APEM journal

Advances in Production Engineering & Management
Volume 14 | Number 3 | September 2019 | pp 323–332
https://doi.org/10.14743/apem2019.3.330

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Effect of aluminium and chromium powder mixed dielectric fluid on electrical discharge machining effectiveness

Modi, M.[a,*], **Agarwal, G.**[b]

[a]Department of Mechanical Engineering, Acropolis Institute of Technology and Research, Indore, Madhya Pradesh, India
[b]Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur, Rajasthan, India

A B S T R A C T

This article studied the impacts of using different powders on the productivity of electro discharge machining (EDM) of Nimonic 8OA alloy. The powders used for experiments are chromium (Cr) and aluminium (Al), though these powders are in contrasts in their thermo-physical characteristics. With the mixing of these powders in dielectric fluid, effect on surface roughness (*SR*), material removal rate (*MRR*), and mechanism of the machining process have been studied in this research work. On going through the results of experiments, it was observed that even volumetric proportion of powders, size of molecules, its density, electric resistance, and heat conductivity of additives were vital parameters that altogether influenced the productivity of powder mixed-electro discharge machining (PMEDM) process. With addition of proper ratio of powders in dielectric fluid, it enhanced the material removal rate, and consequently, reduced the surface roughness. Under a similar molecule volumetric proportion tests, the minutes suspended molecule size of powder prompted the largest material removal rate and consequently, the surface roughness increased. Conclusion is that adding chromium powder improves to the highest material removal rate, but poor surface finish while adding aluminium powder has the reverse effects.

A R T I C L E I N F O

Keywords:
Powder mixed-electro discharge machining (PMEDM);
Aluminium powder;
Chromium powder;
Dielectric fluid;
Productivity;
Material removal rate (*MRR*);
Surface roughness;
Nimonic 80A alloy

**Corresponding author:*
manojmnitjaipur1@gmail.com
(Modi, M.)

Article history:
Received 12 April 2019
Revised 13 September 2019
Accepted 15 September 2019

1. Introduction

Electrical discharge machining (EDM) has been an essential procedure for the die and tool making enterprises for a long time. This machining procedure is finding growing utilization in industries due to the feasibility of machining geometrically intricate shapes irrespective of the hardness of materials that are very tough by utilizing the traditional machining procedures [1]. In EDM, managed distinct electrical sparks between the electrode and the work-piece would produce arcing, i.e. concentration of spark when an excessive amount of scattered tiny material remains in the inter-electrode gap in light of the inability to clear scattered tiny material. Arcing occurs when a succession of sparks strikes more than once on a similar spot.

This, in the end, causes harm to the cathode of the apparatus and the work-piece if the controller of the machine does not stop it quickly. The EDM procedure in this manner ends up unsteady and ineffective. To enhance the effectiveness of ED machining, it is necessary to upgrade process steadiness. This presently remains a major tough task. Kiyak *et al*. [2] conducted experimental work on EDM with AISI P20 tool steel. They examined the impact of process factors on surface roughness (*SR*) in EDM and observed that littler values of ampere-current, pulse-on-duration and proportionately greater value of pulse-off-duration produced a descent surface finish (*SF*). Hasçalık *et al*. [3] did experimental work on EDM with Ti6Al4V and different tool materials. They investigated that the *MRR*, *SR*, electrode wear, and average white layer thickness (*AWLT*) ascend with increment in ampere-current and pulse-on-duration. They also examined the surface-integrity of work with EDM process factors. Fonda *et al*. [4] conducted experimental work on EDM with Ti6AL4V work-piece and reported the impact of properties of the material on EDM efficiency. Chow *et al*. [5] did experiments on micro-slit electrical discharge machining (MS EDM) with Ti6Al4V workpiece. They examined the impact of silicon carbide powder blended with dielectric fluid (DF) on *MRR*, *SR*, and gap size (*GS*). Chow *et al*. [6] conducted experiments on EDM with Ti6Al4V. They observed that the silicon-carbide and aluminium powder blended with kerosene is liable for increasing the gap-size among the electrodes. The developed *GS* escalates the debris removal rate (*DRR*), and material removal depth (*MRD*). They also examined the impact of adding the powders molecule in dielectric fluid on *MRD* and on the *SR*. Zhao *et al*. [7] did experimental work on EDM with steel as a workpiece and red copper as a tool material. They described the mechanism of EDM, and powder mixed electrical discharge machining (PMEDM) process and found that PMEDM process upgrades the machining efficiency and *SF* in contrast with EDM process by picking the suitable factors set. Pecas *et al*. [8] performed the experiments on PMEDM with and without silicon powder blended DF. They reported that the mixing of powder-molecule in DF alters few process parameters and makes the circumstances to accomplish the peak surface quality in vast regions. Pecas *et al*. [9] conducted experiments on PMEDM with AISI H13. They explained that silicon powder blended DF enhances the process polishing-effectiveness and reduces the white layer thickness (*WLT*), depth, and diameter of the cavity. They reported that exact-control of the flushing-rate and volumetric proportion of powder is the requirement for achieving the advancement in the shining ability of process. Kozak *et al*. [10] conducted experiments on EDM with tool steel. Experiments were conducted with kerosene and with powder blended demonized water. They narrated about the impact of process factors on *MRR* and *SR* with various volumetric proportions of powders in dielectric liquids. Kansal *et al*. [11] narrated that DF with powder in PMEDM process reduces the dielectric insulating-strength and enhances the gap among the tool and work. They also found that the addition of powder enhances the process-outcomes. Kansal *et al*. [12] did experimental work on PMEDM of AISID2 die-steel with silicon powder blended DF. They found that the chosen process factors have a remarkable impact on *MR*. Pecas *et al*. [13] carried out the experiments on EDM with AISI H13 work and copper as an electrode with and without silicon powder blended DF. The outcomes of the experiments accomplished confirm a straight connection among the electrode area and the surface quality measures and also a noteworthy execution enhancement when the powder blended DF is utilized. Modi *et al*. [14] described the detail of EDM and PMEDM process and developed the mathematical models of process responses through dimensional analysis (DA) method. Modi *et al*. [15] did the experiments on EDDSG with Ti6AL4V. They reported that Grey-TM methodology enhances machining effectiveness.

Marashi *et al*. [16] reported the intensive review of the impact of powder addition on the mechanism of EDM process, the most influential powder parameters, future patterns in this technology, and a relative survey of powder materials is additionally exhibited in this article to facilitate a deeper insight into powder selection parameters for future investigations. They also portrayed that main factors which must be considered in PMEDM are powder size, type, and concentration. At last in this paper, PMEDM research patterns, gaps, findings, and industrial troubles are discussed extensively. Kalaman *et al*. [17] presented the study about the introduction and survey of the research work in PMEDM. The investigations concerning machining efficiency, surface integrity, and generation of functional surfaces are presented and discussed in the light of current research patterns. Attempts made to improve biocompatible surfaces with the utilization of the process additionally included clarifying the future patterns in PMEDM. Daneshmand *et al*. [18] conducted the experiments on EDM with CK45 steel to examine the impacts of current, voltage, and pulse frequency on *SR*. In this test work, kerosene is utilized as dielectric fluid and copper as an electrode. Design of experiments with non-linear regression model was utilized to estimate the process response. Raju *et al*. [19] carried out an extensive literature study to provide a total description on μ-EDM process, its necessities, execution and applications. The experiment frame-ups and its subsystems, trial studies and optimizing techniques, created micro feature and different applications are additionally described in this paper.

In spite of the favorable outcomes, the EDM procedure with added substances is not yet utilized broadly in industry. One of the essential reasons is that numerous key factors of the PMEDM procedure, incorporating the mechanism of machining with different added substances, which are not surely known. The complicated nature of this procedure, particularly from the impacts of the thermo-physical characteristic of added powders, subsequently, justifies the extra investigation. The objective of the article is to make a precise investigation of the impacts of powder properties in DF on the effectiveness of ED Machining with the end goal to improve the applicability of the procedure in the industry. The release-transivity, particularly, determines the frequency of sparking that controls the whole *MRR*, though the powder-particles striking impact has an insignificant cutting impact providing primarily to the enhancement of the *SF*.

2. Materials, methods and experimental set-up

This paper uses nomenclature given in Appendix A.

Nimonic 80A nickel-chromium alloy is widely utilized in several industries due to its resistance against to corrosion and high strength applications because of excellent mechanical properties at eminent temperature. PMEDM is an efficient process for machining hard-to-cut material like Nimonic 80A. The composition of Nimonic 80A is 19.82 % Cr, 2.59 % Ti, 1.57 % Al, 2.63 % Fe, and balance % Ni. The PMEDM frame-up contains the servo arrangement of ZNC EDM machine (ZNC 50 × 30, die sinking type, EMT ltd., India) is utilized to keep up the predetermined separation among the tool and work, whose width rely on the gap voltage. Total tests were conducted on this frame-up with Nimonic 80A as a work-piece and bronze as an anode. For this reason, an independent fitting has been planned and created within the EDM tank; a different acrylic tank having the capacity of 36 liters of DF was settled on the EDM table with bolts. The different stirrer and pump arrangement are settled in the acrylic tank. The stirrer and pump arrangement is utilized for proper mixing and circulation of powder blended dielectric liquid in the inter-electrode gap. The schematic diagram of this frame-up is displayed in Fig. 1.

Table 1 displays the EDM process factors. The thermal characteristics of aluminim, and chromium powder molecules are depicted in Table 2. Fig. 2(a) displays the mechanism of machining in PMEDM process and the occurrence of series discharge in PMEDM process is depicted in Fig. 2(b).

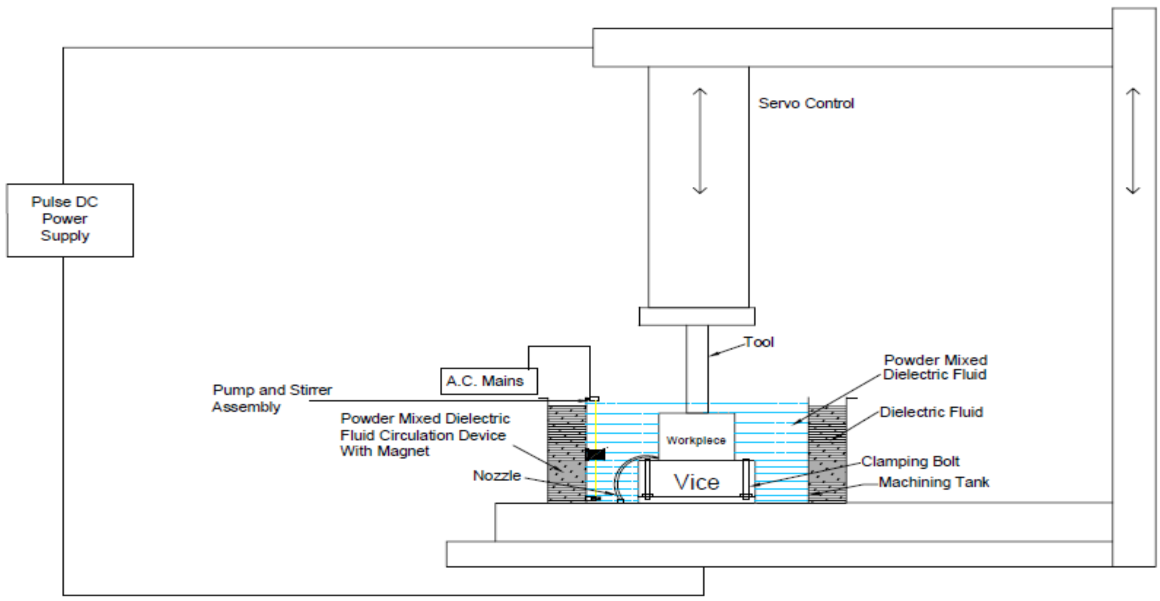
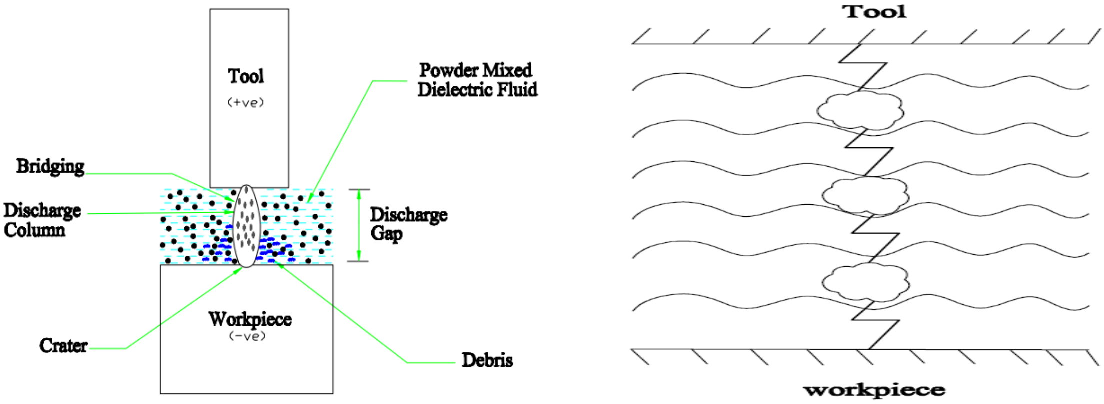


Fig. 1 The schematic diagram of PMEDM frame-up



(a) (b)

Fig. 2 (a) Mechanism of machining in PMEDM processes, (b) Occurrence of series discharge

Table 1 EDM process factors

Electrode (+)	Bronze (ϕ = 10 mm)
Workpiece (-)	Nimonic 80A (ϕ = 20 mm)
Time of machining	Half hour
Dielectric fluid	Kerosene
Flow rate of dielectric fluid	4 l/ min
Powder	Aluminium, Chromium
Powder sizes	0.080-0.090 µm and 15-20 µm
Volumetric proportion of powder molecules (cm^3/l)	0.30, 0.60, 1.20
Current I (A)	2.0, 5.0
T_{on} (µs)	5, 30, 80
Duty cycle	0.67

Table 2 Powders properties

Powder	Density ρ, (kg/cm^3)	Thermal conductivity λ, W/(cm · K)	Electrical resistivity ρ, (Ω · cm)	Melting-point-temperature T_m, (K)	Specific heat C, Cal/(kg · K)
Chromium	7.16×10^{-3}	0.67	2.60	2148	0.110×10^3
Aluminium	2.70×10^{-3}	2.38	2.45	933	0.215×10^3

In these experiments, the levels of input parameters have been selected after the conduction of pilot experiments. The *MRR*, *GS*, and *SR* have been measured as the responses in this experimental work. We conducted the various experiments on PMEDM setup and made the graphs between the input variables and the output responses. From these graph, conclusions were drawn.

3. Results and discussion

3.1 Impacts of powder properties on gap size

Fig. 3 displays the effect of mixing of Al and Cr powder particles in the DF on the *GS*. It was observed that the gap among the anode and cathode with Al powder is marginally more when contrasted with the Cr powder blended dielectric liquid was found attributable to its littler electrical-resistivity. This littlest *GS* would be accountable for extreme gas blast pressure with Cr powder. Furthermore, the Cr powder density is greater than the Al powder density, resulting in arcing rather sparking. Consequently, *SR* is higher with Cr when contrasted with Al powder. Al powder delivered the better *SF* trailed by Cr powder.

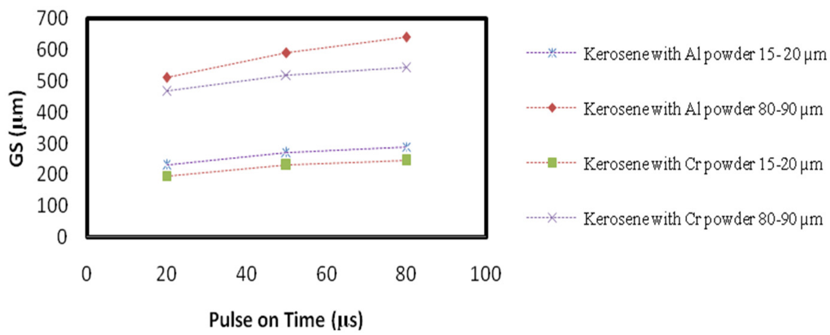


Fig. 3 The impact of mixing of Al, and Cr powders particle on the gap size (I = 5 A, DC = 0.67, Volumetric proportion = 0.60 cm³/l)

3.2 Impacts of powder particle size on material removal rate

Fig. 4 demonstrates the impact of two Al powder-molecule sizes at different volumetric proportions on *MRR*. It was seen that the appropriate mixing of powder-particles improves the machining productivity by additional settling of the electric-release. The enhancement in process durability occurred due to the fairly larger *GS* in inter-electrode gap. The outcomes additionally disclosed that the rise in the size of the powder particle resulted in a decrease in the enhancement of the *MRR*. This can be ascribed to both lesser electrical power density and a more probability of anomalous release.

Moreover, when the size of the molecule was more than the spark-gap (about 06-55 µm), the efficiency of machining evidently decayed. The *MRR* outcomes for the minimal size of the molecule (80-90 nm) at different volumetric proportions of powder particles were even more than those with (15-20 µm) molecule size of powder particles. This is happened due to the existence of less spark gap among the electrodes. For the current at 5 A, and volumetric proportion of molecule more than 0.60 cm³/l, demonstrated a notable falling trend in *MRR*. This was because of the joined impacts of lower electrical-density, the lesser striking of powder particles, unevenly distribution of particles, and very low growth in the release-transitivity.

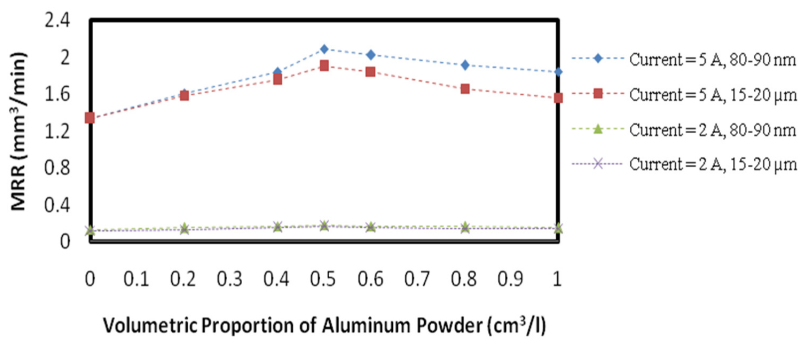


Fig. 4 The impact of particle size and volumetric proportion of aluminium powders on *MRR* (T_{on} = 30 µs, DC = 0.67)

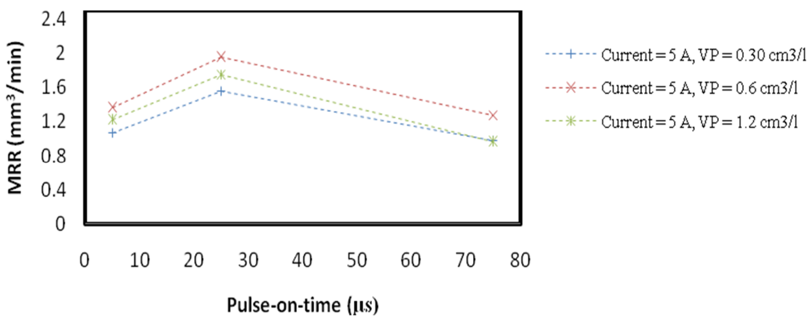


Fig. 5 The impact of T_{on} and volumetric proportion of 80-90 nm aluminium powders molecule on *MRR* (DC = 0.67)

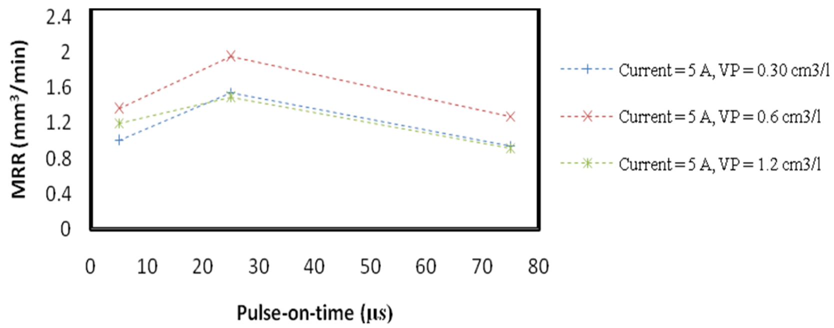


Fig. 6 The impact of T_{on} and volumetric proportion of 15-20 μm aluminium powders molecule on MRR (DC = 0.67)

3.3 Impacts of molecule concentration on material removal rate

Fig. 4 additionally demonstrates that MRR was affected by the volumetric proportion of aluminium powders. The reasonable distinction in MRR is observed for the current at a higher level because of the generation of more spark energy as displayed in Figs. 4, 5, and 6. It was also observed from Fig. 4 that the highest MRR is obtained at 5 A current, 0.6 cm^3/l of Al powders, T_{on} = 30 μs, and molecules sizes under 95 nm. This demonstrates that an ideal spark gap was acquired at this setting of the volumetric proportion of powder and T_{on}, which delivered the optimum factors setting of power density, striking of molecule and release-transitivity in the EDM procedure.

Figs. 5 and 6 demonstrate that the impacts of the volumetric proportion of molecule of 80-90 nm and 15-20 μm aluminium powders particle fluctuated along with the T_{on}. At the lesser T_{on} of 5 μs, 0.6 cm^3/l provide the good MRR, trailed by 1.2 cm^3/l, and with 0.30 cm^3/l being the inferior. Though, it may be found in Fig. 6 that at the 5.0 A current, when the T_{on} was raised to 30 μs, the impacts begun to alter with 15-20 μm aluminium powders particle. The volumetric concentration of 0.6 cm^3/l still delivered the good MRR, however, 0.30 cm^3/l was superior as compared to 1.2 cm^3/l. This pattern proceeded with the rise in the T_{on}. When the time was raised to 80 μs, 0.30 cm^3/l exceed 1.2 cm^3/l in MRR outcomes for both 80-90 nm, and 15-20 μm aluminium powders particle. This was because of extra warming impacts due to the rising the T_{on}. More evacuated molten materials were consequently produced that in the long run decreased the performance of the volumetric proportion of 1.2 cm^3/l in improving the procedure steadiness.

The purpose behind the primary outcomes with 15-20 μm aluminium powders particle was believed to be because of the bigger molecule size and its impacts. It demonstrated that the bigger molecule size of added substances among the spark gap was increasingly delicate to evacuate the tiny work materials production.

3.4 Impacts of molecule characteristics on material removal rate

Fig. 7 demonstrates the impacts of two volumetric proportions of Al, and Cr powders particle on the MRR. The test outcomes demonstrated that chromium generated the best MRR, and aluminium the least when the volumetric proportion of powder was < 1.2 cm^3/l and I = 5.0 A. At the point, when the ampere-current was at 2.0 A, the distinction in MRR turned out to be little because of the less input of energy. Fig. 3 demonstrates that the spark gap for chromium is lesser than that for aluminium as clarified already. In principle, there was a somewhat higher power density and gas explosion pressure for chromium.

Moreover, chromium powder density is double than the aluminium powder, ensuing in a powerful powder-particle collision. Additionally, the heat conductivity of aluminium powder is about 3 times bigger as compared to chromium powder, which showed that more energy is taken out by the aluminium powder blended dielectric liquid. Subsequently, Cr created the biggest MRR.

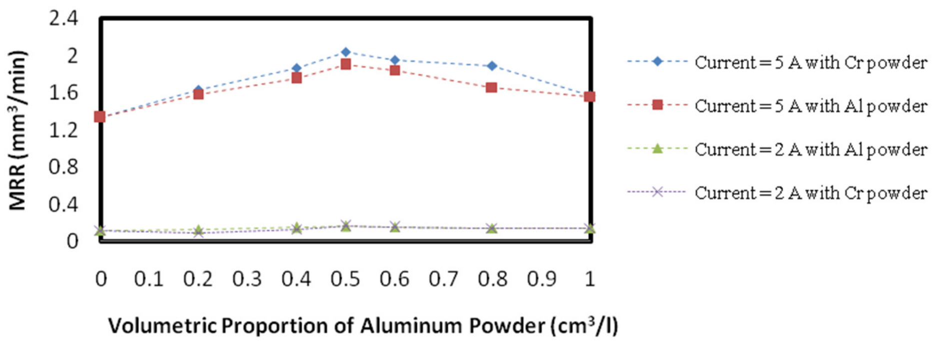


Fig. 7 The impact of ampere-current and volumetric proportion of 15-20 μm aluminium and chromium powders molecule on *MRR* (DC = 0.67, T_{on} = 30 μs)

3.5 Effects of particle size on surface roughness

Fig. 8 demonstrates the impacts of two aluminium and chromium powder molecule sizes with different volumetric proportions on *SR*. The best sorts of powders for upgrading the smoothness of the surface are Al, Cr etc. Aluminium powder-particle creates a good surface for all the molecule proportions. It is predominantly because of the joined impacts of small electrical-resistivity, adequate thermal-conductivity, and less-density of aluminium. Less electrical-resistivity makes a high spark gap, good thermal-conductivity removes more heat, and less-density avoid the arcing among the electrodes. These impacts jointly lead to less density of electrical spark bringing the low gas blast, in this way just shallow holes are created on the machined surface. Al powder produced the best surface finish followed by the Cr powder. The best surface finish is obtained at the volumetric proportion of 1.2 cm³/l of aluminium powder with 15-20 μm particle size.

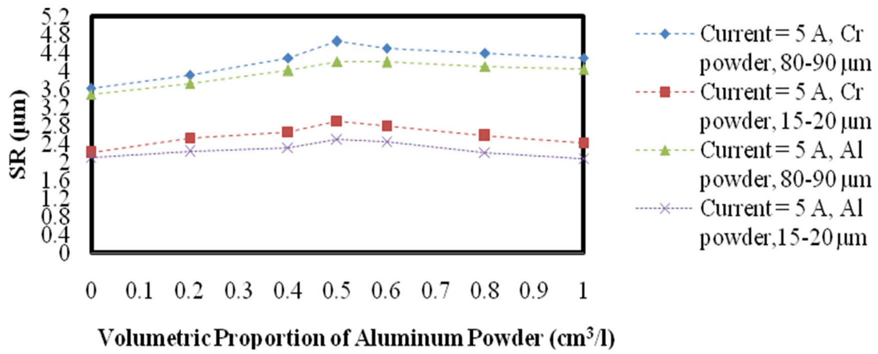


Fig. 8 The impact of particle-size and volumetric proportion of Al powders molecule on *SR* (DC = 0.67, T_{on} = 30 μs)

3.6 Effects of particle concentration on surface roughness

As appeared in Fig. 9, it was seen that at the 5 A current, the aluminium powder volumetric proportion of molecule has built a major effect in *SR* due to the bigger *MR*. It was noticed that the biggest molecule volumetric proportion of 1.20 cm³/l provide the worst *SF* at T_{on} = 80 μs due to

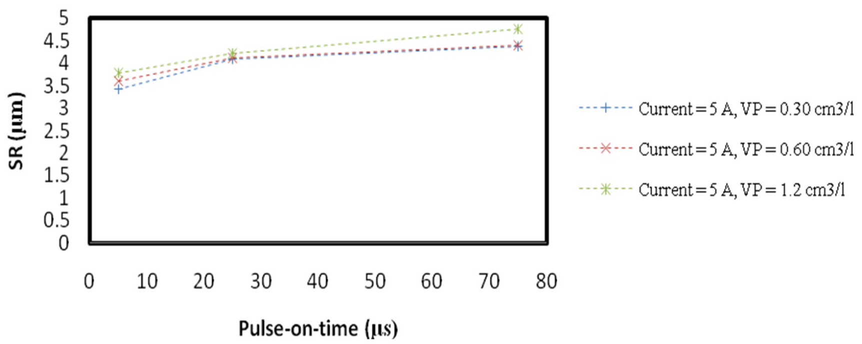


Fig. 9 The impact of T_{on} and volumetric proportion of 80-90 nm aluminium powders molecule on *SR* (DC = 0.67, I = 5 A)

its highest release transitivity. It is also noted from Fig. 9 that the volumetric proportion of powder molecule was not the main parameter controlling the *SR* in the EDM procedure. Alternately, T_{on} seemed by all account, to be the most vital parameter.

3.7 Impacts of molecule characteristics on surface roughness

Fig. 10 demonstrates the impact of seven molecule volumetric proportion levels of aluminium, and chromium powder-particles on the *SR*. It was seen that aluminium powder produced the good *SF* than the chromium powder particle for both the 2 A as well as at 5 A current. This happens because the evacuation of more molten material from work surface in presence of Cr powder as compared to the presence of Al powder in DF. Subsequently, Cr generated the biggest *SR*.

Moreover, chromium powder density is double than the aluminium powder, ensuing in a powerful powder-particle collision and result in arcing. Additionally, the heat conductivity of aluminium powder is about 3 times bigger as compared to chromium powder, which showed that more energy is taken out by the aluminium powder blended dielectric liquid.

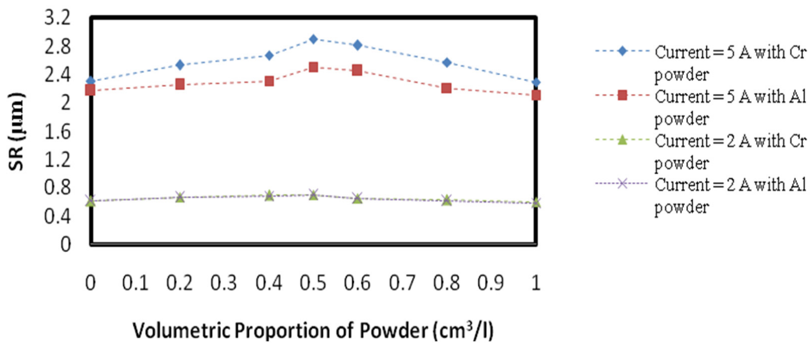


Fig. 10 The impact of ampere-current and volumetric proportion of 15-20 µm aluminium, and chromium powders molecule on *SR* (DC = 0.67, and T_{on} = 30 µs)

4. Conclusions

In view of the test outcomes, the following conclusions are drawn:

- The molecule size, volumetric proportion of powders, its density, electrical-resistivity, and thermal-conductivity are the significant attributes of powders influencing performance of ED Machining process.
- Due to the inclusion of powder particle in DF, the gap for spark was increased.
- Spark gap varies with the mixing of powders of various sizes in the dielectric fluid. Spark gap increases with increasing size of powder molecules. The minimum rise in the gap is produced with a size of 80-90 nm powders and with 15-20 µm generating the highest gap.
- Highest *MRR* was observed with powders of size 80-90 nm and with 15-20 µm generating the smallest. For the *SF*, the opposite pattern is noticed.
- Higher spark gap was observed by adding aluminium powder particles followed by using chromium powder.
- Best *MRR* was observed with adding chromium followed by aluminium powder. For *SF*, the opposite pattern was noticed.
- The volumetric proportion on mixing the powder with the dielectric fluid in the ratio of 0.6 cm^3/l gives best *MRR* outcomes.
- With 2 A, and 5 A current, results are quite higher than the impact of molecule size, volumetric proportion of powder, and other factors.
- The *MRR* and *SR* vary with different combination of molecule sizes, volumetric proportions of Al, and Cr powders in dielectric fluid in PMEDM process.
- Experiments can be conducted by using different combination of materials, dielectric fluids, and also various powders to get different findings in the PMEDM process.

References

[1] Abu Zeid, O.A. (1997). On the effect of electrodischarge machining parameters on the fatigue life of AISI D6 tool steel, *Journal of Materials Processing Technology*, Vol. 68, No. 1, 27-32, doi: 10.1016/S0924-0136(96)02523-X.

[2] Kiyak, M., Çakır, O. (2007). Examination of machining parameters on surface roughness in EDM of tool steel, *Journal of Materials Processing Technology*, Vol. 191, No. 1-3, 141-144, doi: 10.1016/j.jmatprotec.2007.03.008.

[3] Hasçalık, A., Çaydaş, U. (2007). Electrical discharge machining of titanium alloy (Ti–6Al–4V), *Applied Surface Science,* Vol. 253, No. 22, 9007-9016, doi: 10.1016/j.apsusc.2007.05.031.

[4] Fonda, P., Wang, Z., Yamazaki, K., Akutsu, Y. (2008). A fundamental study on Ti–6Al–4V's thermal and electrical properties and their relation to EDM productivity, *Journal of Materials Processing Technology,* Vol. 202, No. 1-3, 583-589, doi: 10.1016/j.jmatprotec.2007.09.060.

[5] Chow, H.-M., Yang, L.-D., Lin, C.-T., Chen, Y.-F. (2008). The use of SiC powder in water as dielectric for micro-slit EDM machining, *Journal of Materials Processing Technology*, Vol. 195, No. 1-3, 160-170, doi: 10.1016/j.jmatprotec.2007.04.130.

[6] Chow, H.-M., Yan, B.-H., Huang, F.-Y., Hung, J.-C. (2000). Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining, *Journal of Materials Processing Technology*, Vol. 101, No. 1-3, 95-103, doi: 10.1016/S0924-0136(99)00458-6.

[7] Zhao, W.S., Meng, Q.G., Wang, Z.L. (2002). The application of research on powder mixed EDM in rough machining, *Journal of Materials Processing Technology*, Vol. 129, No. 1-3, 30-33, doi: 10.1016/S0924-0136(02)00570-8.

[8] Peças P., Henriques, E. (2003). Influence of silicon powder-mixed dielectric on conventional electrical discharge machining, *International Journal of Machine Tools and Manufacture*, Vol. 43, No. 14, 1465-1471, doi: 10.1016/S0890-6955(03)00169-X.

[9] Peças, P., Henriques, E. (2008). Effect of the powder concentration and dielectric flow in the surface morphology in electrical discharge machining with powder-mixed dielectric (PMD-EDM), *International Journal of Advanced Manufacturing Technology*, Vol. 37, No. 11-12, 1120-1132, doi: 10.1007/s00170-007-1061-5.

[10] Kozak, J., Rozenek, M., Dabrowski, L. (2003). Study of electrical discharge machining using powder-suspended working media, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* Vol. 217, No. 11, 1597-1602, doi: 10.1243/095440503771909971.

[11] Kansal, H.K., Singh, S., Kumar, P. (2007). Technology and research developments in powder mixed electric discharge machining (PMEDM), *Journal of Materials Processing Technology*, Vol. 184, No. 1-3, 32-41, doi: 10.1016/j.jmatprotec.2006.10.046.

[12] Kansal, H.K., Singh, S., Kumar, P. (2007). Effect of silicon powder mixed EDM on machining rate of AISI D2 die steel, *Journal of Manufacturing Processes*, Vol. 9, No. 1, 13-22. doi: 10.1016/S1526-6125(07)70104-4.

[13] Peças, P., Henriques, E. (2008). Electrical discharge machining using simple and powder-mixed dielectric: The effect of the electrode area in the surface roughness and topography, *Journal of Materials Processing Technology*, Vol. 200, No. 1-3, 250-258, doi: 10.1016/j.jmatprotec.2007.09.051.

[14] Modi. M., Jha, S. (2009). Modeling and analysis of powder mixed electric discharge machining, *International Journal of Mechanical Engineering*, Vol. 2, 219-223.

[15] Modi, M., Agarwal, G. (2013). Optimization of electro-discharge diamond surface grinding process parameters with multiple performance characteristics of Ti-6Al-4V using grey-Taguchi approach, *Advanced Materials Research*, Vol. 622-623, 14-18, doi: 10.4028/www.scientific.net/AMR.622-623.14.

[16] Marashi, H., Jafarlou, D.M., Sarhan, A.A.D., Hamdi, M. (2016). State of the art in powder mixed dielectric for EDM applications, *Precision Engineering*, Vol. 46, 11-33, doi: 10.1016/j.precisioneng.2016.05.010.

[17] Kalaman, S., Yaşar, H., Ekmekci, N., Opoz, T.T., Ekmekci, B. (2018). Powder mixed electrical discharge machining and biocompatibility: A state of the art review, In: *Proceedings of the 18th International Conference on Machine Design and Production,* Eskişehir, Turkey, 803-830.

[18] Daneshmand, S., Neyestanak, A.A.L., Monfared, V. (2016). Modelling and investigating the effect of input parameters on surface roughness in electrical discharge machining of CK45, *Tehnički Vjesnik – Technical Gazette*, Vol. 23, No. 3, 725-730, doi: 10.17559/TV-20141024224809.

[19] Raju, L., Hiremath, S.S. (2016). A state-of-the-art review on micro electro-discharge machining, *Procedia Technology*, Vol. 25, 1281-1288, doi: 10.1016/j.protcy.2016.08.222.

Appendix A

The following nomenclature is used in the paper:

AWLT	Average white layer thickness
DC	Duty cycle
DF	Dielectric fluid
DRR	Debris removal rate
EDDSG	Electro discharge diamond surface grinding
EDM	Electrical discharge machining
GRA	Grey relational analysis
GS	Gap size
I	Current (A)
MR	Machining rate
MRD	Material removal depth
MRR	Material removal rate (mm^3/min)
MS EDM	Micro-slit EDM
PMEDM	Powder mixed electrical discharge machining
R_a	Average roughness of surface (µm)
SF	Surface finish
SR	Surface roughness
TM	Taguchi method
T_{on}	Pulse on-time (µs)
WEDM	Wire electrical discharge machining
WLT	White layer thickness