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Parametric optimization MRR and surface roughness in wire Electro Discharge machining (WEDM) of D2 steel using Taguchi based Utility approach

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Abstract

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. 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 workpiece 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. Analysis of means and variance on to signal to noise ratio was performed for determining the optimal parameters. It reveals that the combination of T_{on3} , T_{off1} , SV_1 , WF_2 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. 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 from 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.

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 [1]. However, the high carbon and chromium content of these alloys which increase the mechanical strength and hardness of the material due to the formation 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, considered as difficult to cut material [2]. Nevertheless, industry, extremely the press tool sector, dies, moulds 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 and lower cost of production [3]. 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 [4]. Several researchers [5,6] have attempted to improve the performance characteristics such as MRR, surface roughness, surface and subsurface properties. But 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 [7] performed L₉ 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 [8] 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. [9] 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 handling 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 [10]. Zhang et al. [11] analysed 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. [11] 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 increased upto 100 μ s after that its fall down. Surface roughness increased with peak current but dropped as the pulse duration increased. From the analysis of variance (ANVOA) machining polarity, peak current significantly affect 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, micro injection molding and bulk forming technology. The forming tool yield sufficient tool life and integrated microstructural characteristics and high load bearing capacities, due to the requirements the hardened steels are used. Mechanical properties these materials are limited to structuring technologies which are used. Due to this WEDM offers an alternative technology to obtain structural and dimensional accuracies in the miniature die and mold making applications [12]. Since, WEDM technologies apply to micro manufacturing technological applications [13]. 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 sub micron precision. Hence, WEDM can be economically used to machine micro parts, micro die and mould especially in single and batch

production mode [14,15]. 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

Workpiece material and electrode

Experiments were performed on AISI D2 steel as workpiece material, the general chemical composition is given in the Table 1. The electrode material is zinc coated brass wire of 0.25mm 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 12kg/mm².

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

Measurement

The material removal rate (MRR) and surface roughness were selected. The tool wear is not important in WEDM, once the wire passes through the workpiece; 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 material removal rate (MRR) is computed as:

$$MRR = \frac{WRW}{\rho * t} \quad (1)$$

Where, WRW is the workpiece removal weight, ρ is the density of the workpiece, it is the machining time.

The surface roughness's of the anodized samples were measured by using a Hommel surface profilometer (HOMMEL-ETAMIC T8000). The centerline average surface roughness's of the work were measured with 0.8 mm cutoff length. The roughness values were measured at five different locations of the workpiece 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 microhardness of machined surface is measured using CLEMEX microhardness tester under a condition of 25g 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 material removal rate (MRR)

The S/N ratios of the experimental responses are given in the Table 3 and the average values of the MRR for each process parameter and the respective levels are plotted in the 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 increase in pulse on time duration causes more discharge energy onto the workpiece 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 causes higher MRR. As the pulse of time increases from 30 μ s to 42 μ s which is of smaller range, the MRR decreases with a lesser amplitude of variations. This is because of number of discharges within the desired period of time becomes smaller due to time between the two pulses increases (pulse off time) which leads to lower cutting speed. Also, there may be due to reduction in melting rate and spark ignition ratio in the

plasma channel causes lower MRR. Similarly the increase in servo voltage, decreased MRR was attained. This is due to the reduced spark intensity caused by the discharge gap. As the increase in servo voltage leading to an increased spark discharge gap. This reduces the intensity of spark impinging on workpiece surface helps less melting and evaporation. The increase in the wire feed rate from 2 m/min to 6 m/min; there is no much difference in MRR was observed. This may be due to the spark generation from the surface of zinc coated wire 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 surface roughness (Ra)

Figure 2 shows that effect of process parameters on surface roughness (Ra). The increase in surface roughness was observed with increased pulse on time. This is because of increased pulse on time produces larger discharge energy between electrode and the workpiece. It ceases to melt more amounts of material help to create a larger and deeper crater. This influences the increase in surface roughness [16,17]. The increase in pulse on time from 110 μ s to 130 μ s, there were drastic increase surface roughness was observed as seen in the Fig. 2. At higher pulse on time the pulse energy in the plasma channel is more and time to generate sparks and impinges on machined surface is more. The large number of sparks and high intensity spark creates deeper craters, more melted droplets surrounded by globule of debris surrounding it 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 is inconsequential increased and which is not much affecting the ratio pulse energy in the plasma channel between the electrode and workpiece surface. It is observed that the surface roughness decreased with increase in servo voltage 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, causes for smaller craters leading to lower surface roughness [18]. At lower servo voltage the discharge gap was reduced causes higher intensity of spark penetrates into the material, melts more amount of material and forms deeper crater on the machined surface, cause's worsening of the surface lead 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 lead 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 [19] 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 selected. The S/N ratios associated with responses are depicted in the following equations (2) and (3).

$$\eta_1 = -10 \log \left[\frac{1}{MRR^2} \right] \quad (2)$$

$$\eta_2 = -10 \log R_a^2 \quad (3)$$

In the utility concept, the multi-response S/N ratio is given by Manjaiah et al [19,20] as follows:

$$\eta = w_1 \eta_1 + w_2 \eta_2 \quad (4)$$

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 [20]. 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 the 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 the Table 4. The simultaneous optimization of MRR and Ra, the combination of process parameters is T_{on3} , T_{off1} , SV_1 and WF_2 , which is beneficial for simultaneous maximizing the MRR and minimizing the Ra.

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 workpiece surface leading to form a larger deeper crater cause's greater MRR and surface roughness. The dominant parameters are duty cycle (pulse on time and pulse off time) and servo voltage (discharge gap). A lower pulse off time and servo voltage causing, larger number with high intensity spark discharge leads to faster removal of material in a given time [21,22].

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 [23]:

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

Where, V_e is the degrees of freedom for error = 8, $F_{(1, v_e)}$ is the F value for 95% confidence interval = 4.4138, V_e is the variance of error = 0.499, $n_{eff} = \frac{N}{1+v}$; N = Total trial number = 27, V = Degrees of freedom of p process parameters = 8 n_{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, justify that the adequacy of additivity of the model.

Recast layer thickness

Figure 4 shows the microstructure and the recast layer were observed after the etching with Nital 2%. Fig. 4 shows the cross sectioned machined surfaces. 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 resolidified on the surface which affects the surface properties of the component. The recast layer was measured for a varying pulse on time (Ton) it shows that the recast layer melting and deposition rate is increasing with an increase pulse on time duration. From Fig. 4(a) (b) and (c) the layer deposition is an average of 7.2 μ m, 12.15 μ m and 16.16 μ m 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 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 due to the high discharge energy melts more material which is not flushed away from the surface caused by the less thermal conductivity of D2 steel lower heat transfer rate. The conclusion made to reduce the recast layer zone by machining at lower pulse on time (110 μ s) and higher servo voltage (60V). It is found that wire speed has not a significant effect on the recast layer thickness. The outcome of the study is agreement with the Hascalyk and Cayda [24] who pointed out the recast layer deposition related to EDM parameters.

Microhardness

The microhardness of 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 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 the Fig. 5 the surface hardness, increased from the bulk hardness because of over tempered martensite [24] produced by heating and cooling during machining. This rapid heating and cooling increases the carbon content in the recast layer. The surface hardness is also associated with primary and secondary hard particles, precipitates, like oxides are formed during machining.

X-ray Diffractometry

The 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 degree/min. The obtained XRD pattern of the machined surface given in the Fig. 6 shows the presence of Fe_3O_4 and CuFe elements. This indicated the Cu is transferred from the wire surface and disassociated on to the materials surface. Ferrous oxides are formed due to dissociation of dielectric fluid and react with Fe 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, wear resistance were also may 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 speed 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 (R_a) was carried out using Taguchi based utility approach during machining of D2 steel.

2. The pulse on time and servo voltage is the most significant parameters affecting MRR and Ra.
3. The recast layer thickness increased with increase in pulse on time duration and wire speed and pulse off time has no effect on it.
4. The machined surface hardness is increased due to the repetitive quenching effect and formation of Fe_3O_4 . XRD analysis shows the machined surface is oxidized and wire material is transferred to the machined surface are the causes for increased surface hardness.

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Tables

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

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

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

[illegible]

Table 6: confirmation experiments

Optimum values	Predicted S/N ratio	Experimental S/N ratio	Error	CI
$T_{on3}, T_{off1}, SV_1, WF_2$	16.1717 dB	16.0312 dB	0.1405 dB	1.033 dB

Figures

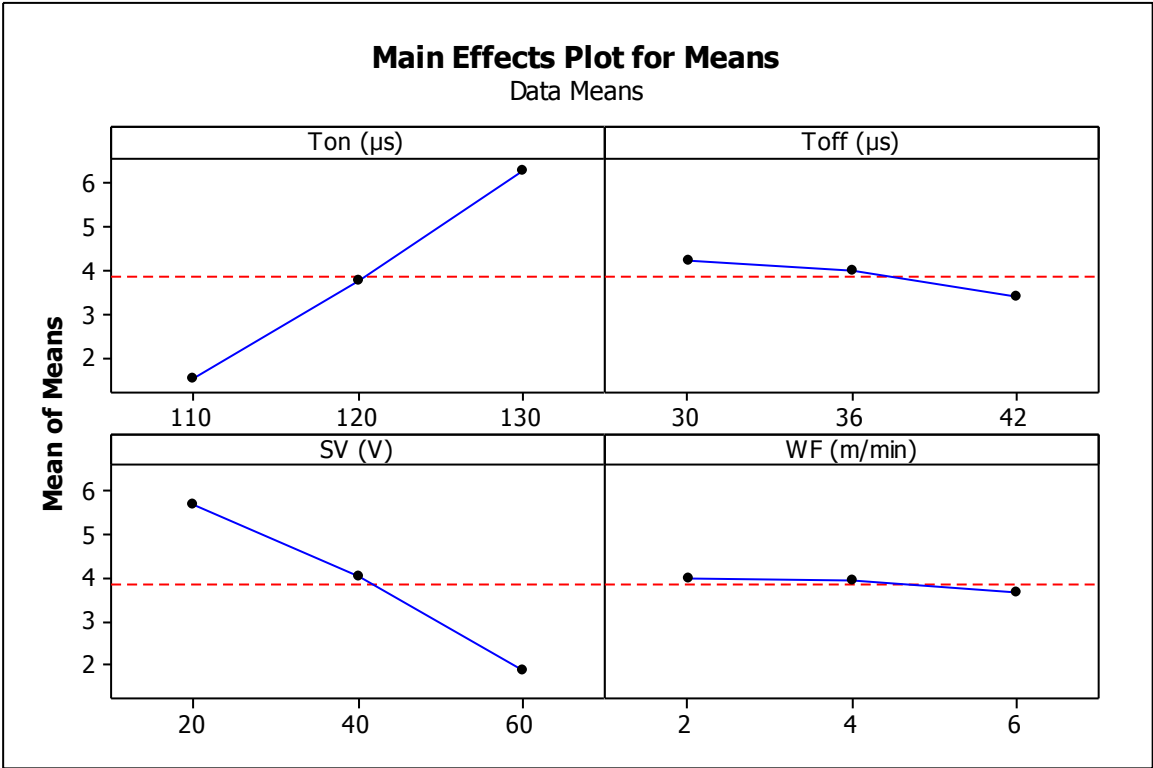


Fig. 1 Effect of process parameters on MRR

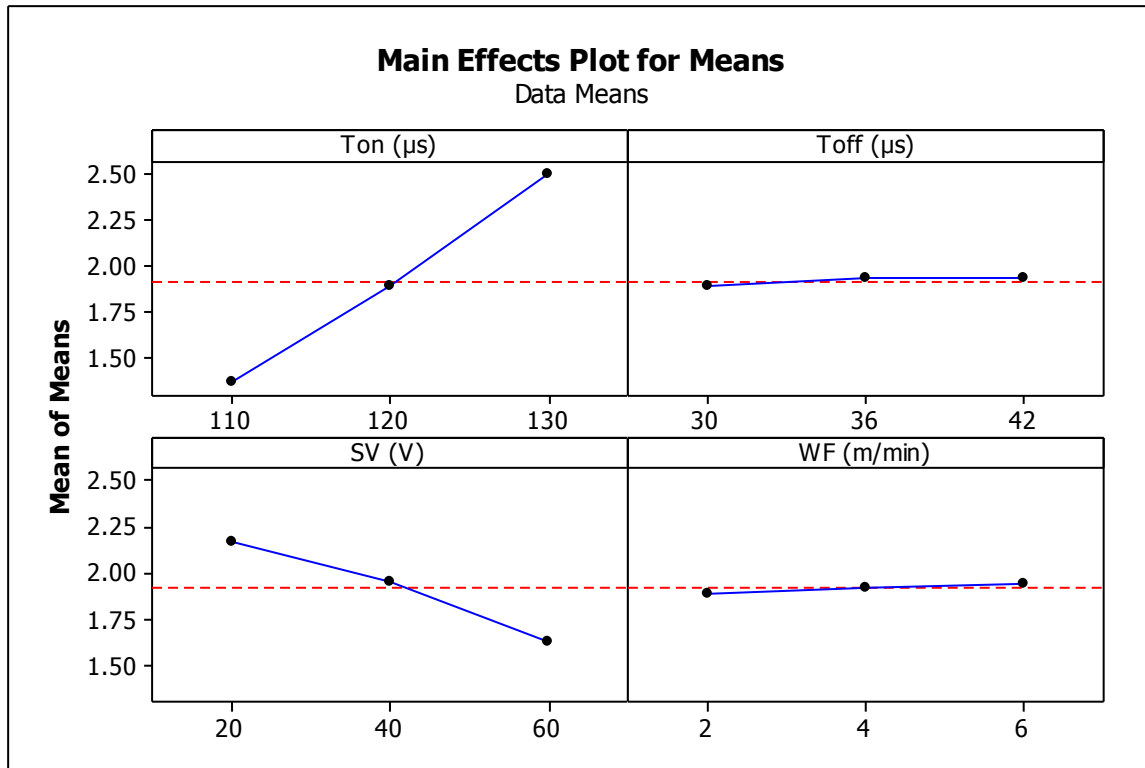


Fig. 2 effect of process parameters on surface roughness

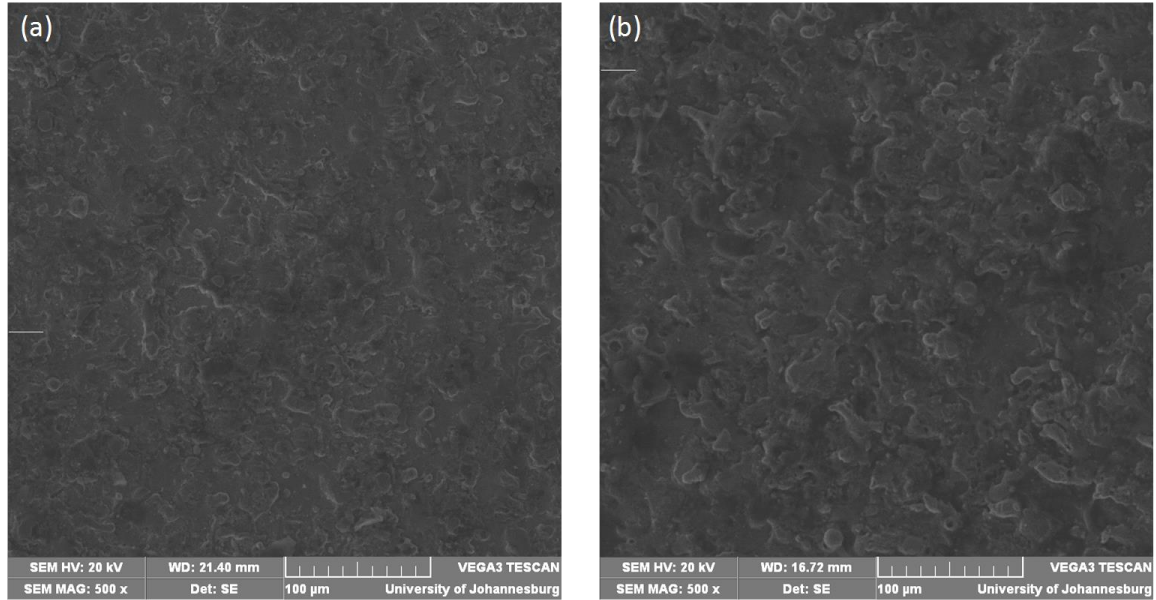


Fig.3 SEM micrographs of D2 machined steel (a) Pulse on time -110 μ s (b) Pulse on time -130 μ s

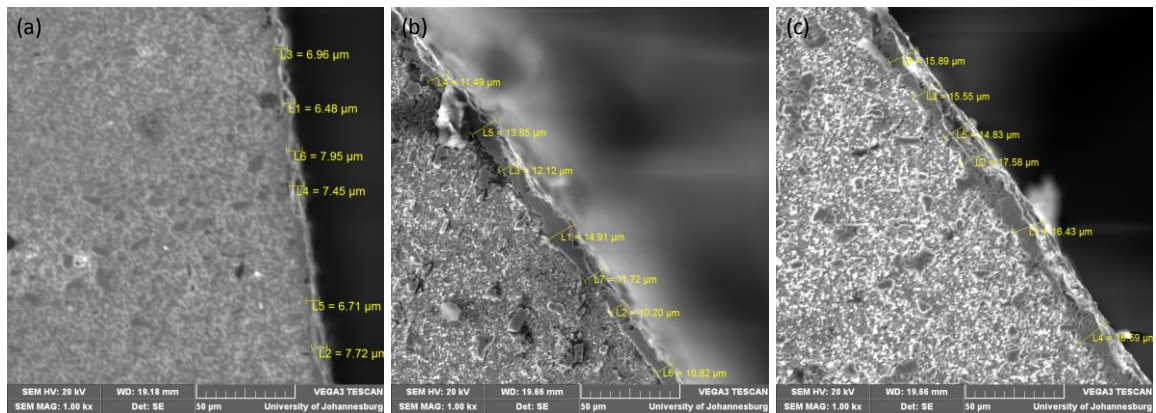


Fig. 4 Recast layer thickness of WED-Machined D2 steel (a) Trial 6, (b) Trial 17, (c) Trial 27

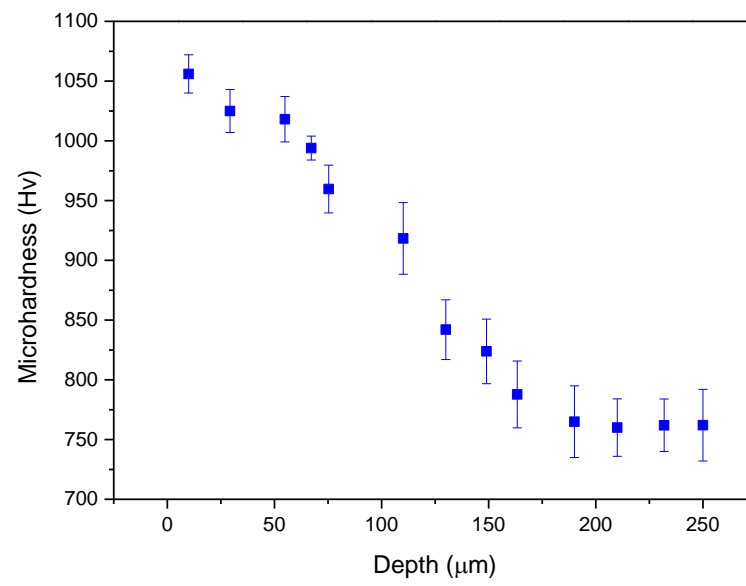


Fig. 5 Microhardness versus depth from the machined surface (Trial 27)

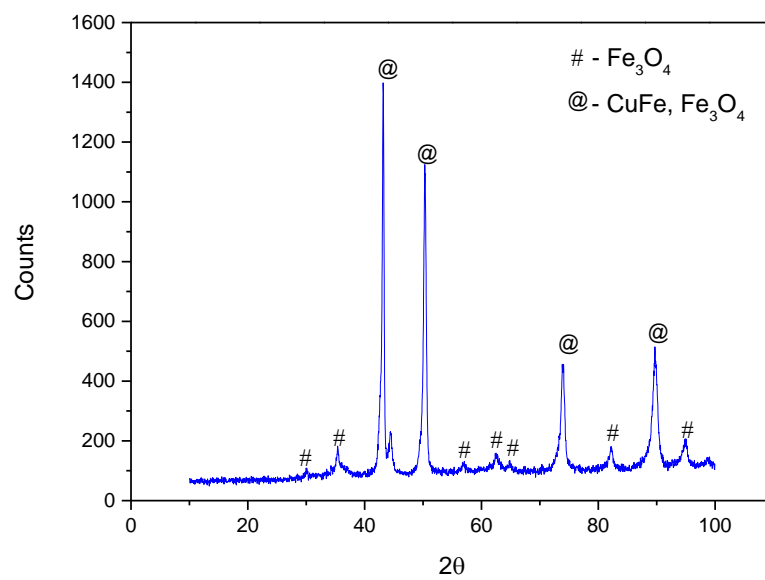


Fig. 6 XRD pattern of machined surface