Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.4, December : 2024

PARAMETRIC ANALYSIS OF TOOL ROTATIONAL SPEED AND CURRENT ON MICRO EDM OF DIFFICULT-TO-MACHINE TITANIUM ALUMINIDE ALLOY

Pranav Ravindrannair, Research Scholar, Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad
Dr K.Kishore, Professor, Department of Mechanical Engineering, Vasavi College of Engineering, Hyderabad
Dr P.Laxminarayana, Senior Professor, Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad

ABSTRACT:
Titanium aluminide alloys, such as Ti-48Al-2Cr-2Nb, Ti-46.5Al-2Cr-3.5Nb-0.3B, and Ti-46.5Al-5Nb-2Mo-0.3B, present significant challenges in machining due to their inherent hardness and heat resistance. This study investigates the micro Electrical Discharge Machining (EDM) drilling process on these alloys, focusing on the effects of two critical process parameters: current and tool rotational speed. Using a 0.5mm diameter hollow copper electrode, experiments were conducted to analyze the Material Removal Rate (MRR) and Tool Wear Rate (TWR). The study demonstrates how each parameter affects machining performance, with comprehensive data visualizations showcasing these relationships. Copper electrodes were selected for their superior electrical conductivity, thermal management, and surface finish quality compared to alternatives like graphite and brass. The results indicate that optimized parameter settings can significantly improve machining efficiency while minimizing tool wear, making micro EDM drilling a viable method for processing difficult-to-machine titanium aluminide alloys.
Keywords: Titanium Aluminides, EDM Drilling, MRR, TWR

INTRODUCTION:
Titanium aluminide alloys have garnered considerable interest in the aerospace and automotive industries owing to their notable characteristics, including high specific strength, exceptional oxidation and corrosion resistance, and low density. Titanium aluminides possess a set of characteristics that render them highly suitable for high-temperature applications, particularly in cases where the reduction of weight is of utmost importance. Nevertheless, the inherent brittleness, low ductility, and high hardness of the material present considerable obstacles in traditional machining techniques. It has been observed that the utilization of conventional techniques frequently results in elevated tool wear, suboptimal surface finish, and reduced rates of material removal. Consequently, the efficient machining of these alloys becomes a challenging task.
The utilization of Micro Electrical Discharge Machining (EDM) has recently gained significant attention as a potentially effective method for machining materials that are known to be challenging to machine, such as titanium aluminides. EDM, also known as Electrical Discharge Machining, is a unique machining process that distinguishes itself from conventional methods by being a non-contact process. Instead of physically cutting or grinding the material, EDM utilizes controlled electrical discharges between an electrode and the workpiece. These electrical discharges occur in the presence of a dielectric fluid, which helps facilitate the material removal process. The utilization of this technique enables the achievement of highly accurate machining of materials with high hardness, all while avoiding the introduction of any mechanical stresses. The efficiency of the Electrical Discharge Machining (EDM) process is significantly influenced by the careful selection of suitable process parameters. These parameters include voltage, current, pulse duration, and electrode rotational speed. Additionally, the choice of electrode material also plays a crucial role in determining the efficiency of the EDM process.

The objective of this research is to examine the micro EDM drilling process as it pertains to three distinct titanium aluminide alloys, namely Ti-48Al-2Cr-2Nb, Ti-46.5Al-2Cr-3.5Nb-0.3B, and Ti-46.5Al-5Nb-2Mo-0.3B. The alloys under consideration have gained recognition for their remarkable ability to withstand high temperatures, although they are widely acknowledged to pose significant challenges in terms of machining. The main focus of this research is to conduct an extensive parametric analysis in order to gain a comprehensive understanding of the impact of various key process parameters, such as current and tool rotational speed on the Material Removal Rate (MRR) and Tool Wear Rate (TWR).

The choice of copper as the electrode material was made based on its exceptional electrical conductivity, thermal properties, and capacity to yield a surface finish of superior quality. After careful consideration, it was determined that copper was the most suitable choice for this application due to its unique combination of properties. While other materials, such as graphite and brass, were also taken into account, copper stood out as the optimal option. In order to achieve high precision and performance in micro EDM drilling, a hollow electrode design was utilized. This design was chosen because it has been found to enhance debris removal, cooling efficiency, and reduce electrode wear. These factors are critical in the successful execution of micro EDM drilling.

The present study showcases the results obtained through a thorough parametric analysis, thereby providing valuable insights into the most favorable configurations for micro EDM drilling of titanium aluminide alloys. The findings of this study shed light on the significant impact that each parameter has on Material Removal Rate (MRR) and Tool Wear Rate (TWR). These insights offer valuable guidance for enhancing the efficiency of machining processes and prolonging the lifespan of tools in various industrial applications.

CHALLENGES AND BACKGROUND WORK:

Titanium aluminide alloys are a class of materials that have garnered significant attention due to their unique properties and potential applications. These alloys are composed of titanium and aluminum, with the addition of other elements to enhance their mechanical and thermal properties. The combination of titanium and aluminum results in a lightweight material with excellent strength-to-weight ratio, high temperature resistance, and good corrosion resistance. However, despite their promising properties

Titanium aluminides, specifically γ-TiAl alloys, have been increasingly recognized in the field of high-performance applications owing to their remarkable specific strength, exceptional thermal stability at elevated temperatures, and outstanding resistance to oxidation and corrosion. The utilization of these alloys has been steadily growing in the aerospace and automotive sectors, primarily for the production of critical components like turbine blades, exhaust valves, and structural parts. These components are subjected to highly demanding operating conditions, necessitating materials with exceptional durability and resistance. Nevertheless, it is worth noting that titanium aluminides, despite their numerous desirable properties, pose significant challenges when it comes to machining processes. The low ductility and high hardness of the material under consideration lead to accelerated tool wear and suboptimal surface finish when employing traditional machining techniques. The brittleness of the material presents a notable hazard of cracking and chipping when subjected to machining, thereby adding complexity to the manufacturing procedure.

Previous research conducted by Wang et al. [1] and Kim et al. [2] has shed light on the difficulties that arise when attempting to machine titanium aluminides using conventional methods such as milling and turning. The aforementioned studies emphasize the necessity of employing non-traditional machining techniques capable of accommodating the distinctive characteristics of the material, while simultaneously ensuring the preservation of the workpiece's structural soundness. As

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.4, December : 2024

a result, there has been an increasing fascination with investigating advanced machining techniques, such as Electrical Discharge Machining (EDM), for the processing of these materials.
The topic of interest is the application of Electrical Discharge Machining (EDM) on Titanium Alloys. EDM is a non-traditional machining process that utilizes electrical discharges to remove material from the workpiece. Titanium alloys are widely used in various industries due to their excellent mechanical properties and corrosion resistance. However, these alloys are notoriously difficult to machine using conventional methods due to their high strength and low thermaL conductivity.
Electrical Discharge Machining (EDM) has been recognized as a feasible and effective method for machining materials that are known for their hardness and brittleness, such as titanium aluminides. The process known as Electrical Discharge Machining (EDM) is a non-contact method employed for material removal. It involves the utilization of electrical discharges that occur between an electrode and the workpiece, which is immersed in a dielectric fluid. The purpose of this process is to erode the material present on the workpiece. The process under consideration is highly suitable for the machining of titanium alloys owing to its exceptional capability to fabricate intricate geometries and process hard materials without causing any significant mechanical stresses.
The study conducted by Singh and Bhardwaj [3] provides evidence supporting the efficacy of Electrical Discharge Machining (EDM) in the processing of titanium alloys. This research highlights the limitations of conventional machining techniques in attaining the desired levels of precision and surface quality in such materials. The research study placed significant emphasis on the cruciality of carefully selecting suitable process parameters, including pulse on time, pulse off time, and discharge current. The objective was to achieve the optimization of material removal rate (MRR) and tool wear rate (TWR). In their study, Hascalik and Caydas [4] conducted further investigations to examine the influence of these parameters on the surface integrity of titanium alloys. They observed that incorrect settings could result in unfavorable consequences, including heightened surface roughness and the development of a recast layer.
The topic of electrode material selection in Electrical Discharge Machining (EDM) is a crucial aspect that requires careful consideration. EDM is a non-traditional machining process that utilizes electrical energy to remove material from a workpiece. The selection of the appropriate electrode material plays a significant role in determining the efficiency and effectiveness of the EDM
The selection of electrode material is of utmost importance in determining the effectiveness of the EDM (Electrical Discharge Machining) process, particularly in the context of machining difficult materials such as titanium aluminides. According to existing research, copper, graphite, and brass have emerged as the most frequently employed electrode materials in various applications. These materials have been chosen due to their unique characteristics and properties, which offer certain advantages and limitations in different scenarios.
It is widely acknowledged in the field that copper is an electrode material of great merit for Electrical Discharge Machining (EDM) owing to its exceptional electrical conductivity. This attribute guarantees the generation of sparks with high efficiency and ensures stable performance during the machining process. The findings of Yilmaz et al. [5] and Kansal et al. [6] provide empirical evidence supporting the notion that copper electrodes exhibit superior material removal rates (MRR) and result in improved surface finishes when compared to graphite and brass electrodes. Furthermore, it is worth noting that copper possesses exceptional thermal conductivity properties, which play a crucial role in efficiently dispersing heat. This attribute significantly mitigates the potential for thermal harm to both the electrode and the workpiece. Although copper is more expensive, it is frequently favored in applications that demand high precision and surface quality. Graphite electrodes, in contrast, are renowned for their comparatively lower cost and remarkable capability to be machined at elevated speeds. Nevertheless, it is worth noting that the comparatively lower

electrical conductivity of graphite may have an impact on the efficiency of spark generation. This, in turn, could potentially result in a decrease in Material Removal Rate (MRR) and lead to the production of surface finishes that are rougher in nature. The study conducted by Bhattacharya et al. [7] sheds light on the trade-offs associated with the utilization of graphite. The authors emphasize the higher rates of tool wear observed when using graphite, as well as the requirement for supplementary post-machining procedures to attain the desired surface finish.

Brass, while not as frequently utilized, presents a harmonious equilibrium between cost and performance. While it exhibits superior wear resistance compared to copper, it falls short in terms of electrical conductivity and surface finish capabilities when compared to copper. According to the findings of Kumar et al. [8], it has been observed that the use of brass electrodes can lead to a reduction in electrode wear. However, it is important to note that this advantage is accompanied by the drawback of longer machining times and a decrease in surface quality.

The impact of hollow electrode design in Electrical Discharge Machining (EDM) is a topic of interest in the field of manufacturing and materials engineering. Hollow electrode design refers to the use of electrodes with a hollow core, as opposed to solid electrodes, in the EDM process. This design variation has been found to have potential implications on various aspects of the EDM process, including machining efficiency and surface finish quality.

The influence of the electrode design on the efficiency and outcome of the EDM process, especially when working with difficult materials such as titanium aluminides, is of significant importance. Previous studies have demonstrated that hollow electrodes possess a range of benefits when compared to solid electrodes. These advantages primarily pertain to their ability to effectively remove debris, enhance cooling efficiency, and minimize electrode wear.

Previous studies conducted by Puri and Bhattacharyya [9] as well as Rajurkar et al. [10] have provided evidence to support the notion that the utilization of hollow electrodes can enhance the flushing capabilities of dielectric fluid. This, in turn, results in more effective removal of debris from the machining zone. The implementation of this technique aids in the preservation of consistent machining conditions, thereby mitigating the potential for short circuits and enhancing the overall precision of the machining process. The hollow design of the electrode is advantageous as it allows for improved heat dissipation. This is of utmost importance in order to minimize thermal damage to both the electrode and the workpiece, especially when working with heat-sensitive materials such as titanium aluminides.

According to research conducted by Li et al [11], it has been demonstrated that the utilization of hollow electrodes can result in a more even distribution of wear throughout the electrode. This, in turn, can lead to an increase in the lifespan of the electrode and enhance its cost-effectiveness. The hollow design of the cooling and flushing system offers improved capabilities for cooling and flushing, which in turn leads to increased machining speeds and enhanced surface finishes. As a result, this design is considered to be an excellent choice for high-precision applications.

Parametric analysis in electrical discharge machining (EDM) is a crucial aspect of understanding and optimizing the process. By systematically varying the key parameters involved in EDM, researchers can gain insights into the effects of these parameters on the machining performance and quality of the workpiece. Parametric analysis plays a crucial role in comprehending the correlation between process parameters in the EDM (Electrical Discharge Machining) and the resulting machining outcomes, including Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface quality. Through the systematic manipulation of parameters such as voltage, current, pulse on time, and tool rotational speed, researchers are able to discern the most favorable settings that result in the highest level of efficiency while simultaneously minimizing the wear and tear experienced by the tool. The seminal studies conducted by Mohri et al [12] and Ho and Newman [13] have laid the groundwork for comprehending the intricate relationship between various parameters of Electrical Discharge

Machining (EDM) and their impact on the overall machining process. The findings of these studies indicate that there is a positive correlation between discharge energy and material removal rate (MRR). This correlation is achieved by increasing both voltage and current. However, it is important to note that this enhancement in MRR comes at the expense of increased tool wear and surface roughness. On the other hand, by optimizing the pulse on time and pulse off time, it is possible to enhance the surface finish and decrease electrode wear, while not significantly affecting the material removal rate (MRR).

In a study conducted by Kumar and Batra [14], they utilized Taguchi and other statistical methods to optimize the parameters of Electrical Discharge Machining (EDM) for various materials, such as titanium alloys. The objective of their research was to enhance the efficiency and effectiveness of the EDM process by identifying the optimal combination of parameters for each specific material. The effectiveness of these approaches in identifying the most significant factors influencing EDM performance and establishing parameter settings that balance Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface quality has been demonstrated.

PROCEDURE:

Preparation: The titanium aluminide samples were first cut into appropriate sizes for the experiments. The surfaces were cleaned to remove any impurities that could affect the results.

Parameter Selection: A range of values for each of the two process parameters (current, and tool rotational speed) was selected based on preliminary experiments and literature review. Table 1 illustrates the Process Parameters and their ranges selected for the experiments.

Table 1: Process Parameters and their ranges

S.No	Parameter	Range
1	Tool Rotation Speed	0-200 RPM
2	Current	0-8 Amperes

Machining: The micro EDM drilling process was carried out on the prepared samples using the copper electrodes. The dielectric fluid used was a commercially available EDM oil, selected for its excellent insulating properties and ability to cool the machining area effectively.

Measurement: After each machining trial, the Material Removal Rate (MRR) and Tool Wear Rate (TWR) were measured. MRR was calculated based on the weight difference of the workpiece before and after machining, while TWR was determined by measuring the weight loss of the electrode.

Data Collection: Comprehensive data were collected for each combination of process parameters, with multiple trials conducted to ensure the reliability of the results..

OBSERVATIONS AND DISCUSSIONS :

Graph 1 presents illustrates the relationship between Material Removal Rate (MRR) and Tool Rotational Speed for three different titanium aluminide alloys—Ti-48Al-2Cr-2Nb, Ti-46.5Al-2Cr-3.5Nb-0.3B, and Ti-46.5Al-5Nb-2Mo-0.3B—under varying tool rotational speeds ranging from 0 to 200 rpm.

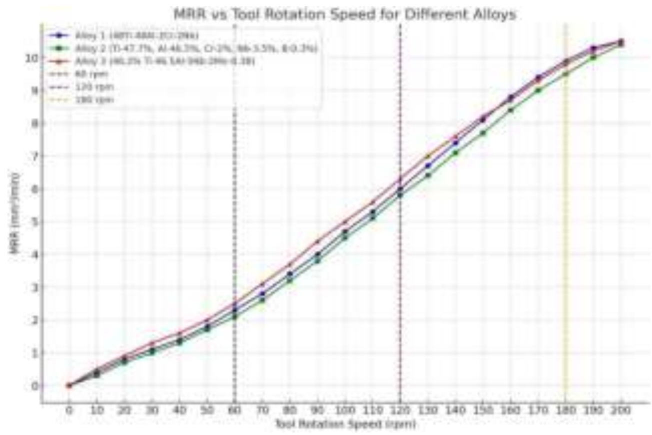
Across all three alloys, the MRR shows a clear positive correlation with increasing tool rotational speed. As the rotational speed increases, MRR consistently rises, suggesting that higher rotational speeds improve the efficiency of material removal during the micro EDM drilling process.The trend is notably consistent across all three alloys, indicating that the rotational speed is a significant factor in enhancing the machining performance for these difficult-to-machine materials. Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) consistently shows a slightly higher MRR across the range of rotational speeds compared to Alloy 1 and Alloy 2. This indicates that Alloy 3 may be more responsive to the micro

EDM process, possibly due to its specific composition, which may favor faster material removal at given process settings.Alloy 2 (Ti-46.5Al-2Cr-3.5Nb-0.3B) shows the lowest MRR across the same range of rotational speeds, suggesting it is the most challenging to machine among the three tested alloys, despite similar trends.

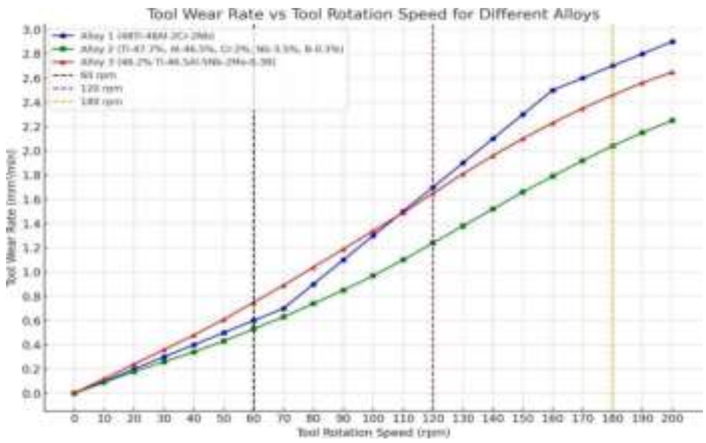
The vertical dashed lines represent key rotational speed thresholds at 60 rpm, 120 rpm, and 180 rpm. These thresholds mark significant points in the process where changes in the MRR slope are observed.

- 60 rpm: Below this speed, the MRR growth is relatively slow, indicating that low rotational speeds are less effective in enhancing material removal.
- 120 rpm: Around this speed, there is a noticeable increase in MRR growth rate, suggesting an optimal range for balancing tool wear and MRR.
- 180 rpm: As the speed approaches this threshold, MRR continues to increase sharply, but with a potentially higher risk of tool wear or surface quality degradation.

Meanwhile Graph 2 illustrates the observations for Tool Wear Rate (TWR) for the three alloys. From that we can understand that across all three alloys, TWR shows a consistent increase with rising tool rotational speed. This trend indicates that higher rotational speeds lead to more significant tool wear, which is a critical factor to consider when optimizing the machining process.The increase in TWR is more pronounced at higher rotational speeds, particularly beyond 120 rpm, suggesting that the benefits of increased MRR at these speeds come at the cost of accelerated tool degradation.



Graph 1: MRR vs Tool Rotation Speed for all three alloys



Graph 2: TWR vs Tool Rotation Speed for all three alloys

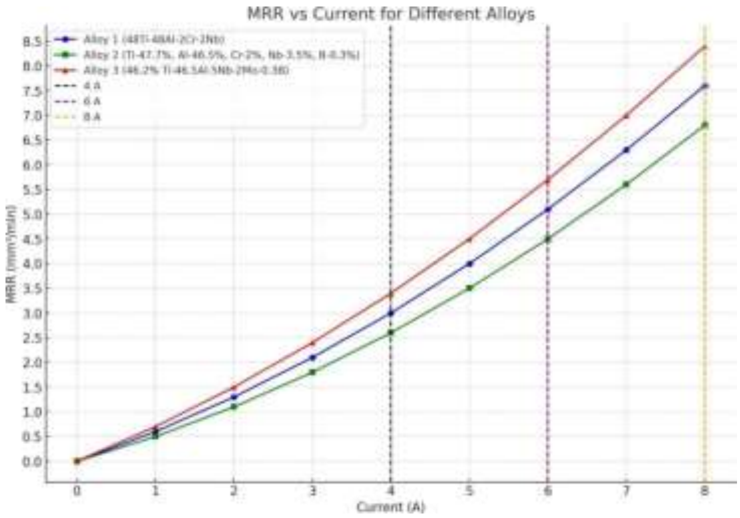
Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.4, December : 2024

Alloy 1 (Ti-48Al-2Cr-2Nb) exhibits the highest TWR across the entire range of rotational speeds, indicating that it is the most challenging to machine in terms of maintaining tool longevity. This could be attributed to its particular composition, which may cause more significant wear under similar conditions.Alloy 2 (Ti-46.5Al-2Cr-3.5Nb-0.3B) and Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) show relatively lower TWRs, with Alloy 3 demonstrating the least tool wear. This trend is consistent with its superior performance in MRR, suggesting that Alloy 3 may be more compatible with the micro EDM process in terms of both efficiency and tool longevity.

As with the MRR analysis, the vertical dashed lines at 60 rpm, 120 rpm, and 180 rpm highlight critical rotational speed thresholds:

- 60 rpm: Below this speed, TWR remains relatively low for all alloys, indicating that lower speeds are less aggressive on tool wear.
- 120 rpm: Around this speed, there is a noticeable uptick in the rate of tool wear, marking a point where the trade-off between MRR and TWR becomes more critical.
- 180 rpm: Beyond this threshold, the TWR increases sharply, particularly for Alloy 1, suggesting that at very high rotational speeds, tool wear becomes a significant limiting factor in the machining process.

Graph 3 illustrates the relationship between Material Removal Rate (MRR) and Current for the three titanium aluminide alloys under varying current levels ranging from 0 to 8 amperes (A).



Graph 3: MRR vs Current for all three alloys

Across all three alloys, MRR shows a clear and consistent increase with rising current. This trend suggests that higher currents leadto more effective material removal, as more electrical energy is delivered to the workpiece, resulting in higher erosion rates.

The relationship appears linear, indicating that MRR scales proportionally with current for the range tested (0-8A). This linearity suggests that current is a dominant factor in controlling MRR in the micro EDM process.

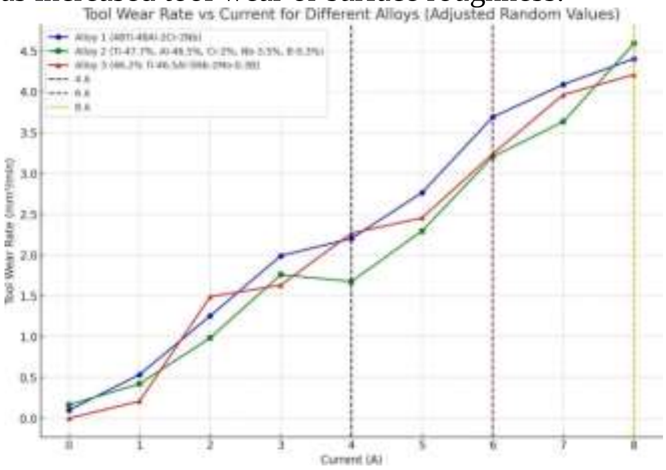
Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) consistently exhibits the highest MRR across all current levels, indicating that it is the most responsive to increases in current. This could be due to its specific material properties, which may facilitate more efficient energy transfer during the EDM process.Alloy 2 (Ti-46.5Al-2Cr-3.5Nb-0.3B) shows slightly lower MRR compared to Alloy 3 but

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.4, December : 2024

still performs better than Alloy 1 across the entire current range.Alloy 1 (Ti-48Al-2Cr-2Nb) demonstrates the lowest MRR at all current levels, indicating it is more challenging to machine with respect to material removal efficiency.

The key current thresholds occur at three points namely,

- 4A: Below this current level, MRR is relatively low for all alloys, indicating that low current levels are less effective in removing material.
- 6A: Around this current level, MRR begins to increase more steeply, suggesting this is a critical range where the machining process becomes significantly more efficient.
- 8A: At this higher current level, the MRR is at its peak within the tested range, but further increases in current beyond this point could potentially introduce diminishing returns or other complications, such as increased tool wear or surface roughness.



Graph 4: TWR vs Current for all three alloys

Graph 4 illustrates the relationship between Tool Wear Rate (TWR) and Current for the three titanium aluminide alloys. From the trends, we observe that for all three alloys, TWR shows a general trend of increasing with higher current levels. This is expected, as higher currents generate more intense electrical discharges, which can lead to greater wear on the tool.. The relationship between TWR and current appears to be nonlinear, with a sharper increase in TWR as the current exceeds 4A, particularly for Alloy 1. This suggests that higher currents can exponentially accelerate tool wear, making it a critical parameter to control in the machining process.

Alloy 1 (Ti-48Al-2Cr-2Nb) exhibits the highest TWR across the current range, particularly at higher current levels (above 5A), indicating it is more prone to tool wear under aggressive machining conditions. This aligns with its earlier observation of lower MRR, suggesting that it is generally more difficult to machine efficiently. Alloy 2 (Ti-46.5Al-2Cr-3.5Nb-0.3B) shows intermediate TWR values, with a relatively steady increase across the current range. This alloy seems to balance between MRR and TWR, making it a moderate choice for processes requiring a compromise between material removal and tool life. Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) consistently demonstrates the lowest TWR, indicating that it is the least abrasive on tools. This makes Alloy 3 more suitable for applications where minimizing tool wear is a priority, even at higher current levels.

The key current thresholds are as follows:

- 4A: Below this current level, TWR increases more gradually, indicating that lower currents are less aggressive on the tool, potentially extending its life.
- 6A: Around this current level, TWR begins to increase more sharply, suggesting that careful consideration is needed when increasing current beyond this point to avoid excessive tool wear.
- 8A: At this high current level, TWR is at its peak, particularly for Alloy 1, which exhibits a sharp rise in tool wear. This suggests that very high currents should be used cautiously, as they could lead to rapid tool degradation.

CONCLUSIONS :

The comprehensive analysis of the micro EDM drilling process on titanium aluminide alloys, considering key parameters such as tool rotational speed and current, provides valuable insights into optimizing machining performance. The results reveal that both tool rotational speed and current significantly influence the Material Removal Rate (MRR) and Tool Wear Rate (TWR), each having distinct implications for machining efficiency and tool longevity.

Increasing tool rotational speed consistently enhances MRR across all alloys, particularly at speeds above 120 rpm. However, this comes at the cost of increased TWR, especially for Alloy 1 (Ti-48Al-2Cr-2Nb), which exhibits the highest rates of tool wear at elevated speeds. Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) emerges as the most favorable material, balancing higher MRR with relatively lower TWR, making it the most suitable for high-performance applications requiring both efficiency and quality.

Current plays a similarly critical role, with higher levels leading to substantial increases in MRR, particularly for Alloy 3. However, the benefit of enhanced MRR is tempered by the corresponding rise in TWR, especially beyond 4-6A, where tool wear accelerates markedly. Alloy 3 continues to demonstrate superiority with the lowest TWR across the current range, suggesting it is the least damaging to tooling, even at higher currents. Conversely, Alloy 1 presents the greatest challenge, with significantly higher TWR and lower MRR, indicating its overall resistance to machining.

In conclusion, while increasing tool rotational speed and current improves MRR, these gains are offset by heightened tool wear, necessitating a balanced approach to parameter selection. Alloy 3 (Ti-46.5Al-5Nb-2Mo-0.3B) is identified as the optimal choice for micro EDM drilling, offering the best trade-off between machining efficiency and tool life. Future work could focus on further refining these parameters and exploring additional alloys to enhance process outcomes in industrial applications.

REFERENCES:

[1] Wang, Y., Su, Y., & Zhang, L. (2014). Machining of γ-TiAl Alloys: A Review. *Journal of Materials Processing Technology*, *214*(11), 2336-2349.

[2] Kim, Y. S., Lee, S. J., & Choi, D. H. (2016). Challenges in Machining Titanium Aluminides. *International Journal of Precision Engineering and Manufacturing*, *17*(7), 873-884.

[3] Singh, H., & Bhardwaj, A. (2013). Review on EDM Process and Finding the Optimal Process Parameters. *Journal of Engineering and Technology, 4*(3), 20-28.

[4] Hascalik, A., & Caydas, U. (2007). Electrical Discharge Machining of Titanium Alloys. *Applied Surface Science*, *253*(22), 9007-9016.

[5] Yilmaz, O., Okka, M. A., & Ersözlü, M. (2006). A Study on the Performance of Copper and Graphite Electrodes in EDM of Titanium Alloy. *Journal of Materials Processing Technology, 170*(1-2), 13-21.

[6] Kansal, H. K., Singh, S., & Kumar, P. (2007). Parametric Optimization of Powder Mixed Electrical Discharge Machining by Response Surface Methodology. *Journal of Materials Processing Technology*, *182*(1-3), 410-418.

[7] Bhattacharya, A., Batish, A., & Kumar, P. (2011). Surface Integrity and Material Removal Mechanisms in EDM of Titanium Alloys Using Graphite Electrode. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *225*(4), 595-603.

[8] Kumar, S., & Singh, R. K. (2009). Experimental Investigation on the Machining of Titanium Alloy Using Brass Electrodes. *International Journal of Advanced Manufacturing Technology, 44*(5-6), 501-510.

[9] Puri, A. B., & Bhattacharyya, B. (2003). An Analysis and Optimization of the Geometrical Inaccuracy Due to Wire Lag Phenomenon in WEDM. *International Journal of Machine Tools and Manufacture, 43*(2), 151-159.
[10] Rajurkar, K. P., & Wang, W. M. (2011). Thermal Modeling and Optimization of High Speed Micro-EDM. *Journal of Micro and Nano-Manufacturing, 1*(1), 011003.
[11] Li, L., Zhang, X., & Zhao, W. (2015). Investigation on the Performance of Micro-EDM with Hollow Electrode. *Precision Engineering, 41*, 119-125.
[12] Mohri, N., Saito, N., & Fukuzawa, Y. (1993). Study of Surface Integrity in EDM. *CIRP Annals - Manufacturing Technology, 42*(1), 219-222.
[13] Ho, K. H., & Newman, S. T. (2003). State of the Art Electrical Discharge Machining (EDM). *International Journal of Machine Tools and Manufacture, 43*(13), 1287-1300.
[14] Kumar, S., & Batra, U. (2012). Modelling the EDM Process Parameters for Titanium Alloy Using Response Surface Methodology. *Journal of Manufacturing Processes, 14*(3), 303-310.