Investigation of material removal rate on Ti-6Al-4V super alloy

Kaustab Sharma¹, Ashish Goyal², Ashok Kumar Sharma³
¹,³Department of Mechanical Engineering, Manipal University Jaipur, Dehmi Kalan, Jaipur, Rajasthan, India, 303007
ashish.goyal@jaipur.manipal.edu

Abstract. The machining of hard material is a challenging task by the conventional machining process. The present experimental study on machining of titanium alloy by the Wire cur electric discharge machining process (WEDM). Experimental has been performed by using the pulse on-time, pulse off-time, peak current, servo voltage and wire tension as input parameters and effect of these input parameters identified on the material removal rate. The design of experimental methodology has used to perform the experiment. Total 27 experiments were performed to identify the optimum material removal rate. The analysis of variance has also applied to process parameters to investigate the significant and non-significant parameters. The experimental results show that the peak current and wire tension has the most significant parameters to influence the material removal rate.

1. Introduction
Machining of Ti-6Al-4V alloy is very tough task by traditional machining methods viz. turning, milling and grinding as of its high hardness and high melting temperature. [1-3]. Wire EDM process is the most suitable process to machine these hard materials such as titanium alloy, shape memory alloy, Inconel alloy etc. Wire electro-discharge machining process was found to be a very influential electro-thermal technique for machining Ti-6Al-4V alloy with any intricate shape. [4-6]. Manjaiah et. al found that the machined surface hardness increases with respect to the base material for longer pulse on time due to the recast layer thickness. It was concluded that the pulse on time and servo voltage have significant on material removal rate and surface roughness [7]. Goyal et. al and Goyal proposed that cryogenically treated tool electrode, current and pulse on time are the major factors that
affect the material removal rate and in turn affects surface roughness also using a cryogenically treated tool electrode results in significant reduction in tool wear rate. [8-9]

Soni et. al showed that formation of micro cracks, micro globules and micro voids occur at high pulse on time [10]. Rasheed et. al found capacitance as the most influencing factor on MRR, TWR and surface roughness [11]. Kale et. al reviewed that cryogenic cooling and machining techniques improve the machining of super alloys in terms of surface integrity and tool life [12]. Feng et. al analysed that on adding Mo to NiTi there is a reduction in MRR, EWR, surface roughness, and recast layer thickness because of increased melting temperature and thermal conductivity of the material [13]. Kumar et. al reported WEDM as an adequate process to machine high strength temperature resistant materials with very little dimensional deviation, also the dimensional deviation is affected by pulse on time, pulse off time, peak current, and servo voltage [14]. Metal removal rate and surface finish were optimized by Scott et al. by explicit by design of experiment approach. The optimum machining condition has been obtaining for the MRR and SR response. Albeit many studies have been carried out in the past and reported in literatures on WEDM of Titanium alloy, but very few scholarly works have been carried out in regards of machining performance. This research focuses on WEDM machining of Ti-6Al-4V for the fabrication of slots for the industrial applications. The figure 1 presents the cause and effect diagram of the WEDM parameters. The figure shoes the important WEDM parameters that are being utilized to maintain during the machining to get the better response from the machine.

2. Experimental methodology:

The Elektra Maxicut 734, Electronica wire EDM machine has used for the experiment purpose. The figure 2 presents WEDM machine which is used for the experimental work. The zinc coated brass wire used as a tool electrode. the diameter of wire was 0.25mm. Ti-6Al-4V alloy has used as a specimen. The dimension of plates was 176mm x 55mm x 2.5mm. The peak current, pulse on time, pulse off time, wire tension and voltage has used as machining parameters and the influence of these machining parameters has been found on material removal rate. The material MRR has calculated as the ratio of the difference of weight of the workpiece before and after machining to the machining time and density of the material.

\[
\text{Material removal rate} = \frac{(W_b - W_a)}{\rho \times t} \text{ mm}^3/\text{s}
\]

Whereas, \(W_b\) = Weight of workpiece before machining.
\(W_a\) = Weight of workpiece after machining.
\(t\) = Machining time in seconds

\[
\text{Material removal rate} = \frac{(W_b - W_a)}{\rho \times t} \text{ mm}^3/\text{s}
\]
\[ \rho = \text{Density of titanium grade-5} = 4.42 \times 10^{-3} \text{ g/mm}^3 \]

The influence of various operation parameters like pulse-on-time, pulse-off-time, current, wire feed rate, wire tension was studied on WEDM on the response i.e. material removal rate. Table 1 presents the selected control factors and their levels for the machining purpose.

Figure 1: cause and effect diagram of WEDM process parameters

Figure 2: WEDM machine set up
3. Results and discussion:

The experimental result for material removal rate of Ti-6Al-4V with different process parameters is presented. Based on results, the Signal to Noise (S/N) ratio plot for MRR has presented in figure 5. It is inferred that, the MRR increases with increase in pulse on time \( T_{\text{on}} \). Increase in \( T_{\text{on}} \) results into high discharge energy that increases the MRR. It is observed that MRR initially decreases with increase in peak current and then starts to rise. Increase in settings of peak current viz. 5 & 15 A respectively. This may be attributed to the availability of higher discharge energy, at high current levels 5 and 15 A.
Table 1: Control factor and their levels

| S.No. | Control factor    | Level 1 | Level 2 | Level 3 | Units |
|-------|-------------------|---------|---------|---------|-------|
| 1     | Peak current      | 5       | 10      | 15      | A     |
| 2.    | Pulse on time     | 115     | 145     | 165     | µs    |
| 3.    | Pulse off time    | 60      | 70      | 80      | µs    |
| 4.    | Wire tension      | 7       | 8       | 9       | N     |
| 5.    | Voltage           | 3-      | 50      | 70      | V     |

Higher discharge energy rapidly overheats the work material which promotes larger melting and vaporization of the work material to generate large craters. This observation is in consonance to the past observations made by the researchers (Mohan et al. 2004). It is observed that MRR increases with increase in current and then after it start decreasing. This may be due to the presence of enough the machining debris in the di-electric fluid, which modifies the plasma channel, enlarging and widening the plasma channel, which reduces the MRR. The voltage doesn’t have any significant effect on MRR. As shown in table 3, among all the process parameters considered, peak current is the most significant in terms of MRR because it has the largest impact and has been ranked one, while wire tension is the second most important process parameter due to its dominant control over the spark discharge energy leading to an increase in MRR. The graph of the main effects of one noise factor and five control factors based on the S/N ratio for the MRR is shown in figure 6.1. The optimal parametric settings are A3, B2, C1, D3 and E3.

Table 2: L27 Orthogonal array for the input parameters and MRR

| S.no. | Ton  | Toff | Voltage | Ip | Wt | MRR   |
|-------|------|------|---------|----|----|-------|
| 1.    | 115  | 60   | 30      | 5  | 7  | 0.1289|
| 2.    | 115  | 60   | 30      | 5  | 8  | 0.1302|
| 3.    | 115  | 60   | 30      | 5  | 9  | 0.1268|
| 4.    | 115  | 70   | 50      | 10 | 7  | 0.134 |
| 5.    | 115  | 70   | 50      | 10 | 8  | 0.1364|
| 6.    | 115  | 70   | 50      | 10 | 9  | 0.1421|
| 7.    | 115  | 80   | 70      | 15 | 7  | 0.1446|
| 8.    | 115  | 80   | 70      | 15 | 8  | 0.1493|
| 9.    | 115  | 80   | 70      | 15 | 9  | 0.1527|
| 10.   | 145  | 60   | 50      | 15 | 7  | 0.1772|
| 11.   | 145  | 60   | 50      | 15 | 8  | 0.1611|
|   | Peak Current | Pulse on time | Pulse off time |
|---|--------------|---------------|---------------|
| 12| 145          | 60            | 50            |
| 13| 145          | 70            | 5             |
| 14| 145          | 70            | 5             |
| 15| 145          | 70            | 5             |
| 16| 145          | 80            | 30            |
| 17| 145          | 80            | 30            |
| 18| 145          | 80            | 30            |
| 19| 160          | 60            | 70            |
| 20| 160          | 60            | 70            |
| 21| 160          | 60            | 70            |
| 22| 160          | 70            | 30            |
| 23| 160          | 70            | 30            |
| 24| 160          | 70            | 30            |
| 25| 160          | 80            | 50            |
| 26| 160          | 80            | 50            |
| 27| 160          | 80            | 50            |

Figure 5: S/N plot for material removal rate

Table 3: Response table for material removal rate (Means)
Table 4 shows the results of analysis of variance based on the S/N ratio for MRR. The S/N ratio calculated for MRR from the observed experimental data has been used to analyse ANOVA and F-test, in order to determine the effects of each parameter on the MRR. It is found that peak current, pulse on time, pulse off time and wire tension have a large impact on the MRR at 95% confidence interval level since p-value is less than 0.05. Figure 6 shows the interaction plot for S/N ratio of the MRR between the process parameters and the material removal rate. It can be clearly observed that, since the lines are not parallel to each other, there is some interaction between the input parameters and the material removal rate. The R-Seq (adj) value is 96.81% which shows the present model have lie significant for the wire EDM process parameters.

Table 4: Analysis of Variance for MRR

| Source         | DF  | Seq SS      | Adj SS     | Adj MS     | F        | P        |
|----------------|-----|-------------|------------|------------|----------|----------|
| Peak current   | 2   | 0.117397    | 0.117397   | 0.058699   | 298.01   | 0.000    |
| Pulse on time  | 2   | 0.014246    | 0.014246   | 0.007123   | 36.16    | 0.000    |
| Pulse off time | 2   | 0.009455    | 0.009455   | 0.004727   | 24.00    | 0.000    |
| Wire tension   | 2   | 0.015229    | 0.015229   | 0.007615   | 38.66    | 0.000    |
| Voltage        | 2   | 0.000910    | 0.000910   | 0.000455   | 2.31     | 0.131    |
| Error          | 16  | 0.000910    | 0.000910   | 0.000455   |          |          |
| Total          | 26  | 0.160389    |            |            |          |          |
4. Conclusion:
- The peak current parameter has most significant effect on the material removal rate followed by the wire tension. The voltage is found the insignificant parameters for the present study.
- The material removal rate (MRR) directly increases with increase in pulse on time (Ton) and peak current (IP) while decreases with increase in pulse off time (Toff) and servo voltage (SV).
- Through this investigation, we have quantified MRR as a function of various parameters involved in the material removal process. These results will be of significant help in the future to determine the material removal parameters for most efficient results.
- Super alloys cannot normally be machined properly. With the use of Wire EDM process, super alloys which have not been used extensively can now be investigated.

Reference:
- Lin, H. C., K. M. Lin, and I. S. Cheng 2000. "The wire electro-discharge machining characteristics of TiNi shape memory alloys." High Temperature Material Processes: An International Quarterly of High-Technology Plasma Processes 4, no. 4.
- Kuriakose, Shajan, Kamal Mohan, and M. S. Shunmugam 2003. "Data mining applied to wire-EDM process." Journal of Materials Processing Technology 142, no. 1 182-189.
- Liao, Y. S., J. T. Huang, and Y. H. Chen 2004. "A study to achieve a fine surface finish in Wire-EDM." Journal of Materials Processing Technology 149, no. 1-3 165-171.
- Lok, Y. K., and T. C. Lee 1997. "Processing of advanced ceramics using the wire-cut EDM process." Journal of materials processing technology 63, no. 1-3 839-843.
- Peng, W. Y., and Y. S. Liao 2003. "Study of electrical discharge machining technology for slicing silicon ingots." Journal of Materials Processing Technology 140, no. 1-3 274-279.
- Yan, Biing Hwa, Hsien Chung Tsai, Fuang Yuan Huang, and Long Chorng Lee 2005. "Examination of wire electrical discharge machining of Al2O3p/6061Al composites." International Journal of Machine Tools and Manufacture 45, no. 3 251-259.
- Manjaiah, M., Narendranath, S., Basavarajappa, S., & Gaitonde, V. N. 2016. Influence of process parameters on material removal rate and surface roughness in WED-machining of Ti50Ni40Cu10 shape memory alloy. International Journal of Machining and Machinability of Materials, 18(1-2), 36-53.
- Goyal, A. 2017. Investigation of material removal rate and surface roughness during wire electrical discharge machining (WEDM) of Inconel 625 super alloy by cryogenic treated tool electrode. Journal of King Saud University-Science, 29(4), 528-535.
- Goyal, A., Pandey, A., & Sharma, P. 2017. Machinability of Inconel 625 Aerospace Material Using Cryogenically Treated WEDM. In Solid State Phenomena (Vol. 266, pp. 38-42). Trans Tech Publications.
- Soni, H., Sannayellappa, N., & Rangarasaiah, R. M. 2017. An experimental study of influence of wire electro discharge machining parameters on surface integrity of TiNiCo shape memory alloy. Journal of Materials Research, 32(16), 3100-3108.
- Rasheed, M. S., Al-Ahmari, A. M., El-Tamimi, A. M., & Abidi, M. H. 2012. Analysis of influence of micro-EDM parameters on MRR, TWR and Ra in machining Ni-Ti shape memory alloy. International Journal of Recent Technology and Engineering, 1(4), 32-37.
- Kale, A., & Khanna, N. 2017. A Review on Cryogenic Machining of Super alloys Used in Aerospace Industry. Procedia Manufacturing, 7, 191-197.
- S. F. Hsieh, M. H. Lin, S. L. Chen, S. F. Ou, T. S. Huang, and X. Q. Zhou, 2016. “Surface modification and machining of TiNi/TiNb-based alloys by electrical discharge machining,” Int. J. Adv. Manuf. Technol., vol. 86, no. 5–8, pp. 1475–1485.
- Kumar, A., Kumar, V., & Kumar, J. 2013. Effect of machining parameters on dimensional deviation in wire electro discharge machining process using pure titanium. Journal of Engineering and Technology, 3(2), 105-112.
- D. Scott, S Boyna, K P Rajurkar, 1991 Analysis and optimization of parameter combinations in WEDM, Int. J. Prod. Res. 29. 2189–2207.