Multi-response Optimization and Effect of Alumina Mixed with Dielectric Fluid on WEDM Process of Ti6Al4V

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Abstract Titanium and titanium alloys (Ti6Al4V) are functional materials that have various uses in the marine, chemical, biomedical, aerospace fields because of their unique combination of mechanical and physical properties. Conventional machining of Ti6Al4V is difficult owing to its high hardness, higher chemical reactivity, and lower thermal conductivity. Non-contact operation between tool and work material such as wire electrical discharge machining (WEDM) process was found to be most effective. In the current study, the effect of different input machining parameters of the WEDM process has been studied for Ti6Al4V. Selected input WEDM process parameters based on past literature include pulse on time (T_{on}), pulse off time (T_{off}), and current while material removal rate (MRR) and surface roughness (SR) as the response variables. Grey relational analysis (GRA) technique along with Taguchi's design was used for attaining multiple objectives simultaneously. A validation study was conducted to verify obtained results from optimization. Lastly, results obtained by GRA at optimal parameter settings were compared with nano-alumina powder mixed with dielectric fluid at a concentration of 1 g/l. Improvement in the value of MRR and SR was found by 22.08% and 16.25%, respectively, for Ti6Al4V.

Keywords WEDM · TI6AL4V · ANOVA · GRA · Nano-alumina powder · Optimization

1 Introduction

Titanium and titanium alloys are functional materials that have various uses in the marine, chemical, biomedical, aerospace fields because of their unique combination of mechanical and physical properties (Chaudhari et al. 2020a, b; Khanna et al. 2020,

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2021b). These materials are highly resistant to fatigue and have a satisfactory tensile strength at higher temperatures. The high toughness of these materials allows them to be used to produce machine parts and molds. Ti6Al4V is one of the most widely used alloys of titanium. It is an α-β titanium alloy that consists of 6% of aluminum and 4% of vanadium. It has a higher strength-to-weight ratio and has great biocompatibility. It is also considered a better corrosion resistive material compared to materials such as stainless steel and various alloys based on cobalt (Arrazola 2009; Khanna 2021a). It is the most commonly preferred material in the aerospace industry due to its lower density, higher strength, and corrosion resistive properties (Gupta 2021). Titanium alloys can be used when direct contact with a bone or tissue is required because of their great biocompatibility (Haghighat 2021). Conventional machining of titanium alloys is difficult owing to their high hardness, higher chemical reactivity, and lower thermal conductivity (Chaudhari et al. 2019, 2020c, d). Furthermore, as the material is very hard, the tool wear rate is very high and the time consumed to machine it is also very high. Various types of coolants are used to decrease the amount of heat generated among the workpiece and the tool, which significantly elevates the cost of production. The incongruities during machining make it challenging to imagine outcomes. Oke et al. (2020) concluded that in traditional machining, the common procedure to date is to cut titanium at high depth, however, with a lower cutting speed. Hence, compared to traditional steel machining the rate of production is significantly reduced. Cutting apparatuses and workpieces undergo a substantial amount of damage, which has been accounted as a significant challenge while machining alloys of titanium utilizing conventional methods of machining. Hence, non-conventional techniques are used to machine this element.

Wire electrical discharge machining (WEDM) is one such unconventional method of machining that can be used to machine titanium alloys (Chaudhari 2019; Prasad et al. 2021). WEDM uses sparks that are generated between the metal workpiece and the tool to remove the material (Sheth et al. 2020; Rathi et al. 2020; Chaudhari et al. 2020e). Materials like titanium alloys are difficult to machine, and WEDM can be used to machine such materials economically and effectively. There are many input process parameters through which one can machine an element and obtain the desired output. WEDM method has numerous process variables which needed to be controlled to acquire a better surface. Along with better surface integrity, higher productivity is also a key requirement of any industry that can be obtained by increasing MRR and simultaneously decreasing SR value. Nanopowder-mixed dielectric fluid for the WEDM process is one of the ways of improving the process capabilities and achieving both objectives simultaneously. Prasad et al. (2021) concluded that T_{ON} and peak current were the most considerable factors on which R_a and MRR were dependent while machining Ti6Al4V using WEDM. Dabade and Karidkar (2016) used L8 orthogonal array (OA) for determining the influence of machining variables on MRR, Kerf width, dimensional deviation, and SR while machining Inconel 718 through WEDM. They concluded that T_{on} was the most important parameter among other parameters. Sivaprakasam et al. (2014) performed micro-WEDM on titanium alloy and with the help of ANOVA determined that voltage, feed rate, and interaction of voltage and capacitance were the most significant parameters for MRR, kerf width, and SR. Chakraborty et al. (2020a) mixed boron carbide (B_4C) of grain size 10 μm with different dielectrics like kerosene, deionized water, and surfactant added deionized water for machining titanium alloy with WEDM. Porwal and Maurya (2019) reviewed that for determining the optimal limit of response variables like MRR, SR, Kerf width. Artificial neural network (ANN) modeling is a better approach compared to mathematical modeling. Pramanik et al. (2019) performed WEDM on titanium alloy and conveyed how the output parameters kerf width, MRR, discharge gap, and wire degradation were affected by input parameters like pulse on time, flushing pressure, and wire tension. Chakraborty et al. (2020b) conducted powder mixed wire EDM (PMWEDM) on Ti6Al4V and concluded that in order to achieve high productivity with lower energy consumption, low pulse is favored. Yi et al. (2017) used cutting fluid suspended with graphene oxide for the drilling of Ti6Al4V and determined that there was a significant improvement in SR up to 15.1% and also the cutting force reduced by 17.21% when graphene oxide was mixed with cutting fluid compared to conventional cutting fluid. A review study conducted by Gupta et al. (2020) showed that powder mixed dielectric fluid has shown better machining of titanium alloys. A comparative study between the regression model and adaptive-network-based fuzzy inference system (ANFIS) model was conducted by Kumar et al. (2019) concluded that the ANFIS model performed better than the regression model in predicting SR and MRR while machining Ti-6Al-4 V. A research experiment conducted by Gugulothu (2020) determined that drinking water was a better dielectric fluid compared to deionized water and the mixture of deionized and drinking water during the electrical discharge machining of titanium alloy. Also, applying analysis of variance (ANOVA) it was figured that T_{on} has a major impact on SR, whereas for MRR the discharge current plays a similar role.

In this paper, Taguchi's L9 orthogonal array was used to conduct the experiments of Ti6Al4V alloy. Selected input WEDM process parameters based on past the literature include pulse on time (T_{on}), pulse off time (T_{off}), and current while MRR and SR as the response variables. The adequacy and significance of machining parameters were tested by ANOVA for each response variable. Taguchi's approach has a limitation of attaining only one response variable at a time. According to the same, the GRA technique along with Taguchi's design was used for attaining multiple objectives simultaneously. A validation study was conducted to verify obtained results from optimization. Nanopowder-mixed dielectric fluid for the WEDM process can improve the process capabilities. Pursuant to the same, at optimized parameter settings obtained, alumina powder was mixed with dielectric fluid at a concentration of 1 g/l, and results were compared to understand the significance of the PMWEDM process.

2 Experimental Setup and Experimentation

Experiments of the present study were performed on concord wire-cut EDM apparatus (DK7732) by using work material of titanium-based alloy Ti6Al4V having dimensions of 10 mm diameter rod. Figure 1 shows the experimental setup of the WEDM process used in the current study. A wire of material molybdenum having a diameter of 0.18 mm is used as a tool electrode along with deionized water as dielectric fluid. The effect of nano-alumina (Al_2O_3) powder concentration mixed dielectric fluid on selected response variables (MRR and SR) has been studied by comparing the results obtained between with and without the addition of nano-alumina powder in dielectric fluid. Nano-alumina powder was mixed properly with dielectric fluid in the main tank, and then it was sprayed through nozzles in the machined zone. SR and MRR were considered as process variables for output, whereas discharge current, $T_{on,}$ and T_{off} were selected as machining variables. For the experimentation, three levels for each of the three control parameters were selected using Taguchi's L9 orthogonal array. All the experiments were repeated 3 times for better accuracy, and the average value has been considered for analysis. MRR was determined by dividing the difference between the initial mass and the final mass after machining against the time taken to machine it. On the other hand, the measurement of SR was

Fig. 1 WEDM setup

Table 1 Taguchi's L9 array with experimental results

Sr. no	T_{on} (µs)	T_{off} (µs)	Current (A)	MRR (gram/sec)	SR (µm)
1	60	5	3	0.003217	5.55
2	60	10	4	0.003571	6.2
3	60	15	5	0.003700	7.16
4	80	5	4	0.004545	6.8
5	80	10	5	0.004774	7.5
6	80	15	3	0.003947	5.21
7	100	5	5	0.005681	7.6
8	100	10	3	0.004518	6.02
9	100	15	4	0.004838	7.13

completed using Mitutoyo make surftest SJ-410 model. The values were obtained experimentally for SR and MRR for the selected nine trials as shown in Table 1.

3 Results and Discussion

3.1 Analysis of Response Variables

MRR plays an important role in increasing productivity, and hence, higher MRR is a favorable outcome for the experiment. Table 1 represents MRR values for the preferred trials of experimentation. Minitab 14 statistical software was considered for the analysis of the experimental data. To obtain the input process variables on each of the output process variables, analysis of variance or ANOVA approach was utilized, with a confidence level of 95%. Table 2 shows the significance of input variables T_{on}, T_{off}, and discharge current on the output parameter MRR. The close relation of the R-square values signifies that the model is appropriate for MRR. As we have considered a confidence level of 95%, the value P for any input parameter should be lesser than

Table 2 ANOVA for MRR and SR

Source	DF	Adj SS	Adj MS	F Value	P Value
ANOVA for MRR					
T_{ON}	2	0.000004	0.000002	94.87	0.01
T_{OFF}	2	0	0	4.21	0.192
Current	2	0.000001	0.000001	27.59	0.035
Error	2	0	0		
Total	8	0.000005			

(continued)

Table 2 (continued)

Source	DF	Adj SS	Adj MS	F Value	P Value
R-sq = 99.22%, R-sq(adj) = 96.87%					
ANOVA for SR					
T_{ON}	2	0.58702	0.29351	2.25	0.308
T_{OFF}	2	0.03376	0.01688	0.13	0.886
Current	2	5.08776	2.54388	19.49	0.049
Error	2	0.26109	0.13054		
Total	8	5.96962			
R-sq = 95.63%, R-sq(adj) = 82.51%					

0.05 to consider that parameter as significant (Chaurasia et al. 2019; Wankhede et al. 2020). The value of P for T_{off} is greater than 0.05, and hence, it can be considered as an insignificant parameter for MRR. The most important parameter for MRR is T_{on} with a contribution of 80% followed by discharge current and T_{off}. Figure 2 shows the influence of the three parameters at various levels of input on MRR. The increase in discharge current elevates the discharge energy which causes the rise in MRR. The increase in the value of T_{on} signifies a rise in the duration of a spark which causes the discharge energy to increase. The reason for this can be attributed to the fact that as T_{on} and current increase, discharge energy and spark intensity also upsurge which causes a rise in the melting and vaporization of the material from the workpiece at

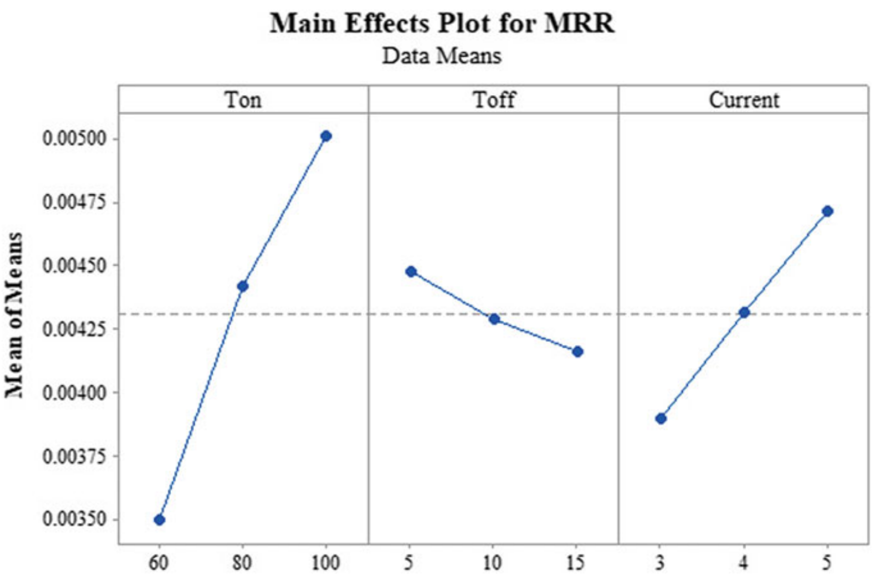

Fig. 2 Main effect plot for MRR

the machining zone resulting in the escalation of MRR (Chaudhari 2019). Hence, an increase in T_{on} increases MRR. However, a continuous decrease in the value of MRR has been observed with an increase in the value of T_{off} because this is due to the absence of the spark during the machining (Chaudhari 2019).

To acquire better surface quality, the minimum value of SR is desired. Table 2 shows ANOVA for surface roughness. As per ANOVA, current plays the most dominant role on the surface roughness with 85.22% contribution. As the value of P was observed to be less than 0.5 for T_{on} and T_{off} which shows that T_{on} and T_{off} are not affecting SR. An extreme close relation between the R-squared values shows the adequacy of the model. A major impact plot for surface roughness contemplating the disparity in the level of input parameters is demonstrated in Fig. 3. Figure 3 shows that the value of SR was observed as increasing with an increase in the value of T_{on}. Because of the increase in the value of T_{on}, the discharge energy increases; this in succession raises the rate of melting and induces to inflate crater size and provides higher SR (Chaudhari et al. 2020c). The amount of SR is found to be decreasing as T_{off} increases. This is due to the decrease in discharge energy with an increase in T_{off}. With the increase in current, the SR appears to be increasing. Ionization of deionized water happens when a high current flows, which generates high discharge and thermal energy (Chaudhari et al. 2020c). Hence, it creates deeper and larger craters and elevates surface roughness.

For MRR, $A_3B_1C_3$ is achieved as an ideal combination of input parameters. From the investigations in the L9 symmetrical exhibit, run 6 delivered the finest MRR of 0.005681 g/s. Furthermore, in the case of SR, the best performing combination

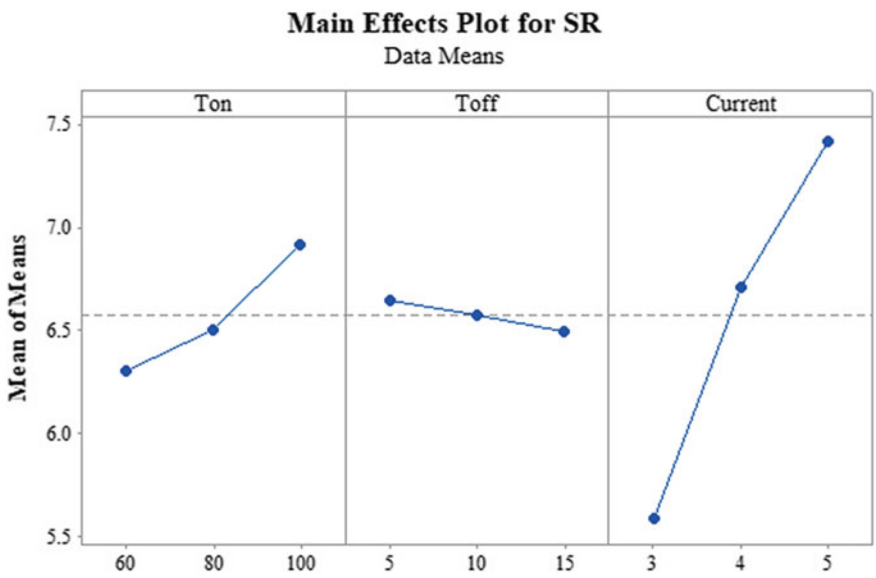

Fig. 3 Main effect plot for SR

Table 3 Validation trial

	Predicted	Experimental
Levels	$A_3B_1C_1$	$A_3B_1C_1$
MRR (gram/s)	0.004768	0.004783
SR (μm)	6.01	6.04

came out to be $A_1B_3C_1$. However, it can be observed that the optimal combination of machining parameters is not the same for both the selected objectives, which shows the need for a suitable optimization technique.

3.2 Optimization

Taguchi's methodology can enhance only a single objective at a time without considering its impact on other output parameters. To fulfill such contradicting objectives at a time, an idea parameter setting is essential. Thereby with the help of GRA, the problem can be converted into a single objective problem. Implementation of the GRA technique has yielded an optimal combination of machining parameters as $A_3B_1C_1$ as shown in Table 3. A validation trial has been conducted to verify obtained results from GRA. Close relation can be seen between the predicted and measured values from Table 3. It shows that the developed model along with GRA was found to be capable of predicting and optimizing the process parameters.

3.3 Effect of Alumina Powder Concentration on Response Variables

WEDM process consists of multiple process variables which should be controlled to acquire great surface. Along with better surface integrity, higher productivity is also a key requirement of any industry that can be obtained by increasing MRR and simultaneously decreasing SR. Nanopowder-mixed dielectric fluid for the WEDM process is one of the ways of improving the process capabilities and achieving both objectives simultaneously. The effect of nano-alumina (Al_2O_3) powder concentration mixed dielectric fluid on selected response variables (MRR and SR) has been studied by comparing the results obtained between with and without the addition of nano-alumina powder in dielectric fluid. Nano-alumina powder was mixed properly with dielectric fluid in the main tank, and then it was sprayed through nozzles in the machined zone. For comparison of results, two experiments were conducted at optimal parameters settings obtained from GRA. The obtained results are shown in Table 4. The MRR and SR values with the addition of nano-alumina powder were obtained as 0.005782 g/s and 4.95 μm, respectively, at input parameters of T_{on} at 100 μs, T_{on} at 5 μs, current at 3 A, and powder concentration at 1 g/l. An increase in

Table 4 Effect of nano-alumina powder on MRR and SR

Condition	Input process parameters	Response variables
With addition of Nano-Alumina powder at 1 g/l	Pulse on time = 100 µs Pulse off time = 5 µs Current = 3 A Powder conc. = 1 g/l	MRR = 0.006241 g/sec SR = 4.55 µm
Without Nano-Alumina powder	Pulse on time = 100 µs Pulse off time = 5 µs Current = 3 A Powder conc. = 0 g/l	MRR = 0.004768 g/sec SR = 6.01 µm

nano-alumina powder concentration has increased MRR due to a higher erosion rate and simultaneously decreases SR due to uniform sparking distribution and uniform flushing of debris (Yih-Fong and Fu-Chen 2005; Chaudhari et al. 2021). It can be observed from Table 4 that MRR and SR of the Ti6Al4V were improved by 23.62% and 31.86%, respectively, with the addition of nano-alumina powder concentration with dielectric fluid at 1 g/l.

4 Conclusions

In the current study, the impact of T_{on}, T_{off}, and discharge current on resulting factors like MRR and SR are examined through the WEDM process for Ti6Al4V. The significance of input parametric quantities such as T_{on} and discharge current is dominant for MRR, whereas in the case of SR, discharge current played a major role. By analyzing the data on ANOVA for MRR, T_{on} came out to be the major affecting factor with the contribution of 80% followed by discharge current. On contrary, change in T_{off} does not show any effect on MRR. Furthermore, the key contribution of about 85.22% by discharge current followed by T_{on} with 9.83% and T_{off} with 0.56% was discovered for the output variable of SR. For both MRR and SR, a very close relationship with the least difference was observed between R-squared and Adj R-squared for SR which shows the suitability of machining parameters. Through GRA, the optimum parametric settings for maximizing MRR and minimizing SR were unveiled to be $A_3B_1C_1$ (T_{on} = 100 µs, T_{off} = 5 µs, and current = 3 A). A validation study showed a negligible difference between predicted and examined values. Lastly, results obtained by GRA at optimal parameter settings were compared with nano-alumina powder mixed with dielectric fluid at a concentration of 1 g/l. It was found that MRR and SR of the Ti6Al4V were improved by 23.62% and 31.86%, respectively, with the addition of nano-alumina powder concentration with dielectric fluid at 1 g/l.

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