Indian Journal of Engineering & Materials Sciences
Vol. 29, February 2022, pp. 80-91

Multi objective study in powder mixed near dry electric discharge machining by using utility concept

Sanjay Sundriyal[a], Vipin[a], & R S Walia[b*]

[a,b]Department of Mechanical Engineering, Delhi Technological University, Delhi 110 042, India

[c]Department of Production and Industrial Engineering, Punjab Engineering College, Chandigarh, 160 012, India

Received: 22 December 2020 ; Accepted: 25 August 2021

Powder mixed near dry electric discharge machining is an advanced hybrid form of electric discharge machining method which makes minimum use of dielectric oil and is quite sustainable in machining terms. In this article an approach has been made to optimize the variable parameters such as tool type, metallic powder concentration, dielectric mist pressure, and mist flow rate in order to study their effect along with their range in order to enhancing the machining performance in terms of increased material removal rate (MRR), improved surface finish, improved micro-hardness, reduction of residual stress and tool wear rate. Analysis of variance along with Taguchi L_9 methodology was utilized for conducting experiments and it was revealed by the confirmation experiments that by this technique, the optimized results for improved material removal rate, improvement of surface finish, enhanced micro-hardness, reduced residual stress and tool wear rate were 0.63 (mg/s), 0.79 (µm), 249 (HV), 286 (MPa) and 1.07 (mg/min) respectively. The optimized values were obtained at Tool diameter (3mm), flow rate of mist (15 ml/min), concentration of metallic powder (8 gm/l) and mist pressure (0.5 MPa) of dielectric medium.

Keywords: Electric discharge machining, Powder, Near dry, Material removal rate, Micro-hardness, Residual stress, Surface roughness, Tool wear rate

1 Introduction

Electric discharge machining (EDM) has played vital roles in the manufacturing sector since decades and this technology has been proven better in terms of machining hard conductive materials with complex geometries as compared to other existing conventional and non- conventional techniques. With continuous revolution in present day machining era, there have been various hybridization of existing machining techniques. Similarly, various hybrid forms of EDM have also been evolved such as Dry-EDM, Near Dry EDM, and Powder mixed EDM etc. Research has been done in the field of EDM for performance enhancement characteristics such as improved material removal rate and better surface finish. Research on machining efficiency of PMND-EDM was done for the different material combination of tool and workpiece electrodes. It was illustrated that that brass tool electrode and W18Cr4V workpiece gain higher MRR[1]. A parametric study for PM-EDM was performed in order to optimize the MRR and surface roughness. Experiments were conducted by utilizing Taguchi L_9 (OA) and keeping metallic powder concentration as one of the process parameters. It was observed that the grain size of powder and powder concentration has a great impact on MRR and surface finish[2]. Response surface methodology was utilized for optimization in PM-EDM and effect of process parameters on MRR and tool wear rate (TWR) was studied. Powder concentration along with other parameters such as peak current, voltage, pulse-on time and duty cycle had a significant effect on MRR and TWR[3]. Effect of the design of parameters in PM-EDM was investigated and analysis of variance was conducted to study the effect of metallic powder concentration on tool wear rate (TWR) and surface roughness (Ra)[4]. Comparison and optimization of Dry EDM and ND-EDM by using Taguchi L_9 (OA) to study MRR and TWR were performed. The experiments revealed that ND-EDM enhances MRR while Dry EDM reduces TWR. Parametric optimization of ND-EDM was also performed by using Taguchi L_{18} (OA) foranalysis of TWR, MRR and Ra. It was revealed that electrode material has the main effect on TWR, MRR, and Ra[5]. Silicon powder as an additive was used along with dielectric oil in EDM to study MRR, Ra, and TWR. PM-EDM leads to a reduction in machining time because the insulating strength of the dielectric gets reduced due to powder additives which result in rapid

*Corresponding author (E-mail: waliaravinder@yahoo.com)

erosion. Analysis of MRR and electrode wear ratio (EWR) in PM-EDM was also studied by using response surface methodology and it was revealed that MRR continues to increase with an increase in powder concentration up to a certain limit and after that, it tends to decrease[6]. Performance index in ultrasonic assisted EDM process was investigated by using graph theory and matrix approach. Role of influential factors such as flushing, cavitation's, abnormal discharge, dimensional accuracy, and surface morphology was studied on performance index of EDM. It was revealed that cavitation has a critical contribution in the EDM process and vibration assisted hybrid EDM shows high-performance index in terms of high dimensional accuracy and surface morphology as compared to customary EDM[7]. Parametric optimization of hybrid EDM process was performed and the effect of a hybrid tool on erosion rate was studied. It was validated that tool with a material combination of copper and abrasive ceramic material enhanced the erosion rate thereby reducing the machining time required for removing the same volume of material by traditional EDM[8]. Micro-hardness of stainless steel was improved through powder mixed electric discharge machining and titanium carbide powder in dielectric oil was utilized to enhance the surface properties of stainless steel. It was illustrated that Vickers hardness value of 1200 was achieved over the machined surface by using titanium carbide powder with the concentration of 25 g l^{-1} in kerosene oil[9]. Evaluation for surface roughness and micro-hardness on die steel (H-11) by EDM using copper and manganese powder metallurgy tool was performed. The micro-hardness value was improved by 97% due to the formation of manganese, ferrite and carbide phases in the machined parts by using the composite tool[10]. A novel optimization route (combining satisfaction function, distance measure approach in conjugation with Taguchi's philosophy) has been introduced. Morphology of the EDM'ed work surface of Inconel 718 has been investigated and it was found to be improved by this novel approach[11]. It was illustrated that discharging energy can be effectively dispersed by adding conductive aluminium powder in dielectric fluid to improve the machining efficiency. It was noticed that higher material removal can be generated by spray EDM as compared to dry EDM and wet EDM for all possible combinations of discharge parameters[12]. The spray-EDM technique reduces the percentage of debris particles which leads to better surface finish and also atomizes dielectric, reducing the tool wear rate as compared to dry and wet EDM. The experimental result obtained value of surface roughness of 2.66 µm. Experiments were carried out in a high speed near-dry EDM of Ti6Al4V and achieved MRR of 648.22 mm^3/min[13]. Increase of air flow rate, peak voltage of EDM, and electrode rotation speed, led to decrease in surface roughness (Ra). Tungsten powder in EDM was used to machine AA6061/10%SiC composite and this additive resulted in increment of MRR by 48.43% and decrement of TWR by 51.12% due to stable and uniform discharges while surface defects such as crater size and deposits of recast were reduced due to decrease in insulating strength of the dielectric[14-16].There was improvement in the heat distribution effect at the inter electrodegapandsurface finish increases by 60% when the aluminium powder concentration waskept at 0.1gm/l in EDM process[17]. Thermal phenomenon in powder mixed near-dry EDM was explained and the tendency of variation in MRR was analysed by varying each process parameter[18,19]. It was proven that the plasma channel was much more stable in powder mixed EDM than the plasma formed in pure kerosene oil because the plasma generated in PMEDM was compressed by the electric bridge of conductive powder particles in EDM oil. Best surface quality was found to be 15 g/l by optimum graphite powder concentration in dielectric fluid[20]. Suspended nano-powders of SiC and Al_2O_3 in µ-EDM processes reduced the surface roughness by 14-24% in an average[21]. Research related to powder mixed near dry EDM (PMND-EDM) in terms of surface roughness, material removal rate, residual stress, tool wear rate and micro hardness was studied and it was proved that PMND-EDM was better in terms of performance enhancement characteristicsas compared to traditional EDM[22-25].

Although several researchers have conducted study to different hybrid forms of EDM but still there is lack of multi-objective optimization related study in this field. Therefore an effort has been made to optimize the effective parameters in order to enhance the productivity of existing EDM along with superior quality machined products.

2 Materials and Methods

This section includesmulti response characteristic optimization using utility function. A unified index term was used as criteria for overall effectiveness or usefulness by taking into consideration the individual utility of each different quality characteristics of the process. Afterwards, plotting was performed by using ANOVA technique for multi responses. At the end, confirmation experiments were performed for each response characteristics.

A number of different techniques have been established till date for multi response characteristic optimization. In this present research study, a simplified methodology by using utility concept with Taguchi's approach has been used to determine the optimal setting of process parameters for multi – objective responses. In fact this multi methodology was brain child of research work carried for different casestudy[26].

Series of experiments was planned for single response optimization and multi response optimization (utility concept) as per Taguchi L_9 (OA) as per Table 1. Each series of experiment was performed in three runs and a total of 27 experiments each were performed for analysis of material removal rate, surface finish, micro-hardness, residual stress and tool wear rate.

2.1 Development ofPowder Mixed Near Dry Electric Discharge MachiningSetup (PMND-EDM)

The setup for powder mixed near dry EDM was designed and developed in the precision manufacturing laboratory (Delhi Technological University, Delhi). The experimental setup for PMND-EDM is shown in Fig. 1 while its detailed line diagram is shown in Fig. 2.It has a minimal input of resources, was relatively environmentally friendly and also gives the desired response characteristics. This indigenously developed setup of PMND-EDM usedheterogeneous mixture of three phases (solid + liquid + gas) dielectric medium. There were several features in the panel of the setup. The panel of the setup includesdielectric mixing chamber, dielectric mist flow meter, manual regulators, and analogous gas pressure gauges which determine the working pressure of dielectric medium. Main features of the powder mixed near dry EDM setup are as follows:

a Mixing chamber

A mixing chamber was designed and manufactured in which oil along with metallic powder and glycerol was mixed in right proportion with compressed air supplied from the compressor at a high pressure, ranging from 0.4 MPa to 0.8 MPa. The designed chamber has a separate inlet for dielectric medium and, in case the pressure inside the chamber goes beyond operational limits, a safety valve was provided on top of it to release the pressure of compressed air.

b Flow meter

A flow meter was integrated with the setup, which can vary the flow rate of dielectric mist within range of 0-20 ml/min. As the flow meter is a transparent body, the flow rate of mist can be easily read from the calibration marking/scale mounted on the flow meter. To avoid metallic powder particle settling, glycerol was added in the tank along with dielectric fluid from the inlet of the tank.

c Mist pressure regulators

The setup also includes manually operated mist pressure regulators mounted on the control panel for regulating air and oil pressure. The setup comprises a display unit for oil and air pressure, which was analogous in nature.

Fig. 1 — Developed experimental setup for PMND-EDM.

Table 1 — Scheme for experiments

Symbol	Process parameters	Unit	Level 1	Level 2	Level 3
A	Tool diameter	mm	2	3	4
B	Mist flow rate	ml min^{-1}	5	10	15
C	Metallic powder concentration	g l^{-1}	2	5	8
D	Mist Pressure	MPa	0.4	0.5	0.6

*Values of other constant parameters: Machining time 10 mins; T_{on} 500µs; T_{off} 75 µs; Discharge current 12A; Voltage 30 V, Tool electrode Copper; Workpiece EN-31, Metallic zinc powder, powder grain size 15µm, glycerol 5%, EN-31 (30mmx15mmx15mm)

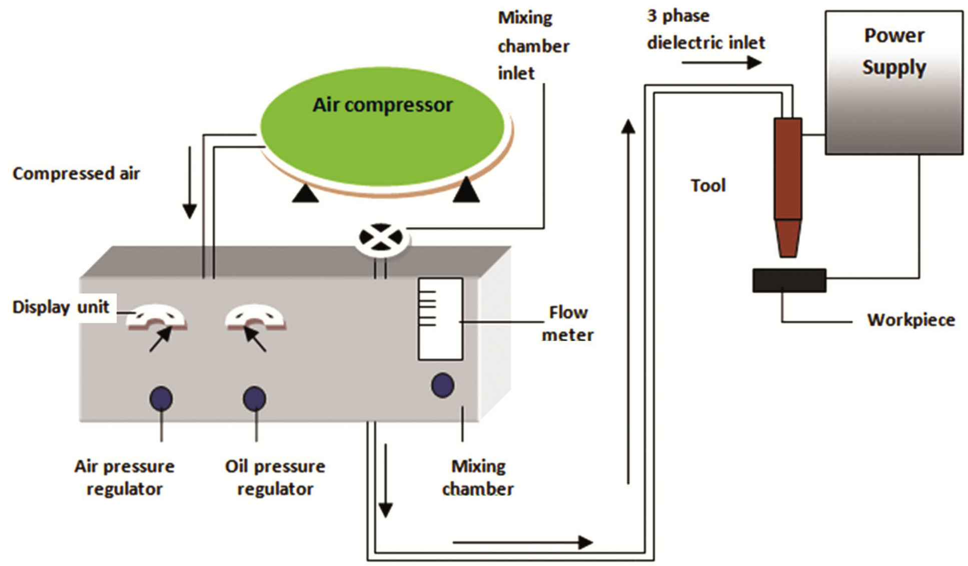


Fig. 2 — Line diagram for indigenous developed setup for PMND-EDM.

d Air compressor

Compressor (NU-air) of 2 horse power was used to supply compressed air. The maximum limit of pressure was 0.8 MPa. The working of air compressor was based on reciprocating mechanism**.**

2.2 Tool electrode design

The customized copper tools were developed in the precision manufacturing lab (Delhi Technological University, Delhi). The concept of design of tool electrodes was taken from previous study in field of near dry EDM[27]. Figures (3 and 4) shows the design feature of the tool electrodes. The other ends of hollow tubular copper were constant in dimension with 6.1 mm inner diameter and 8 mm outer diameter as shown in Fig. 5(a). The tool setup utilizes a flexible tube of 6 mm outer diameter inserted at the top end of the tool as shown in Fig. 5(b).

2.3 Multi-objective optimization of PMND-EDM through Taguchi method and Utility concept

Taguchi method along with utility concept was utilized for multi-response optimization (MRR, Ra, RS, MH and TWR) for determining the process parameters optimal settings in PMND-EDM. Utility concept was defined as the usefulness of the process with respect to the users' expectation. A unified index term was used as criteria for overall effectiveness or usefulness by taking into consideration the individual utility of each different quality characteristics of the process.

Suppose let us consider, Xi was the usefulness measure of a quality characteristics 'i' and if there are

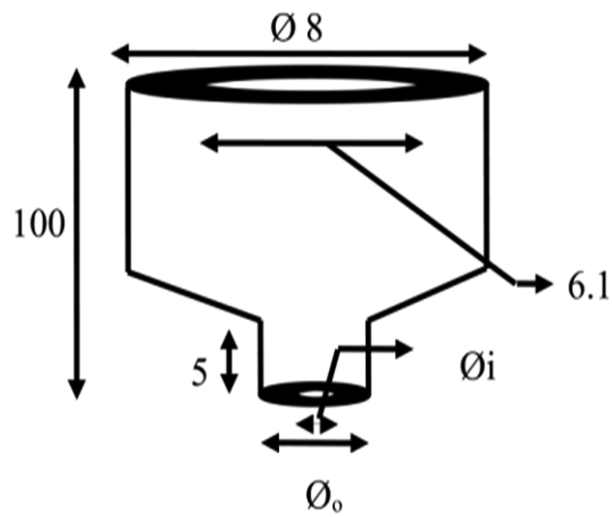


Fig. 3 — Design of tool developed for PMND-EDM; all dimensions in mm.

'n' attributes evaluating the outcome, so combined utility function was expressed as[28]:

$$U(X_1, X_2, \ldots, X_n) = f(U_1(X_1),\ U_2(X_2),\ \ldots\ldots,\ U_n(X_n)) \qquad \ldots (1)$$

where, Ui (Xi) was the utility of the ith attribute. The expression for sum of individual utilities was given by overall utility function for independent attributes by[28]:

$$U(X_1, X_2, \ldots\ldots, X_n) = \sum_{i=1}^{n} U_i(X_i) \qquad \ldots (2)$$

While, overall utility function after assigning weights to the attributes can be expressed as:

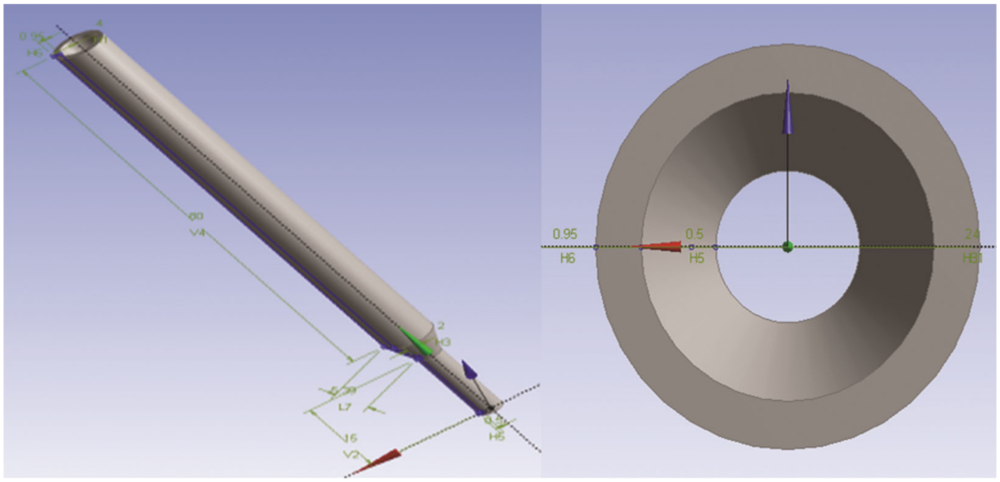


Fig. 4 — Design feature of developed tool.

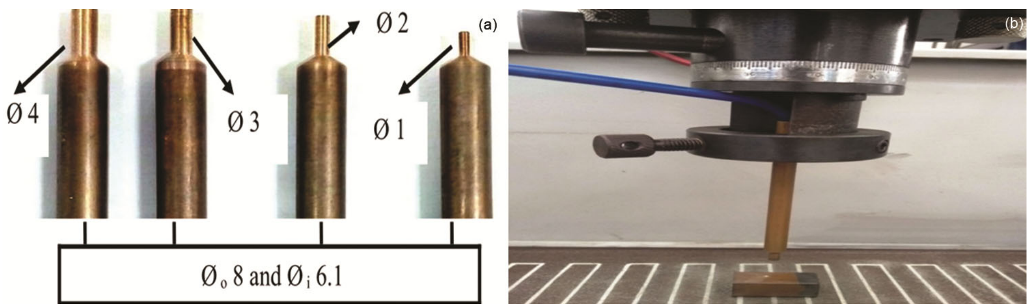


Fig. 5(a) — Hollow copper electrodes of different dimensions (all dimensions in mm), and (b) Tool setup.

$$U(X_1, X_2, \ldots\ldots, X_n) = \sum_{i=1}^{n} W_i U_i(X_i) \quad \ldots (3)$$

where, Wi was the weight assigned to the attribute *'i'*.

A scale (preference) was constructed for each quality characteristics for utility value determination. Preference numbers (P; (0-9)) were assigned for just acceptable and best value. The P_i number was given as[29]:

$$P_i = A \log\left(\frac{Xi}{Xi'}\right) \quad \ldots (4)$$

where, Xi= value of any quality characteristic or attribute i, Xi' = just acceptable value of quality characteristic or attribute i, A=constant, $P_i = 9$ (Assumed at optimum value);

Where, A was calculated by:

$$\boldsymbol{A} = \frac{9}{\log\frac{X^*}{X_i'}} \quad \ldots (5)$$

X^* = optimal best value of single response optimization (Refer Table 3), for $\boldsymbol{X_i}'$ (Refer Table 2)

The weightage should be assigned such that the following condition is satisfied:

$$\sum_{i=1}^{n} \boldsymbol{W} = \boldsymbol{1} \quad \ldots (6)$$

Therefore overall utility was defined as[29]:

$$\boldsymbol{U} = \sum_{i=1}^{n} \boldsymbol{U_i P_i} \quad \ldots (7)$$

The utility was considered higher the better and hence it was maximized, therefore quality characteristics will be optimized automatically (minimized or maximized).

For MRR; $= \frac{9}{\log\frac{0.346}{0.01}}$: $A_{mrr} = 5.847$

For Ra; $\boldsymbol{A} = \frac{9}{\log\frac{0.325}{1.77}}$; $A_{Ra} = -12.228$

For RS ; $\boldsymbol{A} = \frac{9}{\log\frac{106.40}{678}}$; $A_{RS} = 11.19$

For MH; $\boldsymbol{A} = \frac{9}{\log\frac{506.21}{55.63}}$; $A_{MH} = 9.3833$

For TWR; $\boldsymbol{A} = \frac{9}{\log\frac{0.41}{1.81}}$ $A_{TWR} = 13.97$

Table 2 — Individual outcomes for MRR, Ra, RS, MH and TWR in PMND-EDM

Exp. No	MRR ($mg\ s^{-1}$)			S/N dB	Ra (μm^1)			S/N dB	RS (MPa)			S/N dB	TWR (mg/min)			S/N dB	Micro-hardness HV			S/N dB
	R1	R2	R3		R1	R2	R3		R1	R2	R3		R1	R2	R3		R1	R2	R3	
1	0.07	0.06	0.09	-24.11	1.61	1.41	1.77	-4.10	565	558	530	-54.82	1.65	1.45	1.81	-4.31	175	100.25	338.93	41.52
2	0.22	0.10	0.21	-18.12	1.66	1.38	1.35	-3.34	621	551	550	-55.19	1.70	1.42	1.39	-3.57	450	350.78	345.08	49.69
3	0.37	0.30	0.36	-11.04	1.46	1.74	1.56	-4.03	510	659	678	-55.85	1.50	1.78	1.60	-4.24	505.63	501.78	540.89	52.47
4	0.01	0.01	0.01	-40.40	1.33	1.19	1.07	-1.59	370	361	340	-51.05	1.37	1.23	1.11	-1.87	59.37	45.96	50.26	32.39
5	0.03	0.02	0.05	-30.29	0.37	0.51	0.74	5.01	145	169	186	-44.48	0.41	0.55	0.78	4.44	112.23	259	189	42.13
6	0.08	0.05	0.01	-32.60	0.87	0.81	0.86	1.44	239	279	280	-48.51	0.91	0.85	0.90	1.04	132.23	55.63	62.38	34.96
7	0.07	0.07	0.19	-23.21	0.73	0.61	0.94	2.24	251	214	311	-48.35	0.77	0.65	0.98	1.81	148.96	192.85	200.56	43.15
8	0.10	0.07	0.10	-22.39	0.51	0.71	0.57	4.40	230	209	191	-46.46	0.55	0.75	0.61	3.84	237	215	350.22	46.23
9	0.08	0.08	0.10	-22.74	1.36	1.51	1.54	-3.35	556	501	587	-54.79	1.4	1.55	1.58	-3.59	201	222.37	245	45.11
	Overall mean MRR ($\overline{MRR}$)= 0.11mg s^{-1}				Overall mean Ra ($\overline{Ra}$) = 1.113 µm				Overall mean RS ($\overline{RS}$)= 394.11 MPa				Overall mean TWR ($\overline{T}$) = 1.15 mg/min				Overall mean micro-hardness ($\overline{MH}$)= 232.86			

2.3.1 Algorithmfor multi-response optimization for MRR, Ra, RS, MH, and TWR in PMND-EDM

a To find optimum value of response characteristics separately using single response taguchi optimization technique
b Construction of preference scales for each response characteristic from the experimental data using Eqs. (1-7).
c Assignment of weightage to satisfy Eq. 6.
d Finding the utility value for each product using Eq. 7.
e Application of utilities in the orthogonal array as per taguchi design of experiments, and finding the S/N ratios.
f Analysis of the results.
g Determination of optimal setting of process parameters for optimization of the utilities.
h Prediction of response characteristics by using optimal settings of parameters.
i Conducting confirmation experiments and their comparison with predicted value for validation of the results.

Taguchi L_9 optimization has been implemented for parameters tool type, flow rate, powder concentration and mist pressure and the results for individual outcomes are shown in Table 2 while Table 3 shows the values of response at optimal process parameters conditions.

3 Results and Discussion

3.1 Calculation of utility value

Following equation were obtained for preference scale for MRR (PMR), Ra (PRa), RS (PRS), MH (PMH), and TWR (PTWR),29

$$P_{mrr} = A_1 * \log\frac{\boldsymbol{X_{mrr}}}{\boldsymbol{0.01}} \quad \text{... (8)}$$

Table 3 — Optimal setting and values of process parameters for different output responses as per single objective optimization

Response	Process parameters at optimum vale	Predicted optimal values
MRR	A1, B3, C3, D3	0.346 mg/s
Ra	A2, B2, C3, D2	0.325 (µm)
RS	A2, B2, C1, D2	106.40 (MPa)
MH	A1, B2, C3, D3	506.21 HV
TWR	A2, B2,C3,D2	0.41 mg/min

$$P_{Ra} = - A_2 * \log\frac{\boldsymbol{X_{Ra}}}{\boldsymbol{1.77}} \quad \text{… (9)}$$

$$P_{RS} = -A_3 * \log\ \frac{\boldsymbol{X_{RS}}}{\boldsymbol{678}} \quad \text{… (10)}$$

$$P_{MH} = A_4 * \log\frac{\boldsymbol{X_{MH}}}{\boldsymbol{55.63}} \quad \text{... (11)}$$

$$P_{TWR} = -A_5 * \log\frac{\boldsymbol{X_{TWR}}}{\boldsymbol{1.81}} \quad \text{… (12)}$$

The selected quality characteristics were assigned with equal weighs (1/5 each), as all the characteristics were important equally while the equation for utility value calculations was given as[29]:

$$U\ (n,\ r) = P_{MRR}\ (n,\ r) \times W_{MRR} + P_{Ra}(n,\ r) \times W_{Ra} + P_{MH}\ (n,\ r) \times W_{MH} + P_{RS}\ (n,\ r) \times W_{RS} + P_{TWR}\ (n,\ r) \times W_{TWR} \quad \text{... (13)}$$

where, n= number of experiments (1, 2, 3…..9); r = number of repetitions. The utilities values were used in L_9 array, for which the experimental results are given in Table 4. While, main effects and average values of output responses MRR, Ra, RS, MH and TWR in PMND-EDM are given in Table 5. The ANOVA was performed and its pooled data for raw and S/N values is given in Table 6.

The average % value was calculated for utility for different parameters. After that main effects % of micro-hardness were calculated by expression (L2-L1) and (L3-L2). Finally the difference between L2, L1 and L3, L2 was calculated. Analysis of variance was done for TWR S/N ratio on the results obtained at 95% confidence level.

Some of the machined samples are shown in Fig. 6. Based upon the results obtained by pooling, the plot between utility and process parameters is shown in Fig. 7.

The analysis for utilities value was done for mean responses (mean utility) and S/N ratios by considering the higher the better approach for utility. The data from Table 6 was used for plotting of utility in Fig. 7 with respect to different parameters at different levels. It was observed that process parameters that process parameter A at level 2 (A_2), process parameter B at level 3 (B_3), process parameter C at level 3 (C_3) and process parameter D at level 2 (D_2) were most significant in enhancing the utility of the process within the selected parametric range. It was observed that tool diameter (A), mist flow rate (B), metallic powder concentration (C) and mist pressure (D) were significant in affecting the utility value and the S/N ratios as per ANOVA. The utility increases with increase in dimensions of tool diameter because the flushing takes place more efficiently which provides better cooling condition at the tool tip which brings down the temperature at the sparking ends of the hollow tool electrodes. However with further increase in tool diameters there was no increase in the utility as seen in Fig. 7(a).

Table 4 — Utilities values of MRR, Ra, RS, MH, and TWR

Exp. No.	Utilities values			*S/N* [dB]
	R1	R2	R3	
1	1.11	2.21	2.96	6.41
2	4.22	4.32	4.79	12.95
3	3.66	4.34	4.93	12.68
4	6.01	6.34	6.78	16.09
5	5.1	5.44	5.76	14.70
6	7.2	7.76	7.99	17.67
7	3.32	3.65	3.91	11.19
8	4.21	4.27	4.52	12.73
9	6.11	6.49	6.78	16.20

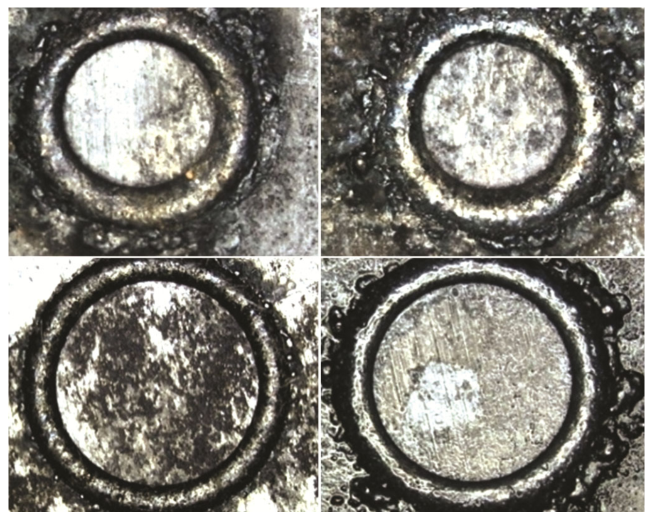


Fig. 6 — Machined samples.

Table 5 — Main effects and average values of output responses MRR, Ra, RS, MH, and TWR in PMND-EDM

LEVEL	Tool Diameter (A) S/N	Tool diameter (A) Raw data	Flow rate (B) S/N	Flow rate (B) Raw data	Powder concentration (C) S/N	Powder concentration (C) Raw data	Pressure (D) S/N	Pressure (D) Raw data
L1	8.12	3.61	8.71	4.03	9.77	4.69	9.93	4.66
L2	14.36	6.48	11.67	4.73	13.29	5.76	12.13	5.24
L3	11.58	4.80	13.68	6.14	11.00	4.45	11.99	5
L2-L1	6.24	2.87	2.95	0.70	3.515203	1.06	2.20	0.57
L3-L2	-2.78	-1.68	2.00	1.40	-2.28	-1.30	-0.13	-0.23
DIFFERENCE	-9.02	-4.55	-0.95	0.69	-5.80	-2.37	-2.34	-0.81

*L1, L2, L3 represent levels 1, 2 and 3 respectively of parameters. (L2-L1) is the average main effect when the corresponding parameter changes from Level 1 to Level 2. (L3-L2) is the main effect when the corresponding parameter changes from Level 2 to Level 3.

Table 6 — ANOVA pooled S/N and raw data for multi responses MRR, Ra, RS, MH, and TWR in PMND-EDM

Parameters	SS (S/N)	SS Raw	Fe Raw	Fe S/N	Ve S/N	Ve Raw	SS' Raw	SS' S/N	P S/N	P Raw	F Ratio Raw	F Ratio S/N
Tool diameter	58.69	37.45	2	2	29.34	18.72	37.0	49.56	39.86	51.1	83.72	6.43
Mist flow rate	37.42	20.72	2	2	18.71	10.36	20.27	28.29	22.75	28.0	46.32	4.10
Metallic powder conc.	19.09	8.68	2	2	9.54	4.34	8.23	9.96	8.01	11.37	19.41	2.09
Mist Pressure	*	1.52	2	*	*	0.76	1.07	*	*	1.48	3.39	*
Error	9.12	4.02	18	2	4.56	0.22	5.81	36.50	29.36	8.03	-	-
Total (T)	124.34	72.40	26	8			72.40	124.34	100	100	-	-

Secondly flow rate was found to be most influential at 3rd level in increasing the utility value as shown in Fig. 7(b). At this level, the flow rate of the dielectric medium at 15 ml/min was most optimum in providing suitable normal discharges at the machining zone along with powder additives which results in improved utility.

The utility value was found to be highest at 3rd level of powder additives (metallic) concentration as shown by the trend of plot in Fig. 7(c). The utility value increased with respect to increase in metallic powder concentration which can be observed in the Fig. 7(c). Powder concentration was significant factor affecting the utility. At low concentration the heat dissipation was not proper due to small discharge gap but with increasing of powder concentration, discharge gap was enlarged. This resulted in improvement of cooling and machining process. All these factors resulted in achieving the highest utility value at 3rd level of process parameter. The utility shows the increasing trend when the air pressure changes from 0.4 MPa to 0.5 MPa as shown in Fig. 7(d). With increase of air pressure there were more molecules at the inter electrode gap which enhances discharging. Due to this phenomenon, there was improvement in deionization effect. Effects of abnormal short circuit and arc discharge were reduced which eventually led to better heat dissipation and reduced heat transfer. All these factors contributed to increase in utility till 0.5 MPa. But with further increase of pressure the gap voltage increases due to which the plasma generated was not uniformly distributed and improper machining takes place which led to decrease in utility value. The deposited molten layers in PMND-EDM are shown in Fig. 8 while conventional EDM'ed surfaces are shown in Fig. 9.

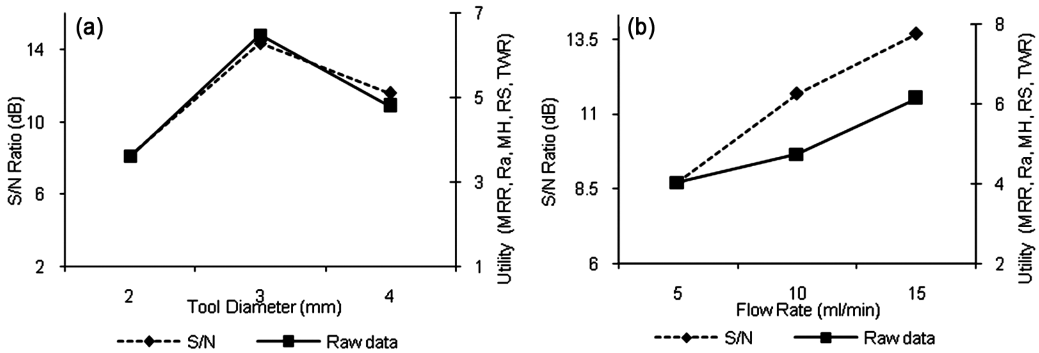


Fig. 7(a) — Effect of tool type on utility, and (b) effect of flow rate on utility.

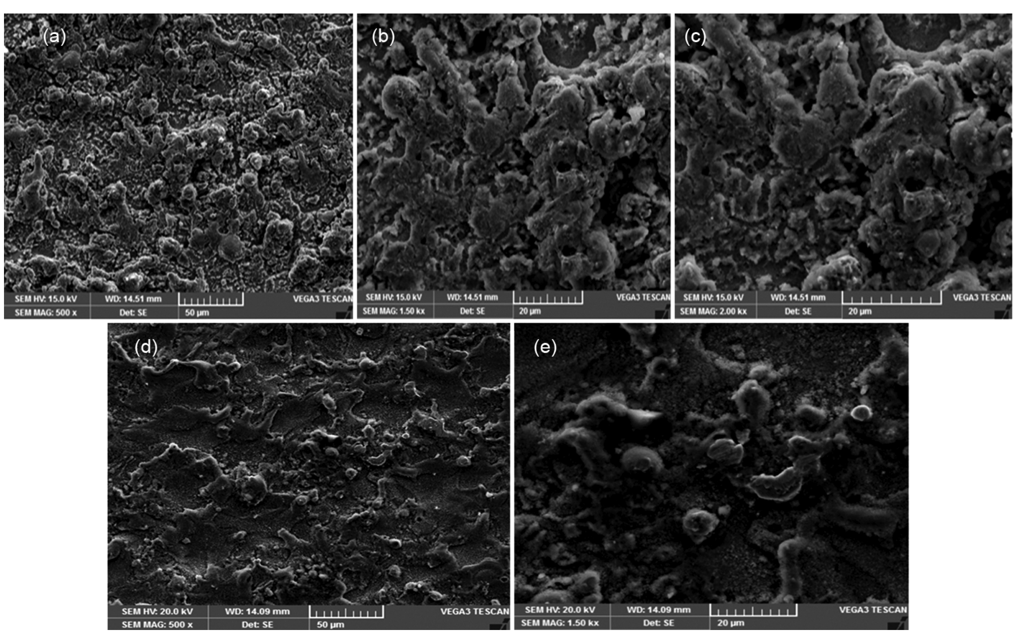


Fig. 8 — Material deposit layers on machined surface at different magnification factor.

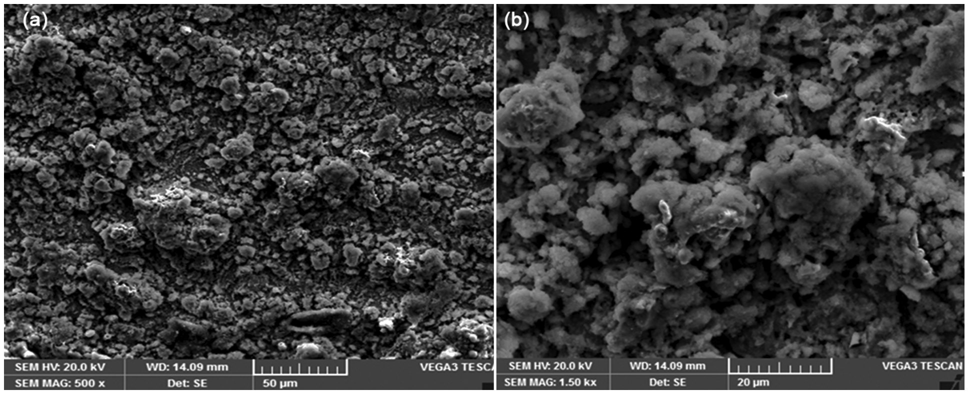


Fig. 9 — SEM image of machined samples by normal EDM at different magnification factor.

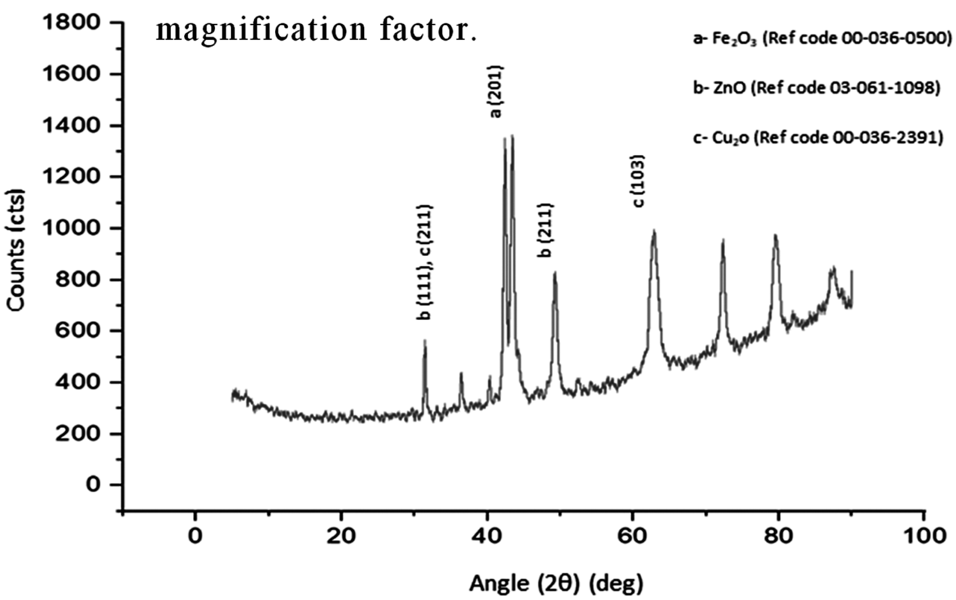


Fig. 10 — XRD results of surface produced by PMND-EDM.

The analysis for X-ray diffraction of the finished workpiece was performed with X'Perthighscoretool. The XRD graph for the machined workpiece was shown in Fig. 10. The maximum peak in the XRD graphs was found for iron oxide at 2θ degree for (201) plane with a cubic crystal system. Additional peaks were found for zinc oxide at 2θ degree of 35.61 degree and 50.48 degree at planes (111) and (211) planes respectively for a cubic crystal system. Some more peaks were found for copper oxide at 2θ of 37.28 degree and 51.23 degree at plane (211), and (103) respectively with hexagonal crystal system. During the XRD interpretation some groups with lower peaks were discounted.

It was also observed that some molten parts of the tool electrode got embedded in the machined workpiece. The copper composition of molten copper material embedded in the machined workpiece was measured by energy dispersive spectroscopy X-Ray (EDAX) as shown in Fig. 11(a and b).

3.2 Estimation of performance characteristics (Utilities of MRR, Ra, MH, RS, and TWR)

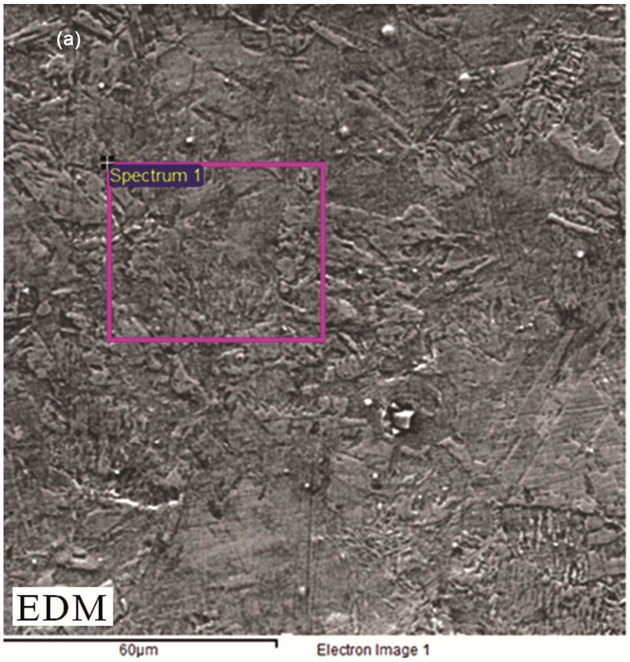
Estimation ofresponse characteristic can be determined by using Eq. 14, [**29**] as:

$$\mu = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - 3\overline{T} \quad \ldots (14)$$

where, μ= Predicted mean; T = Mean MRR, mean RS, mean Ra, mean, MH, mean TWR;

The confidence interval of confirmation experiments at 95 % can be determined by Eq.15:

$$CI_{CE} = \sqrt{F_a(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \ldots (15)$$



Spectrum processing:
Peak possibly omitted: 4.519 keV

Processing option: All elements analyzed (Normalised)
Number of iterations = 3

Standard:
C C 1-Jun-1999 12:00 AM
O_2 O_2 1-Jun-1999 12:00 AM
Cu Cu 1-Jun-1999 12:00 AM
Fe Fe 1-Jun-1999 12:00 AM

Element	Weight%	Atomic%
C	22.07	53.121
O_2	5.966	10.780
Fe	53.56	27.730
Cu	18.394	8.369
Totals	100.00	

Fig. 11(a) — EDAX spectrum for the region of machined sample.

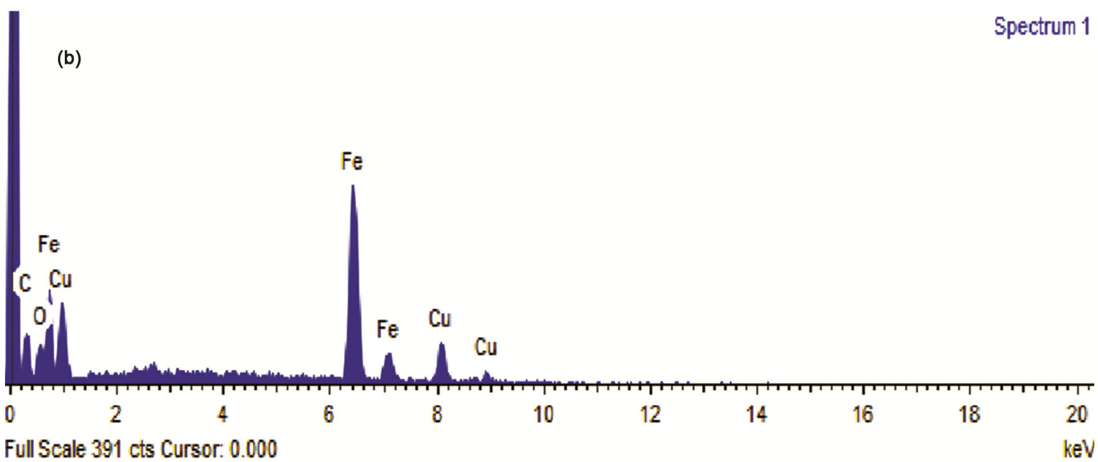


Fig. 11(b) — EDAX (Energy Dispersive Spectroscopy X-Ray) image of a machined sample by PMND-EDM.

where, F_α (1, fe) = the F ratio at the confidence level of (1 –α) against DOF 1, $F_{0.05}$ (1, 18) =3.5546 (Tabulated), $n\_eff = N/(1+[\text{DOF}])$, N (total number of experiments) = 27, Treatment = 9, repetition = 3. R (sample size for confirmation experiments) = 3, f_e (error DOF) = 26.

a Material removal rate

$\mu_{mrr} = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - 3\overline{MRR} = 0.63$

The predicted optimal range of confidence interval of conformation experiments (CI_{CE}) is:

CI_{CE} = +/- 0.24

$\mu_{mrr} - CI_{CE} < \mu_{mrr} < \mu_{mrr} + CI_{CE}$

$0.39 < 0.63 < 0.87$

b Surface finish

$\mu_{Ra} = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - \overline{Ra} = 0.79$

The predicted optimal range of confidence interval of conformation experiments (CI_{CE}) is:

CI_{CE} = +/- 0.06

$\mu_{Ra} - CI_{CE} < \mu_{Ra} < \mu_{Ra} + CI_{CE}$

$0.73 < 0.79 < 0.85$

c Residual stress

$\mu_{RS} = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - 3\overline{RS} = 286$

The predicted optimal range of confidence interval of conformation experiments (CI_{CE}) is:

CI_{CE} = +/- 0.67

Table 7 — Confirmation experiments for quality characteristics

Exp. No	MRR	Ra	RS	MH	TWR
1	0.16	1.21	271.83	255.01	0.91
2	0.43	0.78	290.12	271.43	1.21
3	0.25	0.98	278.91	266.71	1.01
Overall Average	0.28	0.99	280.28	264.38	1.04

$\mu_{RS} - CI_{CE} < \mu_{RS} < \mu_{RS} + CI_{CE}$

$285.33 < 286 < 286.67$

d Micro-hardness

$\mu_{MH} = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - 3\overline{MH} = 249$

The predicted optimal range of confidence interval of conformation experiments (CI_{CE}) is:

$CI_{CE} = +/- 0.42$

$\mu_{MH} - CI_{CE} < \mu_{MH} < \mu_{MH} + CI_{CE}$

$248.58 < 248 < 249.42$

e Tool wear rate

$\mu_{TWR} = \overline{A_2} + \overline{B_3} + \overline{C_3} + \overline{D_2} - 3\overline{T} = 1.07$

The predicted optimal range of confidence interval of conformation experiments (CI_{CE}) is:

$CI_{CE} = +/- 0.12$

$\mu_{TWR} - CI_{CE} < \mu_{TWR} < \mu_{TWR} + CI_{CE}$

$0.95 < 1.07 < 1.19$

3.3 Confirmation of experiments for utilities (MRR, Ra, RS, MH, and TWR)

At optimum settings, the experiments were performed as suggested by utility concept and Taguchi analysis. The values obtained are given in Table 7. It was noticed that the values lies between the prescribed limit or range with 95 % confidence interval.

4 Conclusion

- Powder mixed near-dry electric discharge machining (PMND-EDM) is an advanced method of machining very hard conductive materials with complex geometries which are difficult to be machined by other conventional method.
- PMND-EDM is an eco-friendly process which uses minute amount of metal working fluids (MWF) along with conductive metallic powders for machining purposes. Improvement in heat distribution by the bridging effect at the machining gap due to presence of metallic powder particles resulted in obtaining better quality surfaces.
- For the multi response optimization, the optimized results for improved material removal rate, improvement of surface finish, enhanced micro-hardness, reduced residual stress and tool wear rate were 0.63 (mg/s), 0.79 (µm), 249 (HV), 286 (MPa) and 1.07 (mg/min) respectively. The optimized values were obtained at Tool diameter (3mm), flow rate of mist (15 ml/min), concentration of metallic powder (8 gm/l) and mist pressure (0.5 MPa) of dielectric medium.
- The 95% confidence interval of the predicted mean for the material removal rate was 0.39 < MRR < 0.87; for Surface finish was 0.73< Ra < 0.85; for Residual stress was 285.33< RS< 286.67; for Micro-hardness was 248.58< MH< 249.42; for Tool wear rate was 0.95 < TWR < 1.19.

References

1 Kung K Y, Horng J T, & Chiang K T, *Int J Adv Manuf Tech*, 40 (2009) 95.

2 Goyal S, & Singh R K, *Int J Sci Engg Tech*,3 (2014) 56.

3 SinghS, & Singh J*, Int J Enh Res Sci Tech Engg*, 3 (2014) 291.

4 Aliyu A A, Musa H, & Rohani J M, *Adv Mat Res* (2013) 845.

5 Dhakar K, Pundir H, & Dvivedi A*, J Prod Engg* , 17 (2014) 25.

6 Razak M A, Abdul A M, & Nanimina A M, *Int J Mat Mech, Manuf,* 3 (2015) 40.

7 Kumar S, Grover S , & Walia R S, *Int J Interact Des Manuf*, 12 (2016) 225.

8 RanaR, Walia R S, Murtaza Q , & Tyagi M, *AES-ATEMA International Conference 29 international conference TORONTO*, Canada (2016).

9 Zain Z M, Ndaliman M B, Khan A A, & Ali M Y, *J Mech Engg Sci*, 228 (2014) 3374.

10 GillA S, & Kumar S, *Mat Manuf Process*, 31 (2016) 514.

11 Rahul, Datta S, Biswal B B, & Mahapatra S S, *Arab J Sci Engg*, 42(2017) 1999.

12 Pattabhiraman A, Marla D, & Kapoor S G, *J Mic NanoManuf*, 3 (2015) 1.

13 Shen Y, Liu Y, Zhang Y Y, Dong H, Sun W, Wang X, Zheng C, & Ji R, *Int J Mach Tool Manuf,* 93 (2015) 19.

14 Singh B, Kumar J, & Kumar S, *Mat Manuf Process*, 29 (2014) 287.

15 Singh B, Kumar J, & Kumar S, 30 (2015) 303.

16 Singh B, Kumar J, & Kumar S, *Mat Manuf Process*, 31 (2016) 456.

17 Wu K L,Yan B H, Huang F Y, & Chen S C, *Int J Mach Tool Manuf*, 45 (2005) 1195.

18 Bai X, Zhang Q H, Yang T Y, & Zhang J H, *Int J Adv Manuf Technol*, 68 (2013) 1757.

19 Bai X, Zhang Q H, Zhang J H, Kong D, & Yang T, *J Manuf Process*, 15 (2013) 474.

20 Prihandana G S, Mahardika M, Hamdi M, Wong Y S, Miki K, & Mitsui K, *Int J Prec Engg Manuf,* 14 (2013) 1817.

21 Tan P C, Yeo S H, & Tan Y V*, Int J Prec Engg Manuf*, 9 (2008) 22.

22 Sundriyal S, Vipin, & Walia R S*, Strojniškivestnik J Mech Engg*, 66 (2020) 184.

23 Sundriyal S, Vipin, & Walia R S, *Strojniškivestnik – J Mech Engg*, (2020) 243.

24 Sundriyal S, Vipin, & Walia R S, Advances in Unconventional Machining and Composites, Springer Nature Singapore Pte Ltd, (2020).

25 Sundriyal S, Walia R S, Vipin, & Tyagi M, Materials Today: Proceedings DOI: 10.1016/j.matpr.2019.09.031

26 Byrne D M, & Taguchi S, *Quality Progress*, (1987) 19.

27 Shen Y, Liu Y, Sun W, Zhang Y, Dong H, Zheng C, & Ji R, *J Material Process Technol* 233 (2016) 9.

28 Derek W B, John Wiley, & Sons: New York, (1982) 257.

29 Walia R S, Shan H S, & Kumar P, *Material Manuf Process*21, 8 (2006)907.