Performance Evaluation of SiC Powder Mixed Electrical Discharge Machining: A Case of Wire Cut Mode with Re-Circulating Molybdenum Wire

Muhammad Qaiser Saleem
University of Engineering & Technology, Lahore
Maham Naqvi (mn446@njit.edu)
New Jersey Institute of Technology
Sarmad Ali Khan
University of Engineering & Technology, Lahore
Nadeem Ahmad Mufti
University of Engineering & Technology, Lahore
Kashif Ishfaq
University of Engineering & Technology, Lahore

Research Article

Keywords: Powder mixed electrical discharge machining, wire-cut machining mode, SiC, AISI D2, molybdenum wire

Posted Date: June 28th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-159588/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on July 6th, 2021. See the published version at https://doi.org/10.1007/s00170-021-07562-w.

Abstract

Review of the available literature on powder mixed electrical discharge machining (PMEDM) indicates, that most of the research has been done for “die sinking machining mode” whereas the “wire cut machining mode” has not received due attention despite being an important process variant. This work employs Silicon Carbide (SiC) powder mixed dielectric fluid for machining of AISI D2 in “wire cut” mode with re-circulating molybdenum wire (an economic and chemically stable proposition as tool). The effect of five process parameters (powder concentration, peak current, pulse on time, nozzle flushing pressure and stand-off distance) have been evaluated on surface roughness, kerf width, material removal rate and wire wear ratio using Taguchi’s approach. It is found that for surface roughness, higher current and low to moderate concentration levels (2 to 4g/l) deteriorate surface quality; higher values of pressure and stand-off distance are also seen to adversely affect it. For material removal rate, pulse on time as well as its interactions with powder concentration and current, are statistically significant. A higher pulse on with smaller and moderate powder concentrations (2g/l and 4g/l) reduces MRR. For wire wear ratio, current is the sole significant factor (PCR of ~ 65%). SEM analysis of the machined workpiece for the maximum MRR condition quantifies recast layer as ~ 19microns. An indirect comparison with the reported values for non-powdered EDM process indicates that for the similar wire (molybdenum), the use of SiC powder maintains the surface roughness and kerf values, for a much harder D2 material used in this work.

1. Introduction

Powder mixed electric discharge machining (PMEDM) has offered itself as an effective variant of conventional EDM process. It involves adding certain conductive powders to the dielectric which influence spark attributes during machining and result into high surface quality and increased material removal rate [1–2]. The improvement in surface quality is attributed to increase in discharge gap which reduces the generated heat flux, that then helps form smaller craters (thus better surface quality) [2–5]. Material removal rate (MRR), on the other hand, gets improved because of the increased spark frequency, which is the result of reduced dielectric resistivity [2]. Ease of removal of debris which is made possible by wider discharge gap [5] and smaller craters further contributes to increase in MRR [2].

Review of the available PMEDM literature indicates that various powder relevant variables namely the ‘material’ itself, ‘concentration’ and ‘size’ influence the process outcomes differently [5–9]. Wong et al. [5] found specific combinations of workpiece and powder-mixed dielectric to be resulting into beneficial outcomes when they compared the effectiveness of Si, Al, SiC, Gr, MoS_2 and crushed glass. Graphite and Si were found to be producing mirror like surfaces for SKH-54 tool steel workpiece material (even up-to a pulse current of 2 Amp) whereas, Al was reported to be more effective in producing mirror like surfaces for the workpiece material SKH-51 [5]. For other response measures as well, the favorable outcomes are not found to be specific to the use of any one powder material. Tzeng and Lee [8] reported Cr addition (in Kerosene) to be contributing most, to the increase in MRR than Cr, Cu, Al and SiC powders. They however found the effectiveness of powders towards tool wear rate to be different than pattern observed for MRR. Maximum tool deterioration was reported for the case of SiC, followed by Al and Cr. The Cu was not found to be much influential for either response measure in their work. The ineffectiveness of Cu as an additive was attributed to its high density that kept it from remaining suspended in dielectric [8–9]. Chow et al. [10] in their work on micro-slit EDM, reported SiC to be having higher material removal depth in comparison to Al at their respective optimum concentrations. In yet another work [11], addition of SiC powder in de-ionized water was seen to increase material removal depth. More recently, SiC powder mixed dielectric has been reported to have positive effect in reducing surface roughness for hardened steel [12]. In yet another work employing a different powder material i.e. Gr was not only reported to improve MRR and tool wear rate [2], but was also found to alloy with machined surface [11]. In a recent study Sahu and Mandal [13] reported Gr based PMEDM to be generating surface with maximum flatness for Nimonic 263 in the work that also employed alumina powder in EDM oil. Other than powder material itself, “powder concentration” has also been seen to play its part. Particles beyond an optimum level are mentioned to have similar effect to that of overcrowded debris in the gap thus causing unstable machining [2]. The ensuing bridging effect, short circuiting, arcing and settling issues have been attributed for adversely affecting surface characteristics [2, 4, 8]. Powder concentrations upto 20 g/l are seen to be mostly reported to be used with only limited work employing concentrations in excess [2]. Another important powder relevant variable seen to be investigated is “particle size. It is seen to relate directly with the discharge gap produced. In general, larger particles have been reported to result in wider discharge gaps whereas smaller particles produce smaller gaps [2, 8]. Correspondingly, improved material removal rate and tool wear ratio has been associated with smaller particles [8]. In this regard, work can be found in both micro and nano regimes [2, 14–15] wherein the micro-regime and nano-regime have been seen to be employed mostly in the size ranges of 1–55μm and 20-60nm respectively [2].

While the preceding section discussed how various powder relevant variables generally affect the process outcomes, another important context of discussion pertains to the way these powder relevant variables contribute in terms of their influence when compared with other process variables in a certain parametric combination. Kansal et al. [6] optimized the process parameters of powder mixed dielectric machining for MRR and SF using response surface methodology (RSM). Silicon powder in the range of 20–30 micron was added to kerosene oil (base dielectric) while machining EN-31 tool steel with Cu electrode. They found quadratic model to be statistically significant for explaining the relationship between the independent and the output variables. Powder addition not only increased surface finish but also its high concentration tended to increase MRR. They found maximum MRR at Si concentration of 2g/l and peak current of 12 Amp (the highest employed in their work). Later, Kumar et al. [16] optimized the process for another tool steel grade EN-24 while employing the same process parameters but with different electrode dia. They employed grey relation analysis for process optimization. Batish et al. [17], in another work, evaluated parametric combination that involved various powder specific and conventional EDM variables for various die steel grades. They found powder concentration to be more dominant than certain electrical parameters (such as pulse on time and current) in terms of significance for tool wear rate. For the case of overcut, they noted powder concentration to be second highest contributing factor behind pulse on time. Singh and Yeh [18] used L18 orthogonal array with gray relational analysis to optimize the process when SiC abrasive powder mixed dielectric was used to machine 6061Al/Al2O3p/20p aluminum matrix composite. Eight input variables were considered in their work with performance measures being material removal rate, tool wear rate and surface roughness. As per their confirmatory runs, an increase was noted for MRR (from 0.4267 to

0.530 g/min) whereas reduction was recorded for tool wear rate (from 0.0112 to 0.0096 g/min) and surface roughness (3.64 to 2.82 microns). They also concluded pulse on time to be relatively more important than other investigated parameters for the multiple performance characteristics studied in their work. Aspect ratio, tool electrode lift time, duty cycle, abrasive particle size, abrasive powder concentration, gap voltage, and pulse current were reported to follow the order of importance. In another work on composite machining via PMEDM, Singh et al. [19] used tungsten powder mixed dielectric to machine aluminum alloy 6061/10% SiC composite. They used RSM to model the effect of four electrical parameters (current, pulse on, pulse off and gap voltage) on MRR with and without powder presence. They reported that although all four electrical parameters had significant role in MRR for both i.e. powder mixed and conventional EDM, however change in MRR with respect to pulse off time was more with PMEDM than that obtained in simple EDM. Additionally, surface analysis of the machined workpiece indicated 42.85% reduction in thickness of the recast layer for the case of PMEDM in comparison to when only base dielectric was used. Long et al. [7] while machining different grades of steel in presence of titanium powder mixed dielectric concluded that interactions of titanium powder concentration with workpiece material and with electrode material were among the main factors that influenced MRR. In a more recent work, Kumar et al. [20] while employing different powder materials to machine Inconel-800 at different machining conditions, found powder particles along with current, pulse on time and tool material to be influential factors for tool wear rate.

As evident from above literature, among the parametric sets investigated in specific studies, the powder specific variables have played different (but important role) in differing scenarios. Interestingly, it is pertinent to note that all aforementioned studies were undertaken in “die sinking machining mode”. “Wire cut machining mode” which is an important process variant and otherwise enjoys a respectable place in research and industry due to its extended capabilities, has not been given much attention by researchers in PMEDM domain. Very limited research could be found for wirecut PMEDM and that too only considered special machining scenarios [21–22]. Jarin et al. [21] while employing wire cut mode, mixed carbon nanopowder (at three concentration levels of 0.2, 1 and 2 g/L) in commercially available dielectric to machine gold coated Si wafer at different voltage and capacitance values to compare the performance with unmixed dielectric. They noted higher MRR when machined with powder addition in general with maximum increase reported to be ~ 33% at certain conditions in comparison to un-mixed dielectric. It was also observed that specifically at lower discharge energies, MRR increased with increasing concentration of the powder. Incidentally the pattern of MRR increase was inconsistent at higher discharge energies which they attributed to more abrupt and uncontrolled erosion. They also noted higher spark gaps at higher discharge energies. In another study, Yeh et al. [22] mixed sodium pyrophosphate powder in pure water to machine polycrystalline silicon ingot in wire cut mode. The effects on cutting speed, kerf loss and surface roughness were evaluated. They reported 2.4 times higher cutting speed and an improvement of 16% in surface roughness with powder mixed dielectric in comparison to unmixed dielectric. An EDS analysis however, revealed infiltration of phosphorus into the machined surface for the case of sodium pyrophosphate mixed dielectric.

Ironically, other than the aforementioned special scenarios, no study could be located that thoroughly evaluates the role of powder mixed EDM in wirecut mode. It is important to realize that the dynamics of certain variables in wire cut mode are different than diesinker mode and therefore, the role of process specific variables in conjunction with powder addition is found to lack a thorough investigation. It has also been cited by others [9] that there exists a need to further explore powder material's potential especially when so many variables get combined [9]. Looking at the effectiveness of powders for 'die sinking machining mode' and prevalence of significant research gap in 'wire cut machining mode of EDM', a thorough investigation in this regard is called for. It would be worthwhile to evaluate the role of variables and quantify the benefits for powder assisted wire cut machining mode.

This work quantifies the role of different process variables while employing SiC powder during machining of AISI D2 steel in EDM wire cut mode with re-circulating molybdenum wire which not only provides an economic proposition to be used as a tool but is also reported to have less tendency to chemically react and contaminate machined surface [23–24]. An average size of ~ 15 micron SiC powder was taken with three levels of concentration, stand-off distance, flushing pressure, pulse on time and current. Surface roughness, material removal rate, kerf width and wire wear ratio were the output criteria. Taguchi L27 array was used for experimentation followed by main effect plots and analysis of variance (ANOVA) for determination of significant parameters at 95% confidence level. SEM analysis was used to evaluate re-cast layer thickness of the optimized samples.

2. Experimental Design And Procedure

2.1 Workpiece specimen and setup details

A 20 × 10 × 10mm plate of hardened AISI D2 steel with hardness value of 56 HRC was used as workpiece material. The typical composition and properties are given in Table 1 and 2 respectively. Re-circulating molybdenum wire (dia 0.18 mm) was used as cutting tool to produce a cut of 10 mm length via EDM wirecut machine[3]. Figure 1 provides the schematic of workpiece and the cut produced. Commercially available 99.9% pure silicon carbide powder with an average size of ~15 micron was mixed in commercially available medium duty soluble hydrocarbon oil dielectric at three concentration levels in a tank. A rotary mixer at 2850 rpm was used for the purpose and it was operated continually during experimentation to prevent settling. The solution was pumped to the machining zone for jet flushing (from both, upper and lower nozzle) through piping network and pressure regulating valves at a flow rate of 40 l/min. Two calibrated pressure gauges attached at 1.5" from the outlets were employed to measure supply pressure variations at different experiment conditions. The workpiece was not submerged in dielectric so that role of parameters (stand-off distance and pressure) that could possibly influence the dielectric flow through the gap could be properly studied. Figure 2 presents the schematic of essential components of the machining setup whereas figure 3 shows the actual one.

2.2 Design of experiments

Taguchi L27 orthogonal array was used as design of experiment (DOE) for experimentation phase. Five factors namely current, pulse on, powder concentration, stand-off distance and pressure were varied at three different levels whereas powder type & material were constants. The levels of variables were selected taking guide from the available literature on PMEDM. Table 3 gives the details of the variables' levels employed during experimentation. Table 4 contains constants and key parameters of machine.

2.3 Post experimental measurements & analysis

Surface roughness was quantified by measuring surface roughness parameter “Ra” using surface texture meter[4] with 4mm evaluation length. Ra was measured at four random locations over the cut surface and the average value is reported herein.

Coordinate measuring machine[5] was used to measure Kerf width of workpiece after making a cut of 9mm length (before parting it off completely). Images were taken at the magnification of 70X and three measurements were done (graphically) for each upper and lower side of the workpiece. Average values are reported herein.

Material removal rate (MRR) and Wire wear ratio (WWR) was calculated using equations (1) and (2) respectively.

$$MRR\ \left(\frac{mm^3}{min}\right) = \frac{work\ piece\ weight\ loss\ (gm)}{Density\ \left(\frac{gm}{mm^3}\right) X\ Machining\ time\ (\mathrm{min})} \qquad (1)$$

$$WWR = \frac{WWL}{IWW} \qquad (2)$$

Where WWL is wire weight loss & IWW is initial wire weight.

Main effect plots and analysis of variance (ANOVA) were used for determination of significant parameters at 95% confidence level. Recast layer thickness of the sample with maximum MRR was measured using scanning electron microscope[6]. Etching of the specimens was done in a mixture composed of 2% Nital for 1 min.

Table 1: Typical chemical composition of D2 steel (Weight %) [25-26]

C	Cr	Mn	Si	Mo	Co	V	Fe
1.4-1.6	11-13	≤ 0.6	≤ 0.6	0.7-1.2	≤1.0	≤1.1	Bal.

Table 2: Typical properties of D2 steel [25-26]

Density	Melting Point	Modulus of Elasticity	Coefficient of Thermal Expansion
7.7 g/cc	1421°C	190-210 GPa	10.4×10^{-6} /°C^{-1}

Table 3: Variable factors

Sr. No.	Pressure (kPa)	Concentration (g/l)	Current (Amp)	Pulse On (μs)	Stand-off Distance (mm)
1	40	2	2	100	60
2	50	4	3	130	70
3	70	6	4	150	80

Table 4: Constants and key parameters of machine

Wire Type	Max. Machining Speed	Max Wire Travelling Speed	Accuracy	Software
Molybdenum (re-circulating)	150 mm^2/min	11 m/min	0.015 mm	AutoCut

[3] EDM Machine: Model DK 7725A

[4]Surface Texture meter: Taylor Hobson Surtronic S128

[5]Coordinate measuring machine: CE450 DV

[6] SEM: JEOL JSM 6100

3. Results, Analysis And Discussion

Table 5 gives the results for the experiments performed using powder mixed wire electric discharge machining.

Table 5
Experiment results

Exp.	Stand off	Concentration	Pressure	Current	Pulse on	WWR	Ra	MRR	Kerf
	mm	g/l	kPa	A	µs		microns	mm^3/min	mm
1	60	2	30	2	100	0.003	5.9	2.62	0.25
2	60	2	30	2	130	0.004	5.0	1.65	0.29
3	60	2	30	2	150	0.006	6.3	0.72	0.24
4	60	4	40	3	100	0.010	7.0	1.99	0.29
5	60	4	40	3	130	0.009	7.1	0.5	0.26
6	60	4	40	3	150	0.007	7.4	0.85	0.28
7	60	6	50	4	100	0.019	7.8	1.41	0.25
8	60	6	50	4	130	0.021	7.8	2.03	0.31
9	60	6	50	4	150	0.018	7.2	1.853	0.20
10	70	2	40	4	100	0.020	7.0	2.83	0.29
11	70	2	40	4	130	0.023	6.4	1.242	0.35
12	70	2	40	4	150	0.024	6.3	1.136	0.30
13	70	4	50	2	100	0.009	6.3	3.14	0.25
14	70	4	50	2	130	0.007	6.2	0.824	0.24
15	70	4	50	2	150	0.005	6.9	0.51	0.29
16	70	6	30	3	100	0.009	6.3	1.29	0.26
17	70	6	30	3	130	0.007	6.8	2.99	0.25
18	70	6	30	3	150	0.016	5.6	3.896	0.28
19	80	2	50	3	100	0.009	6.5	1.293	0.31
20	80	2	50	3	130	0.023	6.0	2.116	0.34
21	80	2	50	3	150	0.019	7.1	0.59	0.27
22	80	4	30	4	100	0.020	7.6	4.25	0.35
23	80	4	30	4	130	0.010	7.3	1.633	0.25
24	80	4	30	4	150	0.018	7.2	1.3	0.27
25	80	6	40	2	100	0.004	6.8	1.443	0.33
26	80	6	40	2	130	0.005	6.5	0.62	0.30

Exp.	Stand off	Concentration	Pressure	Current	Pulse on	WWR	Ra	MRR	Kerf
	mm	g/l	kPa	A	µs		microns	mm^3/min	mm
27	80	6	40	2	150	0.005	6.9	0.52	0.32

3.1 Surface roughness

The main effect plots of average surface roughness values are shown in Fig. 4. Two interactions were studied in the analysis. The effect of interactions is given in Fig. 5 whereas Table 6 gives the ANOVA calculations done to identify significant factors. Current had the maximum percentage contribution (PCR) of 29.02% followed by powder concentration (PCR of 21.7%). Surface finish is seen to be deteriorated with an increase in current. At higher current levels, high intensity sparks would be generated thus producing more deep craters. This translates into higher roughness values. Looking at the general trend for powder concentration, it gets indicated that surface quality deteriorates with it in general. Specifically in the range of 2g/l to 4g/l, the surface deteriorates and then afterwards at higher concentration (6g/l), some improvement may be expected. It can be explained on the basis that as powder gets added, it inhibits the insulating properties of dielectric thus reducing resistance to current flow. In the lower ranges of the concentration, this reduced resistance would be confined to limited areas/paths (where bridging would occur) so energy could be more focused and intense as it impinges on workpiece surface thereby resulting into increase in crater depths. As the concentration increases to 6g/l, the saturation would help in achieving widespread bridging thus distributing the energy to multiple locations at workpiece; this would improve the surface finish. Stand-off distance and pressure are also two factors that are found to be statistically significant. A possible explanation for their role could be put forth. The two factors have got to do with the flow characteristics of the incoming fluid stream and their higher values are seen to result in deteriorated surface finish. A higher value of stand-off distance may have contributed to uniform entry of the powdered dielectric (moving along the wire) into the gap (as opposed to splashing etc that may have been the case otherwise). This phenomena as well as higher pressure may have influenced the number of particles and the effective time each individual particle may be available with to contribute to the whole process. The availability of larger number of particles (by virtue of smooth entry to the gap due to appropriate stand-off distance) with higher pressure head (as opposed to velocity head) is expected to have given the powders enough time to have culminated into producing deeper craters on surface. Results also show that although pulse on time is not statistically significant in independent capacity however its interactions with current and powder concentration are found to be significant. A moderate pulse on time of 130 µsec with minimum powder concentration (2g/l) and current (2A) is found to be resulting into minimum surface finish. This combination seems to spread and dilute discharge energy thereby producing minimum craters. Although no work could be found for the role of powder in wire EDM mode for D2 steel, however some indirect comparisons may be made. A previous work that used molybdenum wire for electrical discharge machining of HSLA steel without any powder additive, reported surface roughness of the scale of ~ 6microns [27]. It is pertinent to mention that HSLA steel employed in the previous work had hardness value of 38 HRC with experimentation conducted at pulse on values of 32 & 96 microseconds. Although the average value of the surface roughness obtained in the work presented herein (with SiC powdered EDM) is also of the comparable scale (~ 6microns) however the work presented herein has employed D2 steel that has a much higher hardness of 56 HRC; additionally high pulse on values (100–150μs) have been employed. In a more recent work, Ishfaq et al. [28] reported an improved surface roughness value of 4.47microns with moly wire (without powder) but their work employed much softer SS304 in comparison to the workpiece employed herein. In the context, current work demonstrates the capability of SiC powdered EDM for generating good quality surfaces for harder workpieces.

Table 6
ANOVA for surface roughness (Ra)

Source	DF	SEq. SS	Adj. SS	Adj. MS	P-value	PCR
Stand-off (mm)	2	1.14796	1.14796	0.57398	0.013*	8.71
Powder concentration (g/l)	2	2.64352	2.64352	1.32176	0.001*	21.70
Pressure (kPa)	2	0.98463	0.98463	0.49231	0.019*	7.29
Current (A)	2	3.48685	3.48685	1.74343	0.000*	29.02
Pulse on time (μs)	2	0.29241	0.29241	0.14620	0.195	1.28
Powder conc.× Pulse on time	4	1.24370	1.24370	0.31093	0.038*	8.29
Current × Pulse on time	4	1.14037	1.14037	0.28509	0.047*	7.39
Error	8	0.57852	0.57852	0.07231		
Total	26	11.51796				

* Significant at 95% confidence level

3.2 Material removal rate

Figure 6 presents the main effects plots for material removal rate (MRR) whereas the effects of significant interactions are shown in Fig. 7. The corresponding ANOVA calculations are presented in Table 7.

The analysis yields that not only pulse on time itself is a significant factor but also its interactions with current and powder concentration are significant. Additionally, pressure is also seen to have statistical significance. As can be seen from the results, pulse on time has a negative effect on MRR; an increase in pulse on time reduces MRR. It is believed that with an increase in pulse duration, the pulse energy is shared by many electrons/ions which may have contributed to the decrease in MRR. The argument takes strength considering that the pulse on time has got a strong interaction effect with powder concentration (incidentally this interaction had a maximum PCR of 28.29%). The interaction plots show that at two lesser powder concentration levels of 2g/l and 4g/l, there is a continual decrease in MRR with increase in pulse on. The situation changes when a higher concentration level of 6g/l is used which increases the MRR. The distribution of pulse energy at lower concentration levels of powder is expected to dilute the effect of heat intensity that could have eroded the material at much faster rate thus resulting in lesser MRR. At higher concentration of 6g/l, however the increased MRR may be attributed to the bridging effect that takes over and stronger multiple spark locations at the work piece enable the higher MRR in this case. The interaction between pulse on time and current is also significant with PCR of 12.06%. For longer pulse duration of 130μs and 150μs, 3A current is found to be the optimum however 4A current generates maximum MRR with short pulse duration of 100μs. this is likely due to the fact that shorter pulse duration (100μs) may have insufficient time for the chips to be removed hence maximum current is required for effective deionization of the die-electric while longer pulse durations (130μs and 150μs) requires moderate current (3A) for similar effect. For the effect of pressure which comes out to be another significant parameter, it may be hypothesized that the extreme values of pressure facilitate more favorable fluid flow characteristics that enabled a good mix of powder particles availability as well as time for them to contribute positively to MRR. At intermediate pressure value, may be the flow characteristics are such that a transitory phase exists that is less than the optimum mix of powder quantity & their time in the gap.

Table 7
ANOVA for MRR

Source	DF	SEq. SS	Adj. SS	Adj. MS	P-value	PCR
Stand-off (mm)	2	1.2855	1.2855	0.6427	0.114	3.02
Powder concentration (g/l)	2	0.1924	0.1924	0.0962	0.664	0
Pressure (kPa)	2	5.0093	5.0093	2.5046	0.005*	16.4
Current (A)	2	1.7966	1.7966	0.8983	0.062	4.85
Pulse on time (μs)	2	4.7552	4.7552	2.3776	0.006*	15.48
Powder conc. × Pulse on time	4	8.7666	8.7666	2.1916	0.004*	28.29
Current × Pulse on time	4	4.2478	4.2478	1.0620	0.029*	12.06
Error	8	1.7822	1.7822	0.2228		
Total	26	27.8356				

* Significant at 95% confidence level

3.3 Kerf width

The representative images of kerf width measurements measured at two different experiment conditions are given in Fig. 8. Main effect plots for kerf width are given in Fig. 9 whereas Table 8 shows the ANOVA calculations. No factor is found to be statistically significant at the pre-defined confidence level of 95%. Though, it is seen that “stand-off” is the factor that has PCR in excess of 15%. The trend of main effect indicates that increase in stand-off distance increases the kerf width. The possible reason for this could be that since increase in stand-off increases the distance from where fluid gets thrown, it is very likely that this increase reduced splashing of the fluid near the gap. Too close a supply with fluid splashing would prevent its entry to the gap in effective manner. On the other hand, an increase in the stand-off distance could make fluid to move along the wire making its entry more uniform thereby facilitating more particles to be available in the gap. The effect of the larger number of powder particles once available between electrode and workpiece would be to increase the discharge frequencies resulting in larger over cut. The average kerf value of ~ 0.28mm obtained for the current work with re-circulating molybdenum wire is of the same order as the one (~ 0.29mm) reported by Ikram et al. [29], when they employed single pass brass wire to machine D2 steel of comparable thickness at optimized conditions but without any powder addition. This shows that the currently reported values are pretty much maintained at previously reported values even as a re-circulating wire is employed for this hard material.

Another comparison can be made with a more recent work by Ishfaq et al. [28] wherein they employed molybdenum wire for machining of much softer SS 304 and reported the post improvement kerf value of ~ 0.322mm. Thus, in current work, good control over the process in terms of kerf width is indicated in presence of SiC powder.

Table 8
ANOVA for kerf width

Source	DF	SEq. SS	Adj. SS	Adj. MS	P-value	PCR
Stand-off (mm)	2	0.007831	0.007831	0.003916	0.073	16.03
Powder concentration (g/l)	2	0.001707	0.001707	0.000853	0.481	0
Pressure (kPa)	2	0.005458	0.005458	0.002729	0.137	9.37
Current (A)	2	0.000187	0.000187	0.000093	0.917	0
Pulse on time (µs)	2	0.001338	0.001338	0.000669	0.557	0
Powder conc. × Pulse on time	4	0.007898	0.007898	0.001975	0.211	10.25
Current × Pulse on time	4	0.002685	0.002685	0.000671	0.654	0
Error	8	0.008495	0.008495	0.001062		
Total	26	0.035599				

Wire wear ratio

The results of main effects plots for wire wear ratio are shown in Fig. 10 while ANOVA analysis is shown in Table 9. Among all evaluated factors, current is the only factor which was statistically significant with maximum PCR of ~ 65%. The enhanced current intensity of the spark seems to be taking toll on the tool (wire). It is important to mention that wire wear ratio has not been found to be quantified in the PMEDM domain so a direct comparison may not be possible. Nevertheless, Batish et al. [17] while working die sinking mode of powder mixed EDM for die steels, observed similar pattern for tool wear rate. In general, the minute amount of wire wear observed herein is in line with the previous findings [24]. Azam et al. [24] reported molybdenum wire to be much stable in their work. Their evaluation of the wire post-machining, yielded it to be un-corroded with no contaminated surface; additionally there was negligible change in its diameter.

Table 9
ANOVA for wire wear ratio

Source	DF	SEq. SS	Adj. SS	Adj. MS	P-value	PCR
Stand-off (mm)	2	0.0000309	0.0000309	0.0000154	0.335	0.49
Powder concentration (g/l)	2	0.0000780	0.0000780	0.0000390	0.097	4.14
Pressure (kPa)	2	0.0000776	0.0000776	0.0000388	0.097	4.11
Current (A)	2	0.0008682	0.0008682	0.0004341	0.000*	65.36
Pulse on time (µs)	2	0.0000127	0.0000127	0.0000063	0.616	0
Powder conc. × Pulse-on time	4	0.0000947	0.0000947	0.0000237	0.199	3.53
Current × Pulse-on-time	4	0.0000304	0.0000304	0.0000076	0.661	0
Error	8	0.0000982	0.0000982	0.0000123		
Total	26	0.0012907				

* Significant at 95% confidence level

3.5 Recast layer thickness

The machined work surface was analyzed for assessment of the thickness of recast layer generated during WEDM process where highest material removal rate was achieved i.e experiment no. 22 (80mm, 4g/l, 30kpa, 4A, 100µs). Measurements were taken at multiple locations and an average is reported herein. A representative SEM image is shown in Fig. 11.

The measurements indicated re-cast layer thickness of around ~ 19microns. The values ranging from ~ 14microns to ~ 21microns of re-cast layer alone have been presented in previously reported literature with moly wires and HSLA steel without powder [23]. Here too, the value obtained is of the similar order.

4. Conclusions

In this study, the effect of five machining parameters on the machining outputs (surface roughness, material removal rate, kerf width and wire wear ratio) of AISI D2 steel has been investigated in powder mixed wire electric discharge machining using Taguchi L27 orthogonal array. Following conclusions can be drawn from the presented work

- For surface roughness of the machined workpiece, four of the five investigated parameters namely current, powder concentration, pressure and stand-off distance were found to be statistically significant at 95% confidence level. Further, interaction of pulse on time with current as well as with powder concentration, were found to be statistically significant at the predefined significance criteria.
- Current was found to be the most contributing factor for Ra with PCR of 29.02% followed by powder concentration (PCR 21.70%). As a general trend, increasing the values tended to deteriorate surface quality specifically at low to moderate concentration levels (2 to 4g/l). It has been attributed to their role

in facilitation in high intensity sparks. A higher powder concentration (6g/l) tended to show improvement probably due to greater distribution of the discharge energy in presence of larger number of particles

- The higher values of pressure and stand-off distance were associated with deteriorated surface quality. Explanation for the effect of pressure and stand-off distance has been sought in their possible role in influencing flow characteristics of the dielectric stream that would influence the number of available particles in a certain time period in the gap between workpiece and tool.
- For material removal rate, pulse on time as well as its interactions with powder concentration and current, were statistically significant factors. Additionally, pressure also came out to be significant. Here higher pulse on time was associated with lower MRR. The results are better explained when interactions are considered as well. A higher pulse on with smaller-moderate powder concentrations (2g/l and 4g/l) is expected to distribute/dilute the effect of heat intensity thereby reducing MRR. The addition of higher 6g/l powder concentration results in improvement which could be explained on the basis of enhanced bridging phenomena.
- For wire wear ratio, current is the sole factor that was statistically significant with PCR of ~65%. A higher value of current resulted in more wire wear ratio.
- An SEM analysis of the machined workpiece done for the conditions where maximum MRR was achieved indicated recast layer of ~19 microns.
- An indirect comparison with the reported values indicate that the use of SiC powder maintains the surface roughness and kerf values for a much harder D2 material when machined with re-circulating molybdenum wire.

Declarations

Acknowledgements The work is based on a thesis titled “Powder mixed wire electrical discharge machining: An investigation into the role of different process parameters” submitted to the University of Engineering & Technology Lahore, Pakistan [30].

Authors Contributions

Muhammad Qaiser Saleem conceptualized the research plan, supervised the work, and wrote the article. Maham Naqvi conducted the experiments, performed measurements and analysis. Sarmad Ali Khan helped conduct the main effect plots and analysis of variance. Nadeem Ahmad Mufti modified the article structure and contributed to analysis and discussion. Kashif Ishfaq helped in statistical analysis and data interpretation phases.

Funding

Not Applicable

Availability of data and materials

Not Applicable

Ethical Approval

The research does not involve human participants or animals and the authors warrant that the paper fulfills the ethical standards of the journal. This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal.

Consent to Participate

The research does not involve human participants or animals and the authors warrant that the paper fulfills the ethical standards of the journal.

Consent to Publish

All authors give consent to publish this manuscript in The International Journal of Advanced Manufacturing Technology.

Competing Interests

The authors declare that they have no conflict of interest.

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Figures

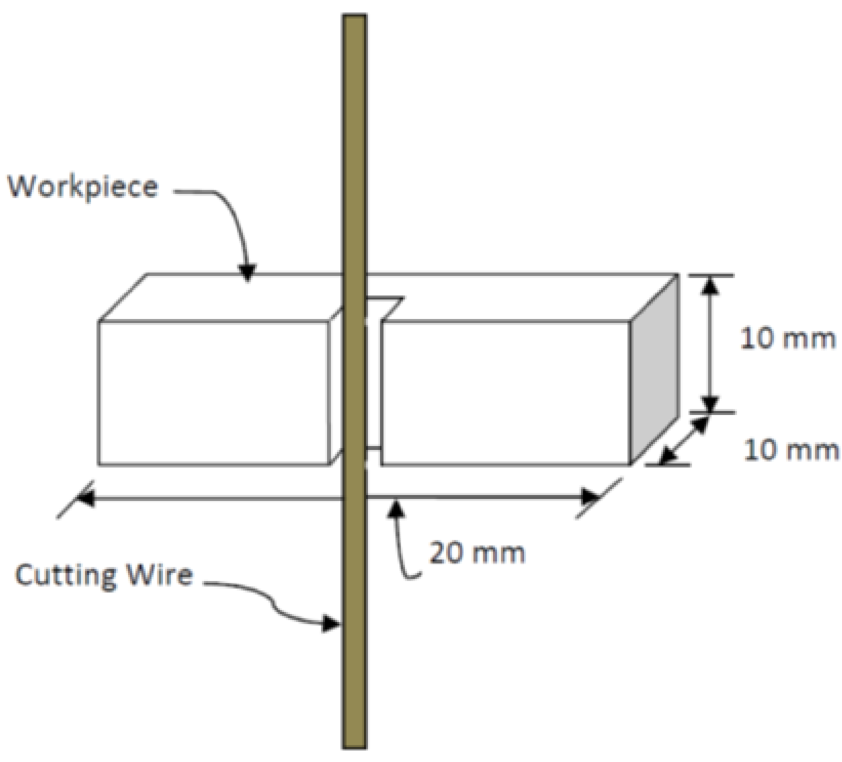

Figure 1

Schematic of the workpiece specimen and cut

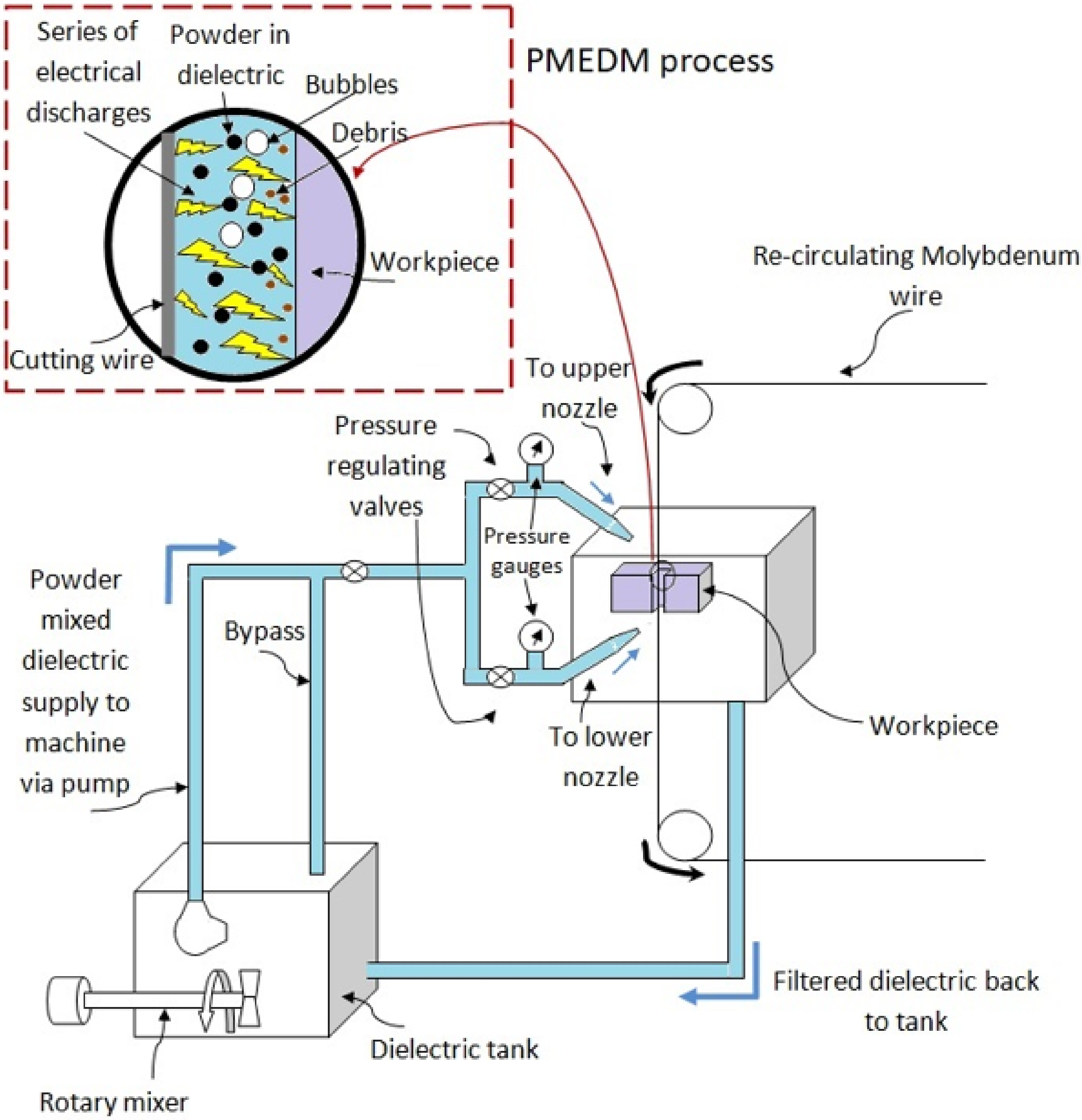

Figure 2

Schemetic of machining setup

Figure 3

Actual machining setup

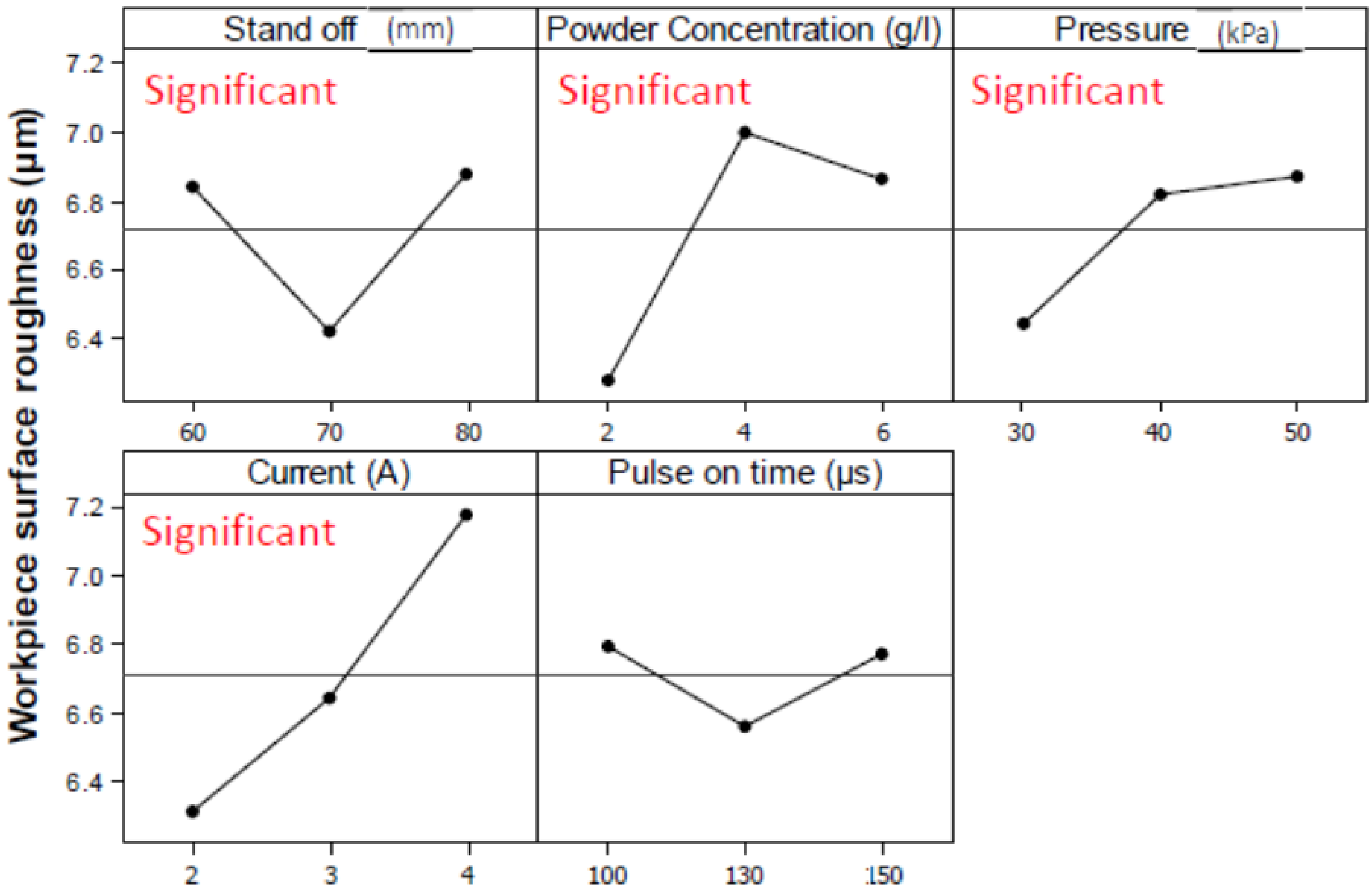

Figure 4

Main effect plots for surface roughness

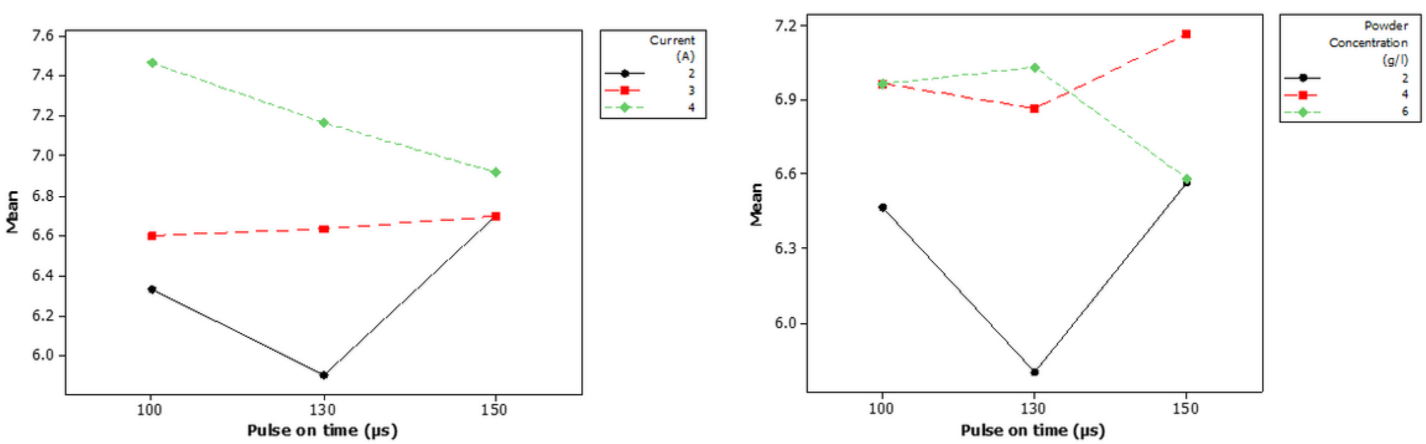

Figure 5

Significant interactions for surface roughness

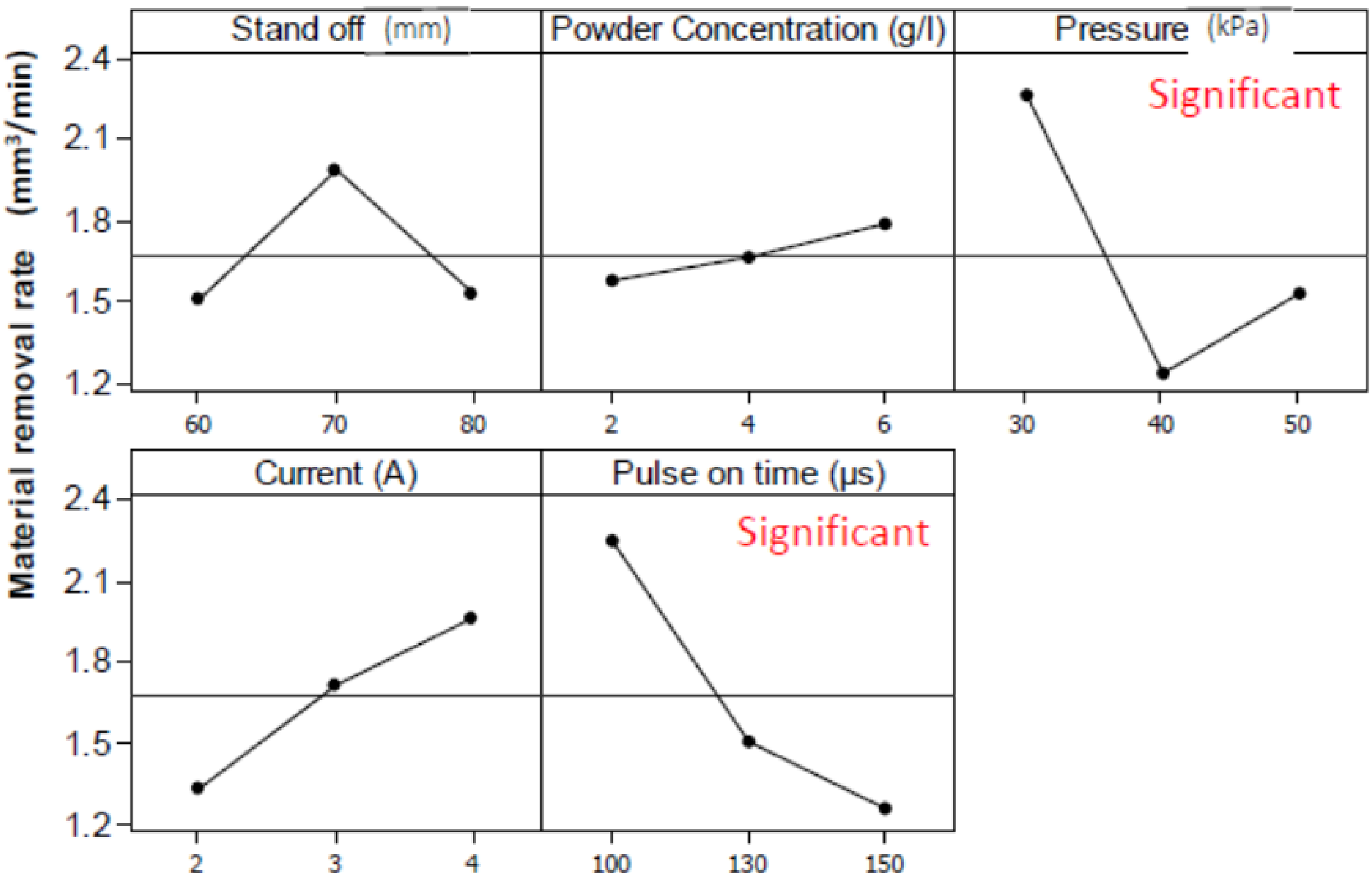

Figure 6

Main effect plots for material removal rate

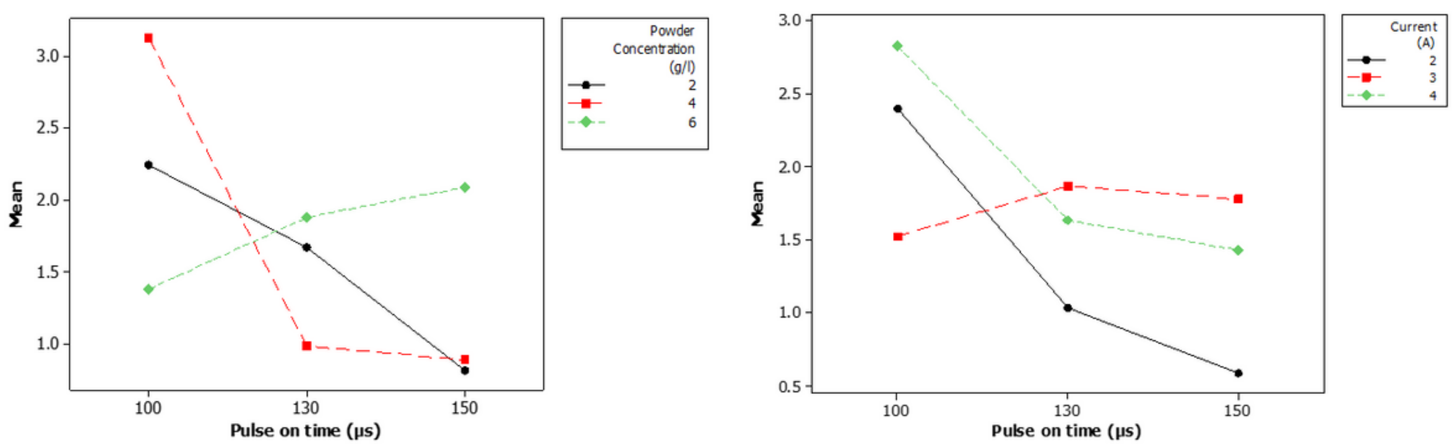

Figure 7

Significant interactions for MRR

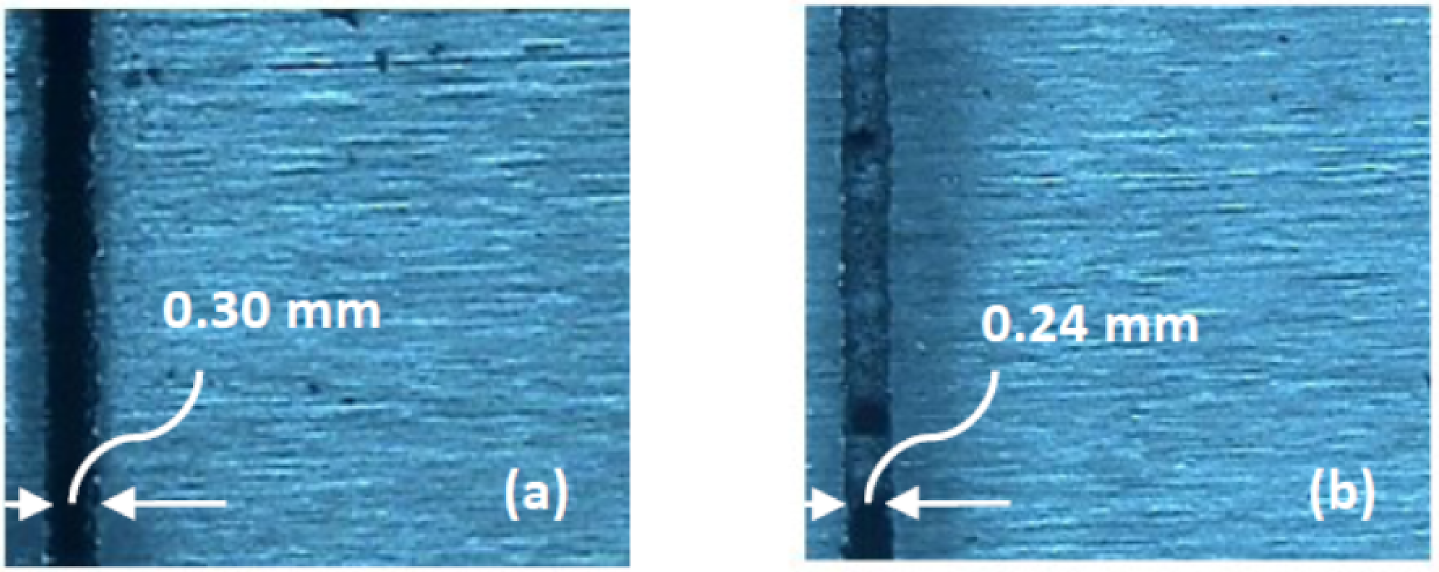

Figure 8

Representative kerf width measurements (a) 80mm, 6g/l, 40KPa, 2A, 130μs (b) 60mm, 2g/l, 30KPa, 2A, 150μs (Standoff distance, conc. pressure, current, pulse-on)

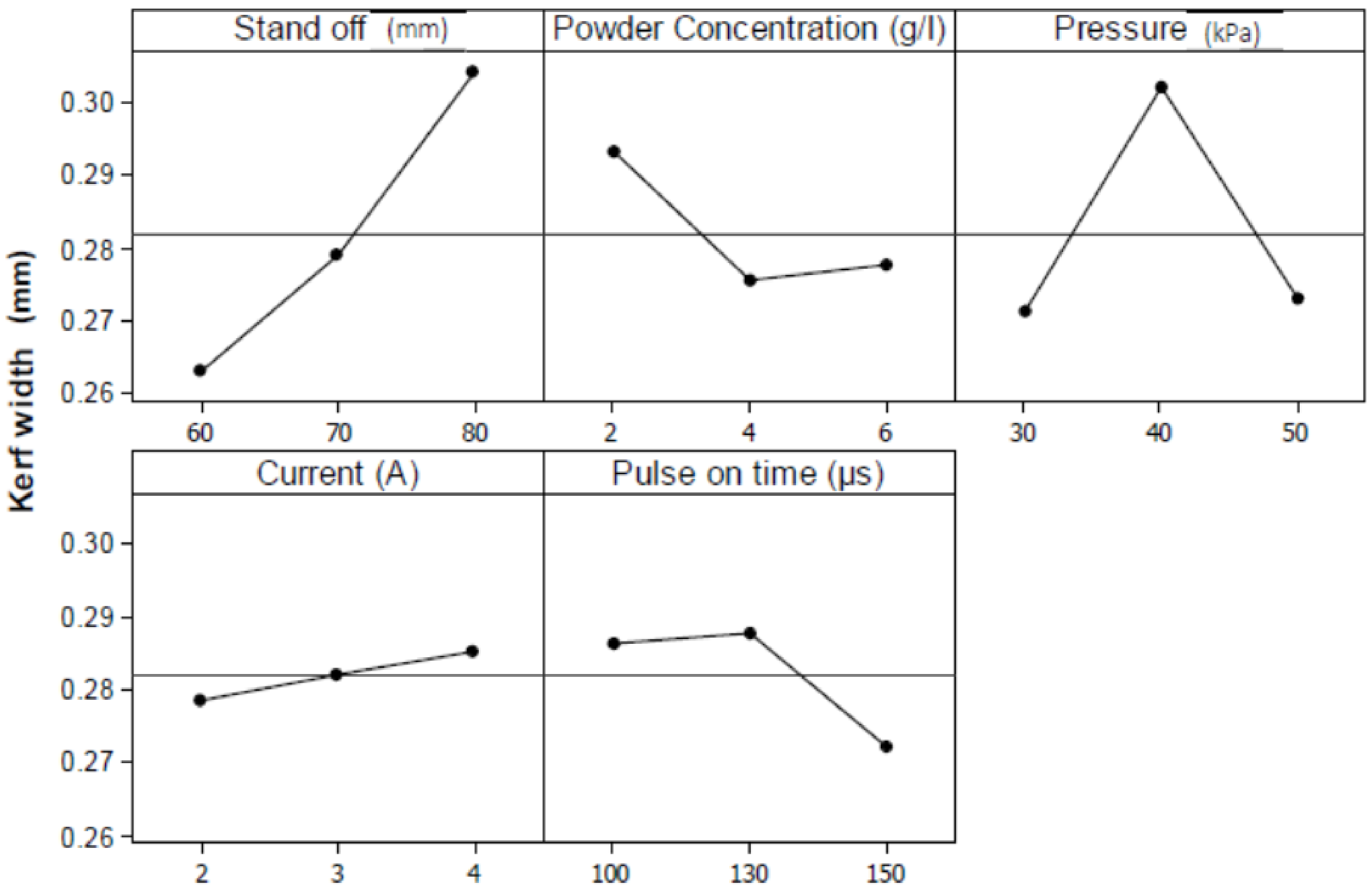

Figure 9

Main effects plots for kerf width

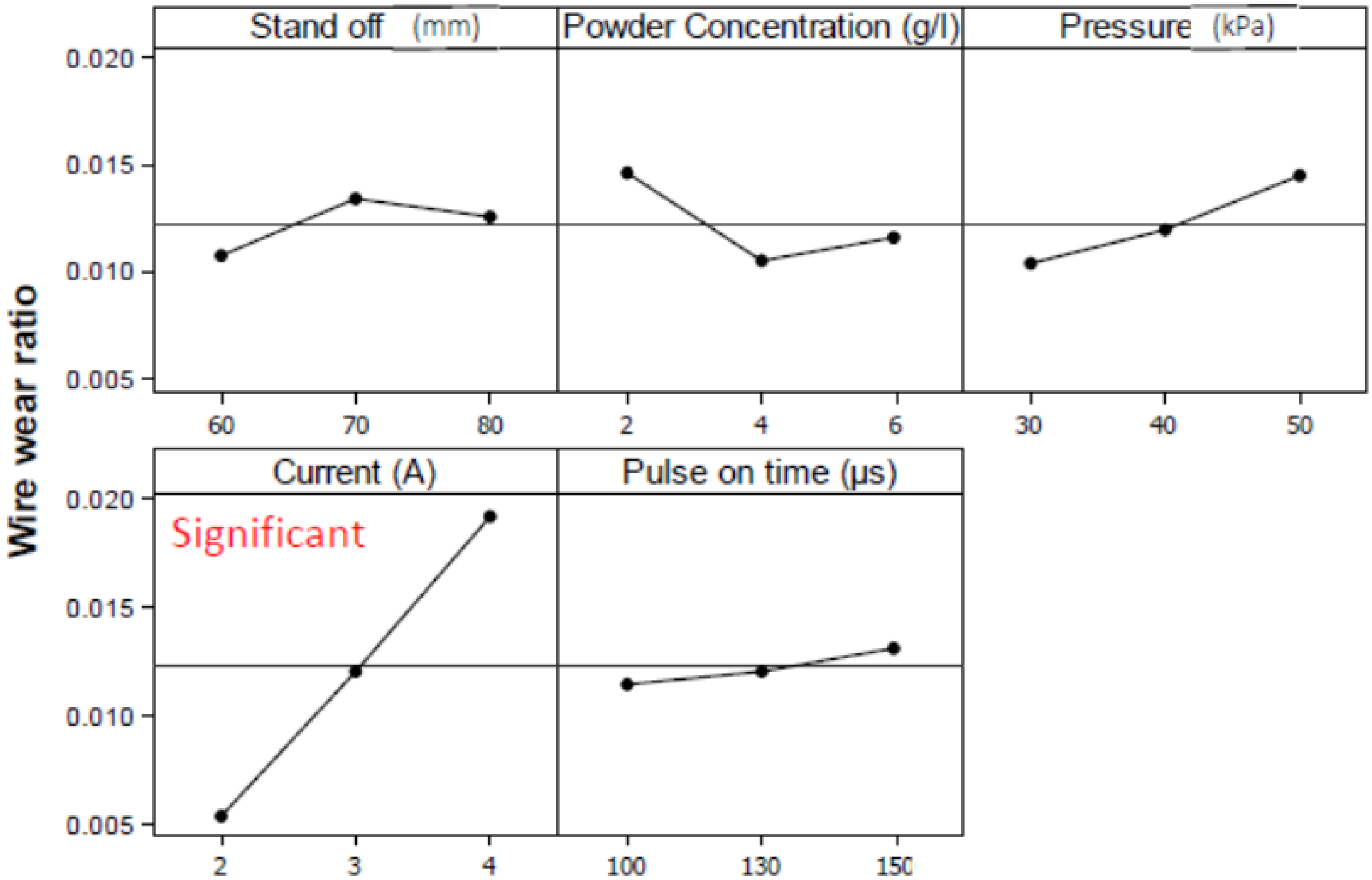

Figure 10

Main effect plots for wire wear ratio

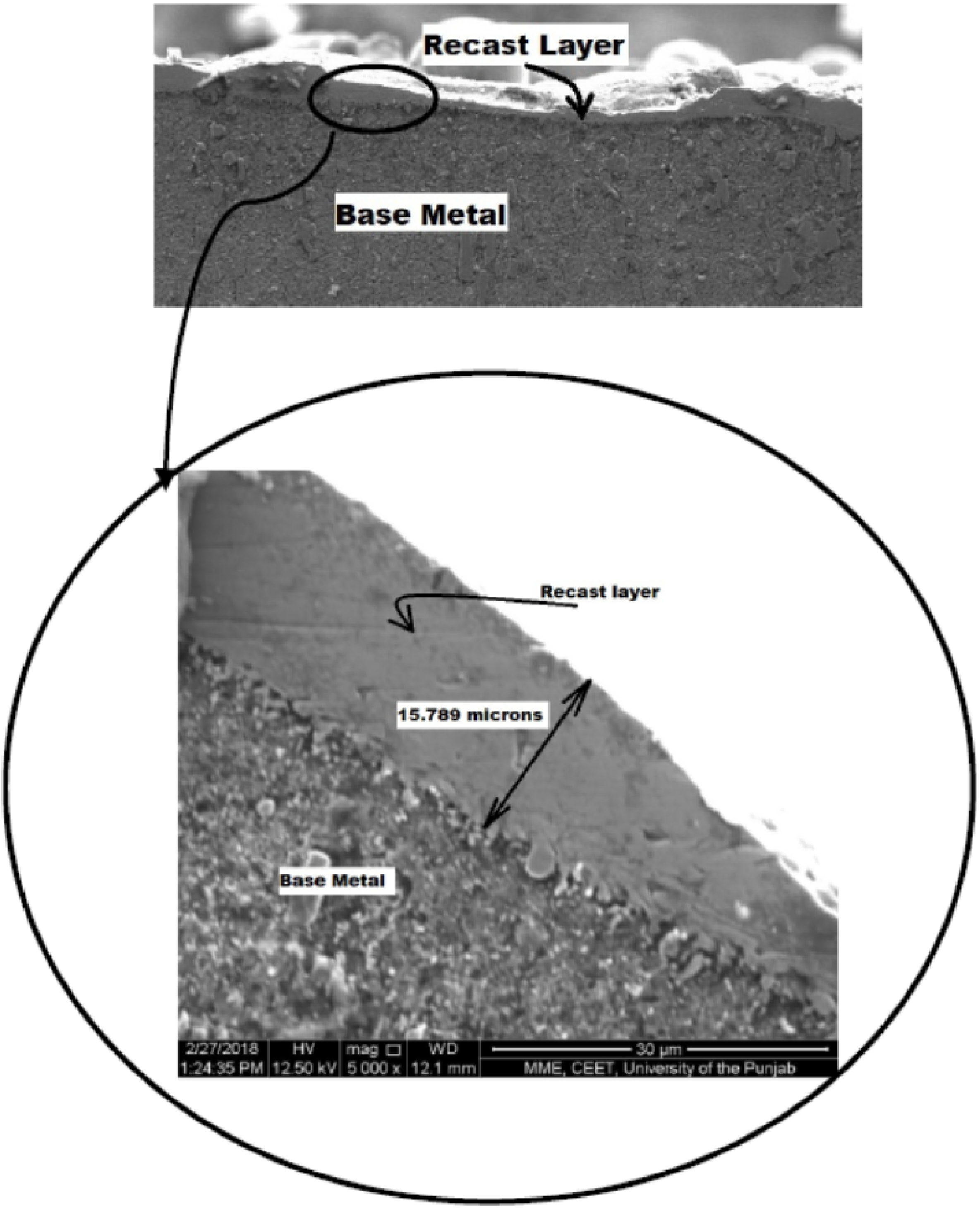

Figure 11

SEM analysis of the recast layer for the experiment where highest MRR is achieved (Experiment 22: 80mm, 4g/l, 30kPa, 4A, 100μs)