depth from the machined surface (trial 27)

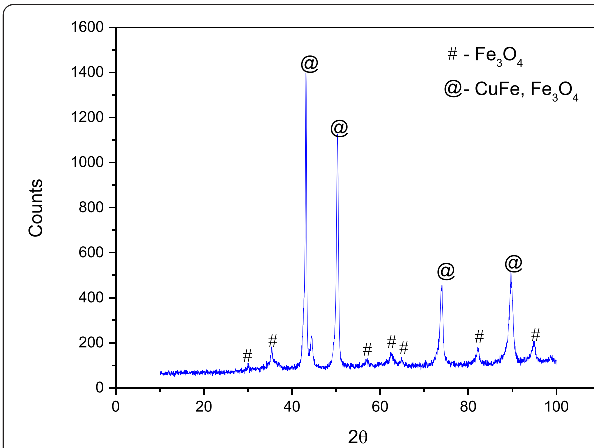

Fig. 6 XRD pattern of machined surface

rapid heating and cooling increases the carbon content in the recast layer. The surface hardness is also associated with primary and secondary hard particles and precipitates like oxides which are formed during machining.

XRD The X-ray diffractometry (XRD) analysis was done on an X-ray diffractometer system, model XPERT-PRO, PANalytical. The range of 2θ from 10° to 100° was used at a scan speed of 2°/min. The obtained XRD pattern of the machined surface is given in Fig. 6. It shows the presence of Fe_3O_4 and CuFe elements. This indicated the Cu is transferred from the wire surface and disassociated onto the material surface. Ferrous oxides are formed due to dissociation of dielectric fluid and react with Fe which leads to form Fe_3O_4 on the machined surface. This is responsible for the improvement of microhardness of the machined surface. In addition, the mechanical and physical properties such as toughness and wear resistance may also improve due to the increased hardness.

Conclusions

In this experimental study, the effect of WEDM process parameters such as pulse on time, pulse off time, servo voltage, and wire feed on machining characteristics was investigated and optimization was performed using utility approach. Summarizing the main feature of the results as follows conclusively.

1. The optimization of WED-machining parameters to determine the optimal combinations to maximize MRR and minimize surface roughness (Ra) was carried out using Taguchi-based utility approach during machining of D2 steel.
2. The pulse on time and servo voltage are the most significant parameters affecting MRR and Ra. This is because the increased pulse on time has higher electrode discharge energy, causes more melting and formation of deeper crater on the machined surface.
3. The recast layer thickness was increased with increase in pulse on time duration due to higher discharge energy caused more melting and re-deposition of molten metal. The wire feed and pulse off time do not have effect on it.
4. The specimen hardness near the outer zone can reach 1056 Hv. This hardening effect arises from the formation of oxides (Fe_3O_4) repetitive quenching effect.
5. XRD analysis shows that the machined surface gets oxidized due to reaction between the de-ionized water and work piece material. Evaporation of wire material caused for the presence of Cu on the machined surface.

Future scope

Further studies can be carried out on the effect of different wire material and wire diameter on machining characteristics of AISI D2 steel. Also, the effect of WEDM process parameters on the residual stresses can be evaluated.

Authors' contributions

MM and AK conducted experiments and collected the data. MM wrote the paper and presented discussion. RFL and SB are MM and AK's scientific supervisors, who guided and supported this work and contributed with theirs expertise and advices. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing intrests.

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Received: 11 May 2016 Accepted: 25 July 2016
Published online: 01 August 2016

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