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ORIGINAL ARTICLE

Performance Analysis on Eco-friendly Machining of Ti6Al4V using Powder Mixed with Different Dielectrics in WEDM

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ABSTRACT – The recent scenario of modern manufacturing is tremendously improved in the sense of precision machining and abstaining from environmental pollution and hazard issues. In the present work, Ti6Al4V is machined through wire EDM (WEDM) process with powder mixed dielectric and analyzed the influence of input parameters and inherent hazard issues. WEDM has different parameters such as peak current, pulse on time, pulse off time, gap voltage, wire speed, wire tension and so on, as well as dielectrics with powder mixed. These are playing an essential role in WEDM performances to improve the process efficiency by developing the surface texture, microhardness, and metal removal rate. Even though the parameter's influencing, the study of environmental effect in the WEDM process is very essential during the machining process due to the high emission of toxic vapour by the high discharge energy. In the present study, three different dielectric fluids were used, including deionised water, kerosene, and surfactant added deionised water and analysed the data by taking one factor at a time (OFAT) approach. From this study, it is established that dielectric types and powder significantly improve performances with proper set of machining parameters and find out the risk factor associated with the PMWEDM process.

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Eco-friendly; HAZOP; Surfactant; Deionized Water; Kerosene

INTRODUCTION

Electrical discharge machining and wire electrical discharge machining are the most efficient non-traditional machining applicable to machine advance materials. Therefore, controlling the process behaviour of EDM is an arduous task. Plenty process parameters are associated with electric discharge machining process such as pulse on time, pulse off time, peak current, gap voltage, wire-speed, wire tension, flushing pressure, dielectrics etc. along with other machines non-controllable parameters [1]. The exploration of complex interaction with all concern parameters is the most anfractuous research field in modern engineering applications. In the present scenario of modern manufacturing, a minimal micron error is not accepted for a specific application where the precise dimension is highly demanded. In this situation, the development of the process characterisation is the major key point of research for enhancing process capability. In this study, authors have used an effective technique of WEDM process for improving the machining efficiency as well as analysing the effect of different dielectric on eco-friendly machining so that the process becomes efficient and inoffensive. Machining characterisation of titanium and its alloy through the non-traditional process is the most challenging research field due to its high hardness and toughness value. Among all the grades of Ti alloy, Ti6Al4V has unique properties such as low thermal conductivity and high weight to strength ratio, which makes it's difficult to cut material. Ti6Al4V comes under the α-β titanium alloy, and it has exceptionally high chemical, mechanical, and metallurgical properties [2]. Owing to high hardness, toughness and superior corrosion properties its low conductivity nature somehow restricted the machining performance of the material.

Well known non-traditional process, namely wire EDM is the most preferred for complex through cutting operation. The main negative feedback of the thermal erosion process is the creation of rough surface and low MRR. As the WEDM process is coming under this group (thermal process), high oxide layers and crack formation also thrust into fatigue failure [3]. Due to high heating and cooling in WEDM process, the inferior machined surface becomes brittle and generates micro-crack, which causes an unexpected result. Then process control strategy is massively essential for enhancing machining efficiency. Several critical process parameters are involved in the WEDM process like mechanical, electrical, dielectric and electrode parameters [4, 5]. Performance efficiency of WEDM process is also strongly dependent on the material characterisation properties based on their thermal, electrical and physical properties. The comparative study was made for modelling and optimisation on different materials using Buckingham pi, RSM, Genetic algorithm and other methodology to model the WEDM responses such as MRR and SR [6-11]. The selection of wire electrodes in the WEDM process also plays a vital role in enhancing the outer response characterisation [12]. Based on the physical and mechanical properties such as tensile strength, conductivity, melting point and fracture toughness, an appropriate wire is selected for machining [13, 14].

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Apart from the control strategy of the input parameter, additionally, the mixing of powder with dielectric can overcome more than one issues related to the WEDM process. Different types of metallic, non-metallic, and abrasive powders and their unique properties make the machined surface smooth and stronger in nature. But degraded surface integrities, namely crater recast layer, micro cracks and globules are adverse effect on material properties [16]. In literature, powder particles used in dielectrics such as SiC, Al_2O_3, graphite and zinc powder to modify the EDM process capability on superalloy [16-18].

In order to achieve superior surface texture, carbon nanotube in dielectric showed a good result of while machining Ti6Al4V by EDM process [19]. Graphite powder with 6 g/l concentration created a large shallow crater, so that surface finish improved up to an optimum level [20]. Low energy density decreases the surface roughness and white layer thickness. 15g/l of Hydroxyapatite powder with dielectric produced a lakargrite coating of $Cazro_3$ that increases the potential of orthopaedic application [21]. Tungsten powder in kerosene dielectric along with other machining parameters resulted in a higher improvement in MRR. The deposition of carbon and tungsten powder on the machined surface consequently enhanced the surface topography [22]. The surface characterisation of β phase titanium alloy was examined through hydroxyapatite mixed EDM [23]. The formation of $Ca_3(po_4)_2$, $CaZr0_3$, Nb8p5, Cao. Tip, Nb405 and $Ti0_3$ are beneficial for excellent metallurgical characteristics for titanium alloy, applicable for grater corrosion prevention. Si powder of 4 g/l concentration provided the best surface quality, whereas 8 g/l Si powder modified the surface structure by generating oxide and carbide layer on the machined surface [24]. Another hybridisation technique of EDM, abrasive powder mixed surface electric discharge machining has been conducted and investigated the influenced parameter on surface properties [25-27].

In terms of MRR and SR, B_4C powder added WEDM process significantly improves the quality of discharge occurrence during machining of titanium alloy as compared to other abrasives. Another benefit for tool wear reduction by producing adhesive carbon particle during B_4C powder mixed WEDM process. The selective parametric effects with B_4C powder mixed dielectric was examined and modelled for enhancing the machining criteria of Ti6Al4V material in wire electric discharge machining [28]. Furthermore, it is required for sustainable manufacturing to reduce pollution in the environment. The emission of toxic gasses take place during the EDM process, due to that in-depth investigation is essential for green machining environment [29].

Due to high precision machining capability in the case of advance material through the WEDM process, it becomes a more popular non-traditional machining process. Past works already reported detail in their research study. Based on the literature survey, it is evident that the powder mixed EDM process has been done developed continuously. In the current state of information in the field of WEDM, very few works have been concentrated on powder mixed wire EDM. The complexity of the process behaviour of PMWEDM is higher than the PMEDM process. Therefore, consideration of the environmental effect on PMWEDM performance makes the process more unique [29]. In the present investigation, the survey report plays a guide and helps to find out the research gap. This investigation deals with the machining of Ti6Al4V material with powder mixed wire EDM, analysing the effect of environmental conditions and different dielectric on performance. Best of my knowledge and belief, no such paper investigated when all those conditions are taken into consideration for WEDM process. Therefore, authors have discussed the hazard and operability analysis by taking one factor at a time approach to evaluate the process of inherent risks and fire safety. HAZOP evaluation technique successfully adopted in this study due to its capability to find the hazard and risk factor in the wire electric discharge machining along with powder and surfactant mixed dielectric. Initially, the HAZOP evaluation technique was developed in the 1960s to analyse the chemical process industry [30]. It is a structured and methodical technique to identify and evaluate the real problem of the complex process in order to avoid serious risks. HAZOP analysis is used in this study for the following reasons:

i. To find out the process deviation to run the full operation for a long time
ii. To determine systematic examination of clutter in the process by controlling each factor setting
iii. To analyse the risk issue related to fire hazards and serious health problems of the operator.
iv. To identify the environment-conscious factor make the process pollution-free

MATERIAL AND METHOD

The experimental study has been conducted on Ezeecut Plus wire electric discharge machine set up, as shown in Figure 1 with a brass electrode material of 0.25 mm dia. A separate dielectric fluid chamber of 20 litres capacity with a starring system was made for supply dielectric during machining. Ti6Al4V was used as work material as it has tremendous applications in the biomedical component, nuclear plant, automobile industry and so on. The material has brilliant mechanical and metallurgical properties. The chemical composition and properties of Ti6Al4V was reported in Table 1, 2. All experiments were conducted on a flat surface workpiece with a dimension of $200 \times 27 \times 2.5$ mm^3. Additionally, boron carbide (B_4C) abrasive with average grain size 10 μm were selected for mixing the powder in the dielectric of WEDM process. Powder properties of B_4C abrasive are provided in Table 3. In the present study, two different dielectric fluids (deionised water and kerosene) are used for the first phase of experimentation. Plan for the experiment has demonstrated in Table 5. Second phase experimentation has been conducted by adding surfactant in these dielectrics. Span 20 (chemical composition = $C_{18}H_{34}O_6$) is used as a surfactant for developing a homogeneous powder mixture in the dielectric [31]. Table 4 shows the selection of input parameter and their level as machining factors such as pulse on time, pulse off time, gap voltage and fluid level. The influence of these parameters is analysed for best optimal output like material removal rate, surface roughness and dielectric consumption.

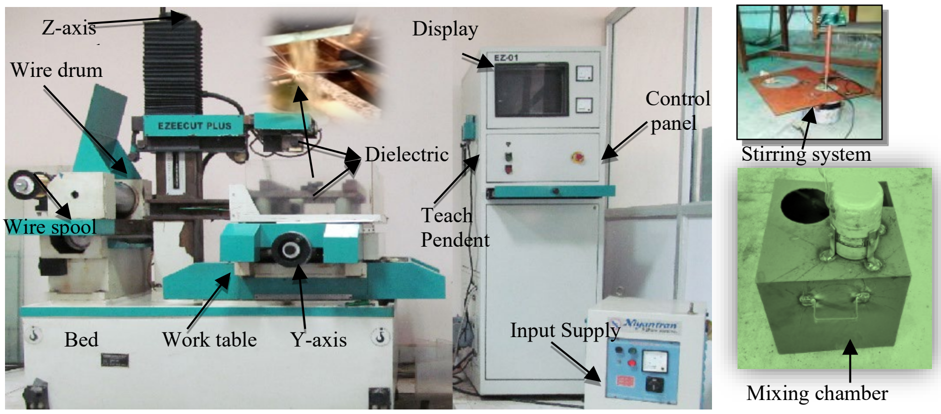

Figure 1. Experimental setup.

Measurement of metal removal rate has been done by dividing the total weight loss during machining by total machining time and density of the workpiece, as in Eq. (1).

$$MRR = \frac{(w_i - w_f) \times 60 \times 1000}{T \times \rho} \tag{1}$$

where W_i and W_f are the weight (gm) of the job piece before machining and after machining, T is the total time, and ρ represents the density of the job piece (gm/mm^3).

Average surface roughness in terms of Ra has been measured through Surftest SJ-410 series. Figure 2 shows one sample measurement of experimentation. Measurement of dielectric consumption has been calculated by dividing the volume of dielectric consumption after machining and before machining by total time and MRR as in Eq. (2).

$$C_D = \frac{(c_a - c_b)}{t_m \times MRR} \tag{2}$$

where, C_D represents dielectric consumption in cm^3, c_a and c_b represents the dielectric volume after machining and before machining. t_m is the total machining time.

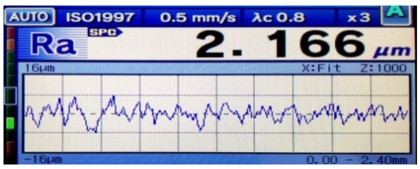

Figure 2. Evaluation of surface profile from surface roughness measurement.

Table 1. Composition of Ti-6Al-4V.

Component	Ti	V	Al	Fe	C	N	Others
Weight (%)	Balance	4	6	<0.20	<0.08	<0.05	<0.12

Table 2. Properties of Ti-6Al-4V.

Properties	Value	Ti-6Al-4V material
Melting point	1604-1660 ºC	
Modulus of elasticity	113.8 GPa	
Ultimate tensile strength	860 MPa	
Density	4.43gm/c.c	
Shear strength	550 MPa	
Resistivity	0.000178 Ohm-cm	
Thermal conductivity	6.7W/m-K	

Table 3. Properties of B_4C abrasive powder.

Properties	Values
Grain size	10 µm
Density	2.57 g/cm^3
Specific Heat	950 J/kg.K
Thermal conductivity	68 W/(m.K)
Melting point	2850 °C
Thermal expansion	5.2 µm/m-K
Electrical conductivity	1.4 × 10^5 Ω^{-1}.m^{-1}

Table 4. Selection of input parameter and their level.

Controllable parameters	Unit	Level / Limit		
		1	2	3
Pulse-on-time	µsec	40	60	80
Pulse-off-time	µsec	4	6	8
Gap voltage	Volts	45	60	75
Fluid level	mm	50	70	90

RESULTS AND DISCUSSION

In powder mixed electric discharge machining, the powder particle acts as an insulator in the dielectric. During machining, an amalgamation of powder helps to create the bridging effect in the narrowest spark gap zone, which caused an early explosion of in plasma channel [22]. The early explosion causes enlarging the spark gap and quickly removes debris particles from the gap. Such a way better discharge has been achieved and obtained a better-quality surface topography [32]. Due to this process capability is enhanced. In the present investigation, four adjustable input parameters are used to obtain output responses like MRR, SR and dielectric consumption. Each process parameter has an individual effect behaviour on these responses at a time. Spark energy is the product of the supplied voltage and current. Therefore, at lower pulse current and gap voltage, the surface finish could result smoother. Also, the high value of current could result in better MRR. A detail elaboration of powder mixed wire EDM process parameter and environmental effect by the one factor at a time (OFAT) approach has been discussed in the following section.

Table 5. Experimental plan and obtained results for the process parameters with different dielectrics.

Sl. no.	Pulse on time (µs)	Pulse off time (µs)	Gap voltage (V)	Fluid level (mm)	MRR (mm^3/min)		SR (µm)	
					Deionised water	Kerosene	Deionised water	Kerosene
1	80	8	75	90	7.548	7.948	4.221	3.54
2	80	8	75	70	8.752	7.711	3.254	2.229
3	80	8	75	50	6.324	5.217	2.54	3.254
4	80	8	60	90	6.014	4.136	2.847	2.61
5	80	8	45	90	5.891	4.995	3.015	4.571
6	40	4	75	50	2.504	3.254	2.109	3.286
7	40	4	60	50	3.529	3.685	3.549	3.445
8	40	4	45	50	2.547	1.988	2.596	2.164
9	80	6	75	90	7.526	8.213	3.288	2.542
10	80	4	75	90	5.854	7.836	2.553	2.31
11	60	8	75	90	6.015	6.751	4.452	2.559
12	40	8	75	90	5.857	3.766	2.139	3.985

Influence of Machining Parameter and Dielectric Fluid on MRR

Two mostly used dielectric fluids such as deionised water and kerosene are applied in the present study. The performance efficiency of powder mixed WEDM is strongly dependent on the conductivity of the dielectric when current pusses through it [31]. Due to changes in dielectrics conductivity, their influence in responses is different in nature. High conductivity easily collapses the dielectric insulation and creates a large gap distance so that debris particle passes away from the machining zone, resulted in a better performance. Figure 3 shows the influence of the machining parameters on MRR, changing various dielectric fluids. It is clear, in Figure 3(a) and 3(b) that a greater MRR is found in kerosene dielectric whereas 3 (c) and (d) illustrate the higher MRR in deionised water. MRR continuously increases with the increases of Gap voltage and pulse on time. The open voltage is functioned between the electrode and workpiece, but discharge occurs after the ignition delay time. Also, the discharge current passed through the gap after the dielectric breakdown, resulting in a uniform discharge crater size. Gap voltage and pulse on time both are directly proportional to the discharge energy. The middle-level value provides the best MRR that shows in Figure 3(b) and 3(d). As compared to both of the dielectric deionised water has a greater effect on MRR when pulse off time and fluid level is the dominating factor.

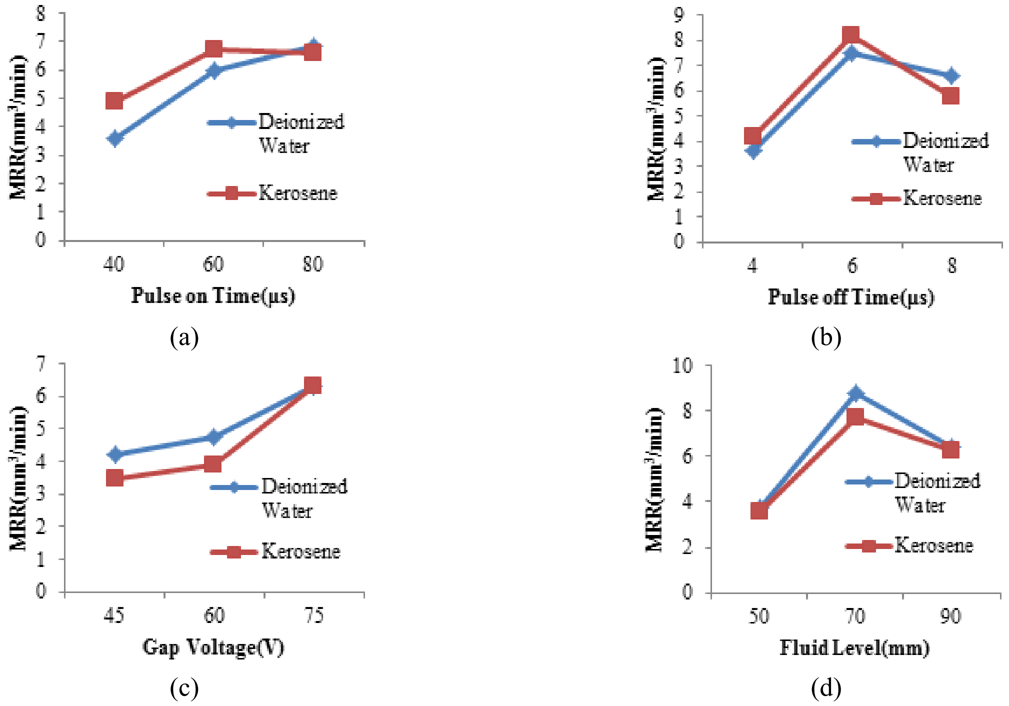

Figure 3. Influence of (a) pulse on time, (b) pulse off time, (c) gap voltage, (d) fluid level and dielectric fluid on MRR.

Influence of Machining Parameter and Dielectric Fluid on SR

Heating and cooling processes are continued during the WEDM machining. Therefore, overheating causes a high degree of metal erosion from the workpiece and results in a deeper crater on the machining surface. On the other side, the effect of cooling action generates micro-crack on the surface. Pulse on time is the greatest dominating factor which directly promotes the supply of high discharge density. A shallow and minimal size crater formation on the job surface leads to superfine surface topography [20]. Thereby it is important to produce a continuous with a small amount of discharge energy during machining so that massive discharge can be discarded. At the same time, removing the molten metal from the machining zone in the form of debris particle is required to avoid ultimate recast layer formation on the machined surface. The type of dielectric play a role on surface roughness.

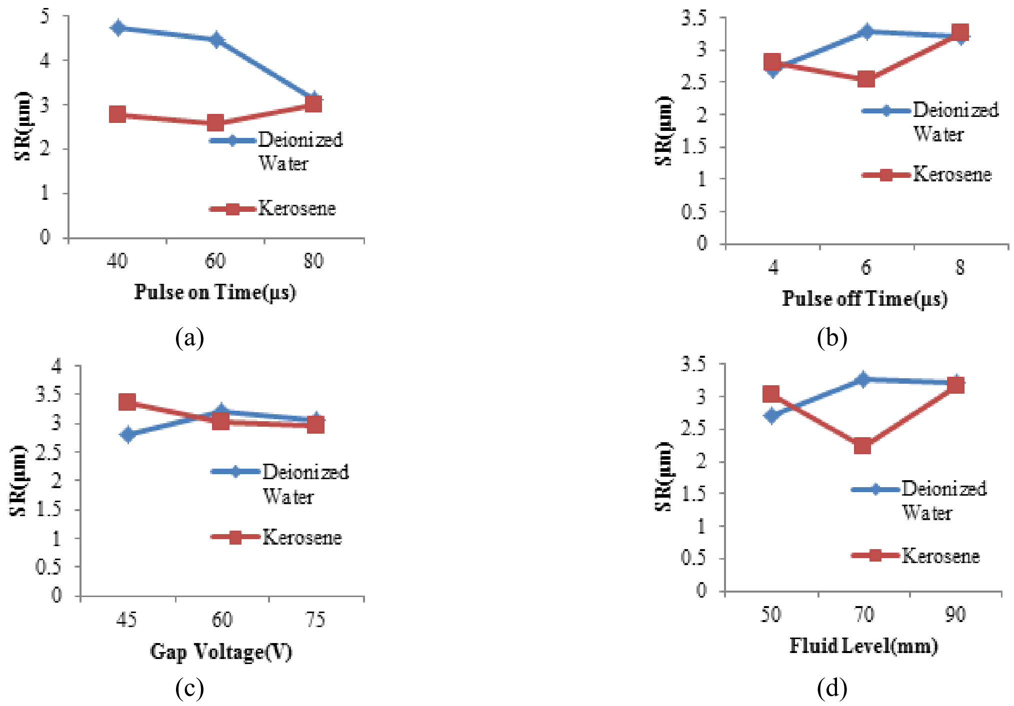

Figure 4. Influence of (a) pulse on time, (b) pulse off time, (c) gap voltage, (d) fluid level and dielectric fluid on SR.

Figure 4 shows the influence of the input parameter, followed by different dielectric on surface roughness. Figure 4(a) and 4(b) show increasing and decreasing of SR by two parameters; pulse on time and fluid level. Surface roughness is deliberately high at low gap voltage as in Figure 4(c). This is due to the low intensity of the spark energy. Figure 4(a), 4(b) and 4(d) show that the mid-value provides the best surface finish. With an increase in pulse on time from 40-80 µs, deionised water delivers a better surface finish. This is due to suspended B_4C powder into dielectric as it breakdowns the insulation and reduced the impulse force. As a result, high-pressure energy during increasing T_{on} helps to create small craters and voids, resulting in a smooth surface finish. For surface roughness, most significant parameters are pulse on time, pulse off time and fluid level. From the experimental results in Table 5, a comparison among these dielectric indicates that deionised water has more significant effect followed by kerosene on surface roughness as well as MRR for both conditions, i.e. single or multi-response criteria. In the next section, experimentation was performed with surfactant added PMWEDM. The surfactant helps to mix the powder in dielectric homogeneously and retard agglomeration of eroded material and carbon scum that increases the efficiency of the process. The addition of surfactant increases the conductivity of the dielectric in the machining zone [31]. The influence of the parametric effect is elaborated in the next section.

Table 6. Obtained results for the environmental factors.

MRR (mm^3/min)		SR (µm)		Dielectric consumption (cm^3)	
Without powder deionised water	With powder surfactant added deionised water	Without powder deionised water	With powder surfactant added deionised water	Without powder deionised water	With powder surfactant added deionised water
6.391	7.562	3.534	2.223	0.634	0.569
8.420	9.201	2.591	1.862	0.419	1.632
5.442	6.547	2.232	2.568	0.587	0.872
7.385	8.225	3.085	2.054	0.271	0.386
4.773	6.852	3.682	3.252	0.342	1.234
3.227	2.587	2.197	2.061	0.169	2.79
2.739	2.358	3.094	2.117	0.285	0.382
3.098	3.254	2.470	2.336	0.410	0.380
6.783	7.89	2.567	1.962	0.3993	1.005
5.775	6.378	2.351	2.572	0.2891	1.984
7.406	6.837	3.724	3.339	0.336	2.11
3.967	4.001	2.812	2.104	2.864	3.457

Influence of Machining Parameter and Surfactant Added Dielectric on MRR

The modification process of the electric discharge machining becomes effectively employed on advanced materials. The next improvement of this technique is known as surfactant added powder mixed wire electric discharge machining.

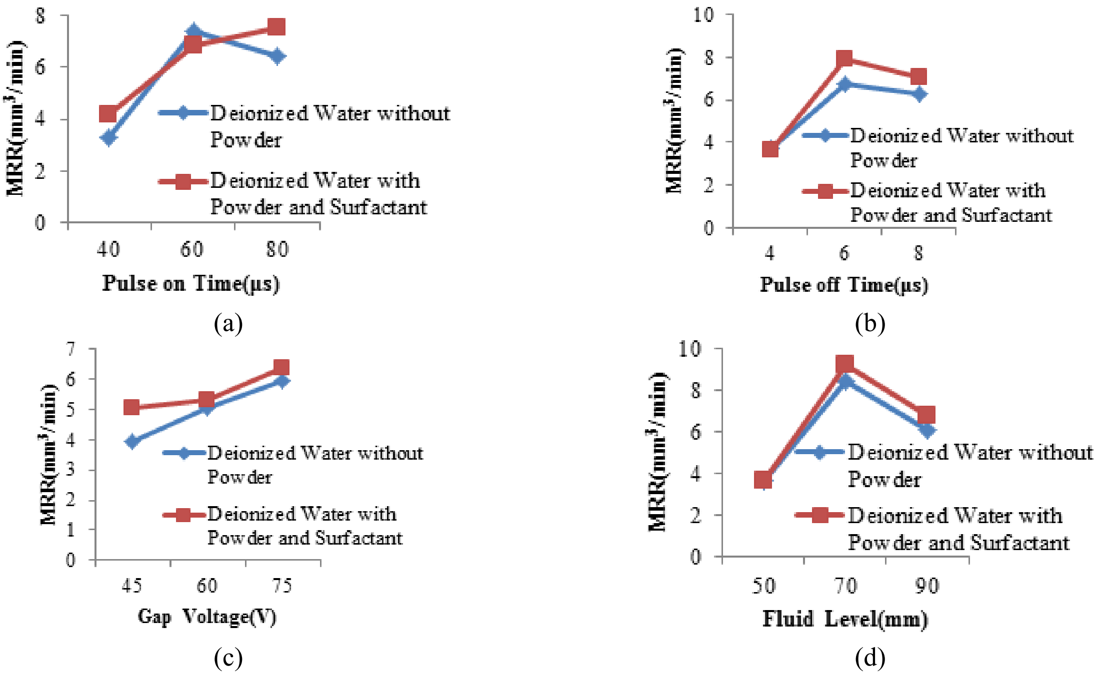

Figure 5. Influence of (a) pulse on time, (b) pulse of time, (c) gap voltage, (d) fluid level and surfactant added dielectric on MRR.

As surfactant increases the conductivity of the dielectric in the machining zone, result in a better quality product and enhances machine capability [31]. Based on the trial run, it is found that up to 6 g/l concentration of surfactant gives better results after that MRR continuously decreases up to 10 g/l. In this study, 6 g/l concentration of surfactant is mixed with dielectric and performed experimentation. In Table 6, the obtained result shows that output responses, i.e. MRR, SR and dielectric consumption, are examined by surfactant-assisted PMWEDM of Ti6Al4V material.

Figure 5 shows the influence of the input parameter of the surfactant added PMWEDM process. Figure 5(a) and 5(c) illustrate that an increase in pulse on time and gap voltage resulted in increasing in material removal rate. The mid-value of pulse off time and fluid level leads to maximum MRR as in Figure 5(b) and 5(d). Less amount of MRR is found in deionised water without mixing the powder. In addition to surfactant, the powder mixed wire EDM is more stabilised than without using surfactant added deionised water. This is happening due to the uniform distribution of discharge energy by increasing the conductivity of the working fluid resulting enhance in MRR.

Influence of Machining Parameter and Surfactant Added Dielectric on SR

The influence of the input parameter and surfactant added dielectric with powder mixed on surface roughness of the machining surface is shown in Figure 6. Surface roughness in PMWEDM has been dependent on various reasons, i.e. how much distribution of the powder undergoes in the machining zone, the increment of dielectric conductivity and decrement in dielectric strength [27, 34]. However, the addition of surfactant in dielectric impulse force increases by the high discharge energy results in deeper erosion and micro-crack on the machine surface.

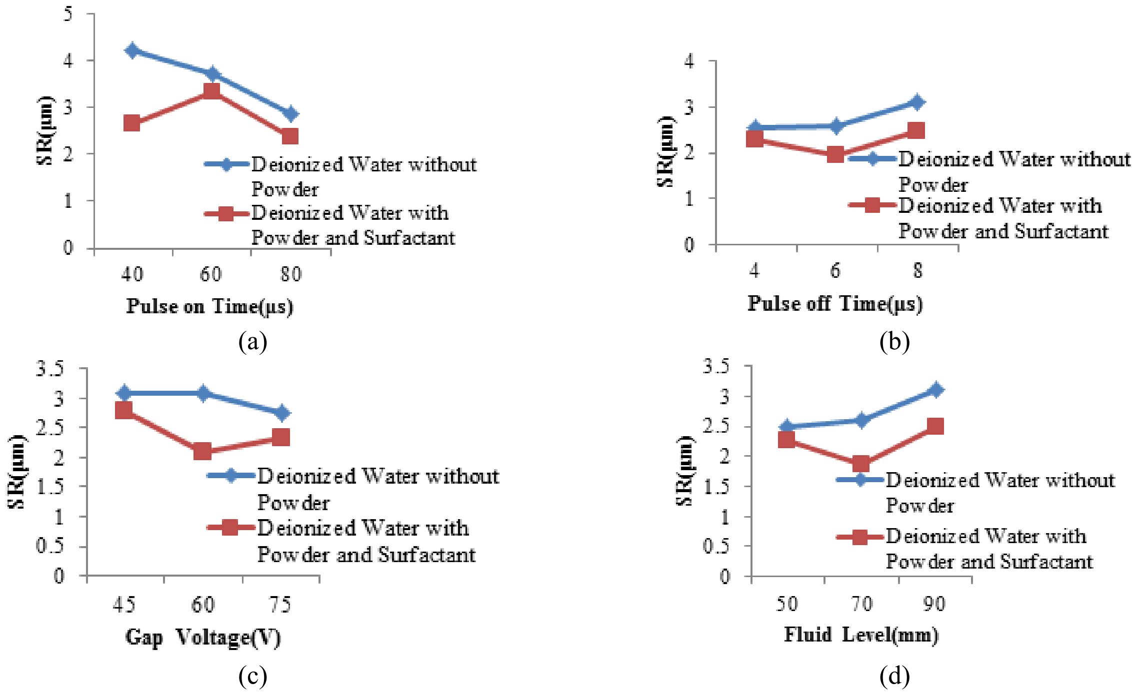

Figure 6. Influence of (a) pulse on time, (b) pulse off time, (c) gap voltage, (d) fluid level and surfactant added dielectric on SR.

Also, more smoke produces in the fluid tank due to high heat energy which causes a negative effect on the environment. Figure 6(b), 6(c) and 6(d) represent that initially, SR decreases and then increases by changing low to the high value of T_{off} and fluid level when surfactant adds in the dielectric. In the case of T_{on}, surface roughness initially increases and then decreases as in Figure 6 (a). Fluid level mostly influences on SR as it provides the lowest output. This is due to repeated application for a long time of powder mixed deionised water, and it is required to set an appropriate fluid level; otherwise, it causes poor surface finish. The overall conductivity by adding surfactant with dielectric decreases the strength of dielectric, which causes for generating enlarge spark gap. Thus expanding gap helps to remove particle from gap zone resulting in a better surface finish. Moreover, Lower input energy, as well as selected dielectric level, creates shallow and small crater, which leads to superfine surface topography.

Influence of Machining Parameter and Surfactant Added Dielectric on Dielectric Consumption

Dielectric consumption is also one important factor which directly associated with pollution as well as hazard creation for the operator. Figure 7 demonstrated the effect of input factor on dielectric consumption. Higher dielectric consumption contaminates the environment causes health regarding issues on the machine worker. Ultimately it affects the overall cost of the product by losing an amount of dielectric.

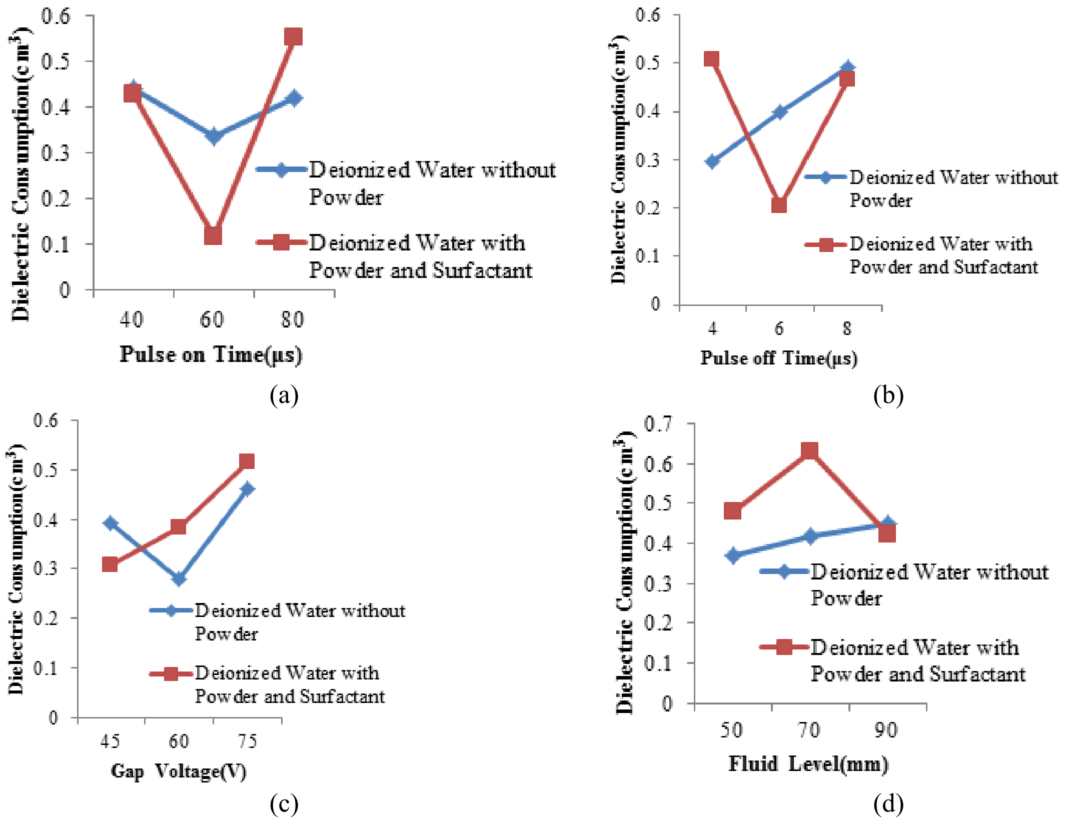

Figure 7. Influence of (a) pulse on time, (b) pulse off time, (c) gap voltage, (d) fluid level and surfactant added dielectric on dielectric consumption.

Figure 7(a) and 7(b) show that dielectric consumption firstly decreases and then increases due to extensive evaporation of the dielectric by surfactant added deionised water with powder mixed. At the same time, mid-value of pulse on time and pulse off time provide the lowest dielectric consumption. This is due to stable discharging and not discrete sparking in the machining zone. Less dielectric consumption achieve in deionised water when the fluid level is minimum, as in Figure 7(c). With an increase in the fluid level, an increase in dielectric consumption for deionised water is shown in Figure 7(d).

Analysis of Hazard and Operability Study

Plenty of process parameters and electrical, mechanical instruments are associated with powder mixed wire EDM. All possible data are collected by the HAZOP study for improving the performance efficiency so that less wastage and eschew form contamination in the environment and low energy consumption [35]. Figure 8 shows different steps in the preparation of the HAZOP worksheet. Initially, a node is selected then focused on design intention and developed a deviation with combined guidewords.

The next recommendation for safety guard is followed by considering all other possible parameters. Finally, hazard and operability analysis have been prepared. Best of my knowledge and from the literature survey following major objectives are found in PMWEDM:

Objective (a)-Influence of process parameter and dielectric on metal removal rate
Objective (b)-Influence of process parameter and dielectric on surface roughness
Objective (c)-Influence of process parameter over dielectric consumption
Objective (d)-Influence of process parameter over surfactant
Objective(e)-Influence of process parameter over the environment

Table 7 represents the HAZOP analysis worksheet for the PMWEDM process, and the surfactant added PMWEDM process. Due to high discharge energy, spark intensity is developed as a result of evaporation occurs on the metal piece as well as dielectric fluid during the machining operation. This result indicates the release of toxic emission vapour causes increases contamination in the environment. Dielectric fluid type and level play a significant role to provide safe operation. Low MRR indicates low process efficiency, which leads to time consumption and higher cost of the product. Hydrocarbon based dielectric fluid creates a carbon layer on machining surface and fire hazard. So it is recommended to use more other natural oil as a dielectric instead of hydrocarbon, which gives better results and harmless environment. Dielectric should have a great flashpoint that helps to minimise the fire risk. Recommendation for best output and risk-free operation has been highlighted in Table 7.

Low surface roughness is also a challenging task. Proper control setting, dielectric fluid and suitable powder selection are the major key point in the research area of wire EDM. This investigation shows that the powder effects on machining criteria and search for the significant parameter. With an increase in T_{on} initially, SR increases and then decreases but for

T_{off}, it is vice versa. So it is concluded that more discharge energy causes more emission in spark energy, resulted in a large amount of profile inaccuracy and wastage of product. The high amount of dielectric consumption is also a major factor to disturb the environment. The result shows that middle value of T_{on} and T_{off} provides the lowest dielectric consumption and gap voltage is directly proportional to the gap voltage. All are associated with high discharge that directly proportional to the discharge density of the spark. However, fluid level causes less effect for deionised water without powder.

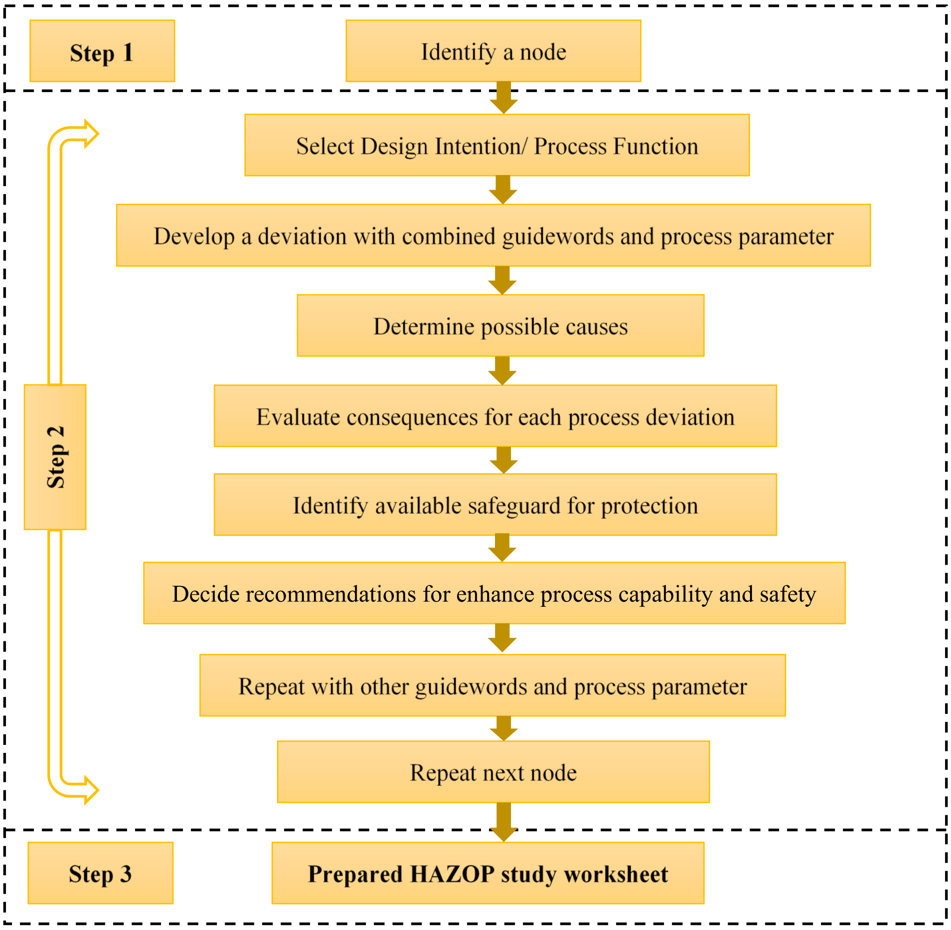

Figure 8. Different steps of HAZOP study.

The total amount of dielectric consumption is due to one major superficial issue of wrong dielectric selection as well as chemical agent, powder and surrounding cover around the flushing area. Trained skill operators and other recommendations should be adequately maintained to resolve the hazard issues. In powder mixed wire EDM, the environment is mainly polluted due to the unskilled operator, unstable input supply voltage, high room temperature, improper ventilation and cleanness of the machine surrounding. Installation of the AC in the machine room and scheduled maintenance is required for eco-friendly machining operation.

Table 7. HAZOP analysis worksheet for PMWEDM.

Objective	Deviation	Guide words	Causes	Consequences	Recommendation
(a) -Influence of process parameters and dielectric on metal removal rate in PMWEDM	High energy consumption and cost of production	High	1. High pulse off time (11 µs) and gap voltage 2. Low Dielectric pressure 3. Low wire tension 4. Selection of dielectric 5. Unskilled worker	1. Large time taken 2. Fast wire breakage 3. Reduce machining efficiency 4. Low profit	1. Skilled operator 2. Advance precision machine 3. Hybridisation of process 4. Selection of proper input parameter 5. Selection of proper electrode material and dielectric

(b)-Influence of process parameters and dielectric on surface roughness in PMWEDM	Low quality, wastage of product and cost of production	High	6. High pulse on time-(100μs) 7. High peak current-11A 8. Low gap voltage and wire tension 9. Low fluid pressure 10. Kerosene or deionised water	5. Fast wire breakage 6. Wastage of time 7. Required another process for further machining 8. Reduce machining efficiency 9. Low profit	6. Skilled worker 7. Advance precision machine 8. Hybridisation of process 9. Selection of proper input parameter 10. Proper selection of electrode material and dielectric 11. Replace abrasives with Nano-size
(c)- Influence of process parameters over dielectric consumption in PMWEDM	High risk and cost of production	High	11. Low level volume of dielectric 12. Poor flashing system 13. Improper selection of dielectric 14. High current	10. Health problem 11. Loss of dielectric 12. Effect on eye skin and lungs 13. High generation of vapor	12. Skill operator 13. Proper maintenance 14. Choose other natural dielectric 15. Machine room ventilator 16. Avoid high concentration of surfactant 17. Safety protector for operator like mask, eyeglass, gloves
(d)-Influence of process parameters over surfactant in PMWEDM	High wastage	High	15. Powder selection 16. Wrong selection of dielectric 17. Dielectric pressure 18. Surrounding cover	14. Desecration of active environment 15. Skin irritation 16. High reaction	18. Proper mixing with dielectric 19. Skill operator 20. Proper maintenance before and after machining 21. Suitable stirring system 22. Surfactant concentration 23. Input parameter selection 24. Safety protector for operator like mask, eyeglass, hand gloves
(e)-Influence of process parameters over the environment in PMWEDM	High hazard creation and low process efficiency	Low	19. Unskilled operator 20. Unstable input supply voltage 21. High room temperature and humidity 22. Improper machining operation 23. Less competency toward the machine operation	17. Low productivity 18. Higher production cost 19. Hazard on machine maintenance 20. Desecration of environment 21. Uncertain machine failure	25. Skill operator 26. Proper ventilation 27. Install AC in the machine room 28. Periodically maintenance of the overall machine 29. Clean machine environment after and before machining.

CONCLUSION

The present study focused on eco-friendly machining of 'difficult to cut material' by using an innovative technique, namely, powder mixed wire EDM corresponding to the different dielectric fluids. Ti6Al4V is used as workpiece material. The effects of process parameters and characteristics of dielectric and powder are also highlighted in the text. Based on the present study, authors have drawn the following conclusions:

i. In recent innovation technique of Wire EDM, namely powder mixed wire EDM, B_4C with 10 µm size abrasive powder successfully adopted in this investigation which significantly improves process efficiency.
ii. Increasing pulse on time leads to higher MRR, and pulse off time value of 6 µs provides the best output. Gap voltage is indirectly proportional to the surface roughness, which indicates lower discharge intensity causes high surface finish.
iii. As compared to the various dielectric, kerosene has a slightly higher impact on responses. Due to some disadvantages of kerosene such as carbon layer formation on machine surface, more generation of toxic vapour emission during machining and creation of fire hazard, deionised water is used in WEDM process instead of kerosene.
iv. The next improvement of the process is surfactant added PMWEDM, and the obtained result proves that surfactant help to increase the modified plasma channel as a result best output is achieved. At the same time, the chemical composition of the surfactant created serious health problems as well as polluted environment rigorously, so it is required to follow the proper recommendation for safe operation.
v. Fluid level is the major influencing parameter on dielectric consumption as it is directly proportional to the fluid level in surfactant added PMWEDM.
vi. HAZOP study is demonstrated for better production quality, cost of production, safety operation, and contamination towards the environment during WEDM process.

The interaction of various process parameters makes the process more complicated. Obtained an optimum setting for best output multi-objective optimisation is quite essential. Other dielectrics such as natural oils, distilled water with different powder can be utilised for harmless operation, low dielectric consumption and environmentally conscious production. This is the area where authors have concentrated in future works.

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