Process parameters and TiAlN coating impact on microwire-EDM of Ti6Al4V using PVD technique in biomedical application

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The growing demand for products made of cutting-edge materials with increased attributes motivates material scientists to investigate prospective variants of such materials. Among the various categories of life-saving advanced materials are biomaterials, although shaping most of them according to the needs encounter manufacturing constraints due to their specific mechanical properties. For example, the extremely tough alloy Ti6Al4V, is renowned for its outstanding mechanical compatibility with the human body. Nonconventional means of machining have gained popularity keeping focus on the challenging machining circumstances that are well-known for their very precision and machining accuracy, no matter what type, shape, or hardness is being machined. Electrical discharge machining (EDM), for example, is the most prevalent efficient means of material removal, along with wire EDM (WEDM), μ-WEDM, and so on. Excess material should be removed for more particular applications of complex and baroque shapes, with a high degree of smoothing and finish, is one of the most advantageous characteristics of wedding metal dielectric material (μ-WEDM). In this study, we examined the effect of variable pulse-on (T_{on}), pulse (T_{off}), time (to), flushing pressure (FP), wire feed rate (WFR), wire tension (WT), voltage (SV), and peak current (PC) on μ-WEDM's reliability of the machined section (SR) using physical vapor deposition (PVD) technique to deposit aluminium nitride (TiAlN) coating on the surface of the metal. The results demonstrate a substantial reduction in roughness in the mechanically produced surfaces, further demonstrating, and confirming the biocompatibility of metals dielectric materials (μ-WEDM) with tissues within the human body.

***Keywords*: μ-WEDM; Ti6Al4V; PVD; Aluminum Nitride (TiAlN).**

INTRODUCTION

Titanium (Ti), one of the most widely used metals in the world, is renowned for its mechanical properties, as well as its superior strength-to-weight ratio offered at high temperatures. Due to their outstanding merits, titanium alloys are desirable and necessary in contemporary industries[1]. The aviation industry widely employs titanium and its alloys owing to their combined mechanical and physical properties, titanium being sturdy and a lightweight metal. Due to its superior properties, the most adept strength-to-weight ratio is found in titanium, compared to other metals or alloys commonly used in medicine. Titanium alloys are renowned for their exceptional fatigue strength and corrosion resistance[2]. Embedded titanium bars, plates, and sticks can continue to function normally for roughly 20 years. One of the most popular and promising materials for medical implants is titanium alloys, particularly Ti6Al4V. The chemical permanence of titanium's solid oxide exterior layer to the depths of 10 nm is largely responsible for the metal's remarkable chemical and corrosion resistance. The typical life span of titanium bars, plates, and sticks that have been implanted in the body is up to 20 years. Additional advantages of titanium alloys is their nonferromagnetic nature, which makes it possible to safely analyze individuals who have various types of titanium inserts inside their bodies using MRIs and NMRIs[3]. Titanium and titanium alloys have several characteristics that limit their machinability and make them difficult to work with. These characteristics include exceptional tensile strength, reduced ductile yield, a modulus of elasticity with a 50% lower value, and about 80% less thermal conductivity than steel. Due to its legitimacy as a connection between bones and tissues, invulnerability to consumption, solidity, adaptability, and perfection with bone development, titanium is now widely associated with biomedical science and engineering. It additionally serves for a variety of therapeutic purposes, comprising external prostheses, dental implants, hip and knee

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Figure 1 Ti6Al4V-based orthopaedic hip joint implant.

Figure 2 Titanium-based orthopaedic implant.

substitute operations, and delicate machinery[4]. When it comes to mating with tissues and bones, titanium alloys have excellent biomechanical similarities. However, due to its access to unexpected cost, properties, and machinability, titanium's application is somewhat constrained. Some titanium implants are shown in **Figs. 1 and 2**.

It is exceedingly challenging for researchers to cut such difficult-to-machine materials since doing so results in the development of a great deal of heat and a high wear proportion in the cutting region. To solve this difficulty, nontraditional machining techniques, often known as the modern machining approach, are introduced. The workpiece may deflect more and experience more "spring back" due to the lower elasticity modulus. Greater tool clearances and more stiff setups are therefore needed. Electric discharge machining (EDM), which enables the user to set the spacing between the tool and the workpiece, is thought to be more suitable for use in machining operations[5]. Titanium and its alloys are regarded as hard-to-machine materials because of their well-known poor thermal characteristics. EDM is a thermal erosion practice that may erode any electrically sensitive material, regardless of its hardness. As a result, titanium alloys can be machined using a practical and affordable alternative, the EDM method. Unlike conventional mechanical machining techniques that use shear forces between the tool and workpiece to remove the material, which in turn generates excessive heat gradients linked to the procedure and produces metastable martensitic microstructure, giving the components generated high tensile strength, but limited flexibility[6]. Prominent gap cooling followed by flushing are crucial and required to enhance the EDM of Ti6Al4V[7], and inner flushing is an example of conventional flushing techniques used in EDM. The majority of EDM activities, including macro and micro EDM, are suited for side flushing. Today, wire electric discharge machining (WEDM), another effective method of cutting such materials, is widely used in industrial settings to manufacture even the most complicated and intricate geometry in such materials[8]. Due to its weak thermal conductivity, titanium, a material that is challenging to machine, offers inadequate machinability. As a result, tool wear is unrestrained, increasing machining costs. In the X-ray diffraction and optical microscopic investigations, some significant improvements in its resistance to wear has been noticed by utilizing TiAlN coating using physical vapor deposition (PVD) process[9]. It is imperative to enhance the surface characteristics of implant materials. There are many techniques established nowadays to cover the implant material. One example of this is PVD[10]. Different PVD techniques, such as magnetron sputtering, electron beam evaporation, cathodic arc deposition, ion beam deposition, pulsed laser deposition (PLD), and others, produce significantly different types and densities of seed particles, which in turn produce growth defects with varying sizes, shapes, and densities. Although the plasma-based deposition process is a powerful source of seed particles that can lead to the formation of growth defects, the type of PVD technique that is used to prepare the thin films also has a significant impact on the density of generated growth defects. PVD methods are recurrently used to deposit a broad range of materials on a variety of surfaces. The procedures employed to evaporate the material in consideration and are used to categorize PVD processes generally. The most common methods for depositing titanium nitride-based coatings are magnetron sputtering, cathodic arc, and PLD[11]. PVD techniques have become more popular due to their broad range of applications in the blending and production of highly firm new materials with minimally intrusive thicknesses ranging from micrometers to angstroms[12]. Using PVD, porous coatings for implants can be produced[13]. Metallic implants that have been surface treated have increased osseointegration activity at the bone-implant contact[14]. Moreover nanostructures can have thin layers deposited on them by means of PVD technology[15].

Biocompatibility, mechanical behavior, corrosion behavior, processability, and availability are the qualities of interest in terms of biomedical applications[16]. In addition to having better biological and mechanical qualities, Ti6Al4V has excellent corrosion resistance. Since titanium and its alloys better meet the required properties than any other metallic material, including stainless steel, Cr-Co alloys, commercially pure (CP) Nb, and CP Ta, titanium is seen to be the most appropriate metal for use in medical applications[17]. Titanium is an excellent biomaterial due to its superior tissue acceptance and corrosion resistance, but its tribological behavior and mechanical characteristics prevent it from being used for intense wear applications or the replacement of hard tissue. The traditional Grade 5 titanium alloy, Ti6Al4V, was replaced with titanium alloys in order to get around these limitations[18]. Appropriate compositional design and copper mold casting are two ways to attain high strength and low Young's modulus in titanium alloys. A nano or ultrafine-structured matrix and a micrometer-sized dendritic β-phase comprise the unique bimodal microstructure, which is responsible for the combination of mechanical characteristics and elastic modulus[19]. According to microstructural investigations the Ti6Al4V titanium alloy, which is made by injection casting and has rapid cooling, has better qualities than material that is made commercially[20]. The alloy Ti6Al4V is nontoxic and does not cause the body to reject it. Ti6Al4V is distinct from other materials due to these features. Because of its qualities connected to production, Ti6Al4V alloy is suitable for the purpose of generating lightweight, very durable components for biomedical applications[21]. Machining is a crucial step in the process to qualify an implant material for use in medicine[22]. Surface integrity, chip formation, lubrication strategy, metallurgical aspect, and cutting tool wear are some of the fundamental performance parameters due to which titanium alloy presents machining issues[23]. The primary causes of titanium alloys' poor machinability are their high hardness and capacity to hold it at extremely high temperatures, intense chemical affinity, low modulus of elasticity, and weak thermal conductivity[24]. Due to their intrinsic characteristics, titanium alloys are considered to be challenging materials to process, particularly at higher cutting speeds[25]. Materials having low plasticity, such as titanium alloys, have limited formability[26], and it has been observed that near the machined surface, there is an upsurge in the number of dislocations during machining[27]. Even at lower cutting rates, the chip–tool interface temperatures during machining are significantly higher than those of most materials and appear to concentrate near the cutting edge[28]. Therefore, an analysis and consideration are given to the cutting tools, machining settings, and processing factors used to enhance machinability and decrease surface defects in titanium alloys[29]. When machining difficult metals like titanium, the ideal process parameters are crucial, the cutting zones are effectively cooled by flooded and mist jet environments, which also result in reductions of 30–40% in tool wear and cutting forces[30]. Methods of cutting, blanking, bending, stamping, and other processes that produce surgical instruments and implants all depend on the quality of the cut surface[31]. In an artificial physiological solution of the unaltered specimens, the coatings of TiAlN improved the corrosion resistance and showed high biocompatibility when assessed for cell density, morphology, and vitality as coatings showed good biocompatibility when examined as possible protective layers for medical implants[32].

The wear characteristics and surface characteristics of the Ti6Al4V alloy have been examined in this work as reduction in surface roughness (SR) leads to reduction in the wear of implants thereby enhancing its biocompatibility. The fatalities and wear trace widths of coated Ti6Al4V alloys with TiAlN coating were computed following a wear test. The coating was applied using the PVD process. The outcomes showed that the alloy with the coating provides a considerable improvement in wear resistance, and additionally, that the TiAlN-coated Ti6Al4V alloy has higher wear resistance.

MATERIALS AND METHODS

In this study, seven distinct input factors were selected as the course of action regulating input variables for cutting Ti6Al4V (**Table 3**). **Tables 1 and 2** demonstrate the chemical composition and mechanical characteristics, respectively. The workpiece specimen was examined utilizing Taguchi's L27 orthogonal array under three different levels of input parameters. It is a tool that emphasizes parametric variation while leveraging an orthogonal array and uses a signal-to-noise (S/N) ratio technique to reduce complexity[33]. The log of those runs can be seen in **Table 3**.

Three distinct levels of input variables are employed with the μ-WEDM machining method (**Table 4**). SR, which is impacted by the kind of contact, precision, friction, and deformation of the machined components, also acts as a barometer for how effectively they perform in practical applications. Therefore, it is vital to understand how cutting input parameters influence the roughness of the machined section of the sample.

Ti6Al4V served as the foundation for the samples' preparation. Ti6Al4V plate was cut into test specimens that were 20 × 65 × 3 mm in size. Before coating, the substrates were cleaned using 600-grit grinding paper, then cleaned separately for 10 minutes in acetone and alcohol, then rinsed in distilled water and dried. The alloy's mechanical characteristics as a substrate along with the way coating treatments may influence these characteristics were usefully investigated thorough examination of PVD coatings[34]. In a study of TiN coatings placed by ion implantation and PVD procedures, Nolan *et al.* came to the conclusion that both methods enhanced Ti6Al4V wear resistance[35].

On the Ti6Al4V substrate, 2 μm thick PVD TiAlN sheets were deposited using a filtered arc deposition system (FADS). While the substrate bias was initially held at 950 V for 1.5 minutes to allow for sputter cleanup of the specimen surface, the chamber pressure was 6.7 103 Pa. These circumstances were used for 10 minutes to deposit TiAlN. To ensure that the coating was applied uniformly to the substrate surface, the surface was horizontally swept by an ion beam. An estimated 410°C was the highest sample temperature at any point throughout processing. The coating surfaces were analyzed by scanning electron microscopy (SEM) to determine surface topography because PVD and plasma nitriding are known to have notably different surface effects.

The current research work analyzes the TiAlN PVD-coated Ti6Al4V as TiAlN[27]. TiAlN is a great option for improving the wear characteristics of Ti6Al4V alloy. After application, the coating creates a tough, wear-resistant surface layer that is resilient to adhesive and abrasive wear, minimizing material loss and enhancing the component's life. TiAlN coatings provide enhanced resistance against corrosion as well. This is especially useful in situations where the Ti6Al4V alloy may be subjected to harsh conditions, like high humidity or chemical exposure. Due to the low coefficient of friction of TiAlN coatings, there can be less friction between moving parts, which improves tribological performance, reduces heat generation, and saves energy as shown in **Fig. 5**.

TiAlN coatings have the potential to increase Ti6Al4V components' fatigue strength, which is crucial for applications involving dynamic stress or cyclic loading. PVD techniques frequently produce coatings with a uniformly smooth surface finish, which can enhance the component's overall appearance and offer a more reliable and consistent surface for functional purposes—a surface that is particularly crucial for biomedical applications. Moreover, TiAlN coatings are renowned for their resilience to high temperatures. Their ability to retain their characteristics at high temperatures qualifies them for use in high-temperature settings.

The trials were conducted using an electrical CNC wire-cut μ-EDM machine, as shown in **Fig. 3**. Each servo-driven axis on this machine can be programmed to move in accordance with a CNC code using the control panel. Brass wire (0.25 mm) served as the cutting element in this experiment. To operate the machine, a brass wire that can be reused is wound up and held in reserve in a wire drum that rotates at a speed of 1,500 revolutions per minute.

The chosen levels of process parameters for the current project are shown in **Table 4**. The roughness is a measure of its texture. If there are significant discrepancies, the surface is coarse; if there are minor changes,

Table 1 Chemical composition.

Al	H	Fe	Ti	V	O
6%	0.01%	0.25%	89.55%	4%	0.2%

Table 2 Mechanical properties.

Mechanical Aspects	Hardness No. Brinell	Poisson's Ratio	Fatigue Strength	Tensile Ultimate Strength
Metric	335	0.341	511 MPa	950 MPa

Table 3 Experimental runs.

S. No.	Ton (μs)	Toff (μ-s)	FP (kg-pascal)	WFR (m/min)	WT (kgf)	SV (Volts)	PC (Amp)	SR (μm)	SNRA1	MEAN1
1	105	50	3	3	8	13	3	1.02	−0.172	1.02
2	105	50	3	3	10	18	8	0.72	2.85335	0.72
3	105	50	3	3	12	23	13	1.3	−2.27887	1.3
4	105	55	12	12	8	13	3	0.82	1.723723	0.82
5	105	55	12	12	10	18	8	1.2	−1.58362	1.2
6	105	55	12	12	12	23	13	1.25	−1.9382	1.25
7	105	60	21	15	8	13	3	0.62	4.152166	0.62
8	105	60	21	15	10	18	8	1.13	−1.06157	1.13
9	105	60	21	15	12	23	13	1.21	−1.65571	1.21
10	110	50	12	15	8	18	13	1.03	−0.25674	1.03
11	110	50	12	15	10	23	3	1.42	−3.04577	1.42
12	110	50	12	15	12	13	8	1.21	−1.65571	1.21
13	110	55	21	3	8	18	13	0.79	2.047458	0.79
14	110	55	21	3	10	23	3	1.23	−1.7981	1.23
15	110	55	21	3	12	13	8	1.45	−3.22736	1.45
16	110	60	3	12	8	18	13	1.1	−0.82785	1.1
17	110	60	3	12	10	23	3	1.03	−0.25674	1.03
18	110	60	3	12	12	13	8	1.2	−1.58362	1.2
19	115	50	21	12	8	23	8	1.06	−0.50612	1.06
20	115	50	21	12	10	13	13	0.9	0.91515	0.9
21	115	50	21	12	12	18	3	1.63	−4.24375	1.63
22	115	55	3	15	8	23	8	1.76	−4.91025	1.76
23	115	55	3	15	10	13	13	1.88	−5.48316	1.88
24	115	55	3	15	12	18	3	1.91	−5.62067	1.91
25	115	60	12	3	8	23	8	1.69	−4.55773	1.69
26	115	60	12	3	10	13	13	0.8	1.9382	0.8
27	115	60	12	3	12	18	3	1.01	−0.08643	1.01

Table 4 Detail of inputs with their levels.

Inputs	Level 1	Level 2	Level 3
Ton (μs)	105	110	115
Toff (μs)	50	55	60
FP (kg-pascal)	3	12	21
WFR (m/min)	3	12	15
WT (kgf)	8	10	12
SV (Volts)	13	18	23
PC (Amp)	3	8	13

Figure 3 Process runs on the workpiece.

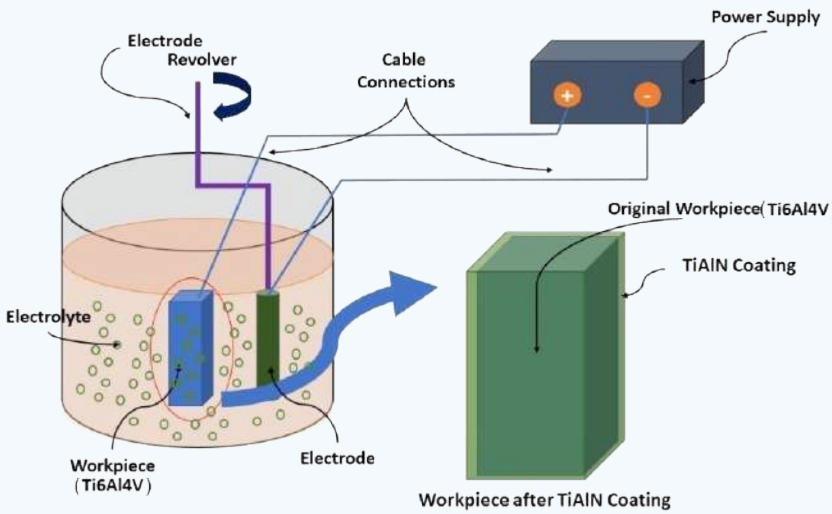

Figure 4 General layout of the experiment.

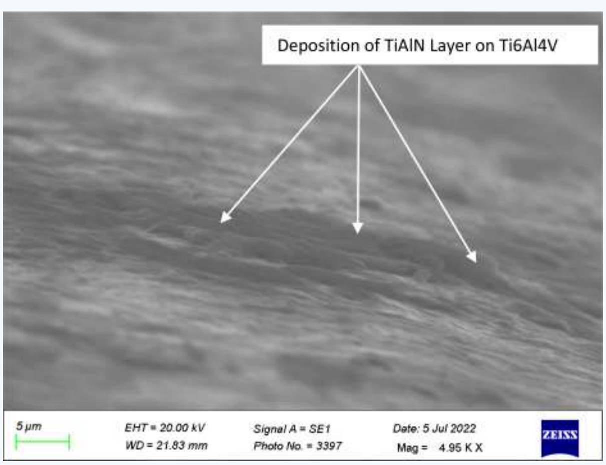

Figure 5 SEM images showing deposition of TiAlN layer on Ti6Al4V SEM by PVD coating.

the surface is even. The Mitutoyo surf test, which calculates roughness using the roughness criteria and displays findings in millimetres, was applied in order to gauge the degree of unevenness. The choice of variables, their strength, and quantity are crucial for producing enough current to flow into an electrode and produce a spark that will jump to the work material. The input factors were proposed as pulse period, pulse break, mean current, voltage in V, and feed wire[11]. The relationship between the response characteristics and the parametric variables can be seen by plotting the statistics for the response curves (primary effect) and the S/N statistics. It was possible to determine the ideal standards of critical input by examining the response curves with an ANOVA table while taking into account the average response characteristics finding the factor that had a substantial impact on the machining performance process is what ANOVA is concerned with[31].

RESULTS AND DISCUSSION

Taguchi's L27 orthogonal array is employed to detect any discrepancies between experimental and desired values. This employs the S/N ratio, to cite the response's average and standard deviation, respectively. The present work uses optimization to uncover quality features like SR through smaller-the-better characterization.

$$\text{Smaller the better} = -10\log 1\textstyle\sum_N (R)^2 \qquad (1)$$

The ANOVA (**Table 5**) depicts the significance and their impact on experimental runs, Ton (μs) was found to be the most significant parameter T-on are shown as the significant input variables in the ANOVA table since they have p-values less than 0.05. The underpinning of an ANOVA is comparing variation within a given sample to variation amongst samples of data. **Table 5** also provides the percentage of each factor's contribution; T-on was found to be a highest contributor with 25.29%. **Table 6** the difference between levels shows that T-on contributed the highest effect (Δmax – min = 2.51045) on the SR followed by wire tension (WT; kgf) (Δ max – min = 2.10922), SV (volts) (F) (Δ max – min = 1.95054), T-off (μ-s) (Δ max – min=1.87232), wire feed rate (WFR; m/min) (Δ max – min = –0.92234), flushing pressure (FP; kg-pascal) (Δ max – min = 1.43355) and peak current (PC; Amp) (Δ max – min = 0.96588). MINITAB 19 statistical software was used to create all the data computations and visualizations. The experimental operations were carried out at 27 optimal input variable combinations, and the appropriate SR values were obtained.

When diverse input parameters are present, different amounts of mean SR (and its integrity) observations are observed. **Figure 6** illustrates the manner in which process parameters influence the SR. It was shown that as the T-on increases beyond a certain value, SR increases. This results in thermal softening of the workpiece, a decrease in smeared materials on the machined surface, and the lowest SR because of increased friction among the tool and the workpiece as the T-on increases. **Figure 2** also shows that when the feed rate goes up, the Ra value increases. This is because the workpiece's greater resistance to the tool, which increases with feed rate, causes more established seams to form on the tool, deteriorating the surface and raising the SR value, which can be seen from **Fig. 5**. Similarly, it can be seen that an increase in servo feed has increased the SR.

Better substrates for adhesion, growth, and viability were offered by EDM. As a result, EDM therapy presents itself as a viable surface modification for orthopedic implants, provided that the implant integrates well with the surrounding bone tissue[37]. In both in vivo and in vitro experiments, surface characteristics such as roughness, topography, porosity, chemistry, and energy have a major influence on the formation of new tissue and the absorption of collagen and proteins[38,39]. The most beneficial and prudent factor for the creation, adhesion, growth, and differentiation of new bone cells was discovered to be the nanoscale SR of the material surface[40]. Hence the overlaid texture on the surface created by EDM may provide a better surface for osteoblast growth and implant attachment.

From **Table 7**, the optimal parameters for operation were A1, B3, C3, D2, E1, F1, and G3, by employing the above combination. The μ-EDM has been more advantageous as it converts machined zone into oxide and a layer of controlled carbide was induced, which imparts a hydrophilic surface and enhances biocompatibility (**Fig. 5**).

Table 5 ANOVA for S/N ratios.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage contribution
Ton (µs)	2	28.392	28.392	14.196	3.19	0.004	25.29
Toff (µ-s)	2	16.945	16.945	8.473	1.90	0.191	15.09
FP (kg-pascal)	2	9.663	9.663	4.831	1.09	0.369	8.61
WFR (m/min)	2	12.541	12.541	6.270	1.41	0.282	11.17
WT (kgf)	2	22.082	22.082	11.041	2.48	0.125	16.67
SV (volts)	2	17.972	17.972	8.986	2.02	0.015	19.01
PC (Amp)	2	4.676	4.676	2.338	0.53	0.604	4.16
Residual Error	12	53.403	53.403	4.450			
Total	26	165.674	112.811				

Table 6 ANOVA for means.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
T-on (µs)	2	0.64909	0.64909	0.32454	4.37	0.038
T-off (µ-s)	2	0.38889	0.38889	0.19444	2.62	0.114
FP (kg-pascal)	2	0.22216	0.22216	0.11108	1.50	0.263
WFR (m/min)	2	0.31920	0.31920	0.15960	2.15	0.159
WT (kgf)	2	0.32720	0.32720	0.16360	2.20	0.153
SV (volts)	2	0.24562	0.24562	0.12281	1.65	0.232
PC (Amp)	2	0.07642	0.07642	0.03821	0.51	0.610
Residual Error	12	0.89109	0.89109	0.07426		
Total	26	3.11967				

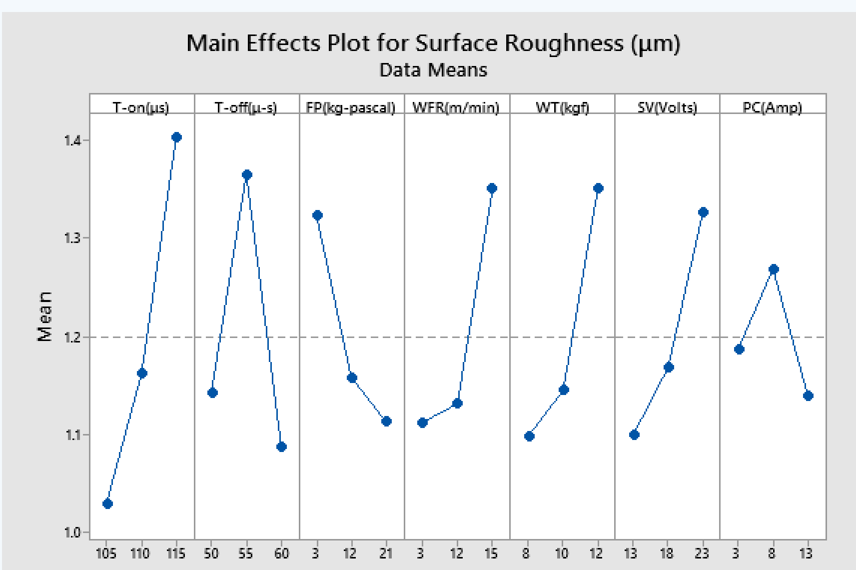

Figure 6 Plot showing SR.

Table 8 shows the summary of the model and it can be depicted that the generated model has a strong relationship between the model (93.77%) and the response variable (85.16%).

SUMMARY AND CONCLUSION

The WEDM of Grade 5 Ti6Al4V alloy was subjected to an experimental investigation in this study using various input variable combinations. Before the machining trials, the workpiece specimens were coated with TiAlN using the PVD process, which improves the material's brittleness and increases its machinability.

As a result, the research described above can be summarized as follows:

- This carefully planned experiment made use of the L27 orthogonal array, helped deduce acceptable results of minimizing specimen SR, enhancing hospitability, and appropriateness with human bones and tissues in case of direct physical contact.
- From the ANOVA, it was observed that SR was significantly affected by Ton (µs) and servo feed (SV) with a contribution of 25.29% and 19.01%, respectively.
- From the results, it was observed that Taguchi's L27 orthogonal array determined optimum cutting conditions, significantly reduced the SR during machining of and hence, it was recommended that industries could use these optimum cutting conditions for improving the machinability of Ti6Al4V alloy within the given range and improve the biocompatibility of the material using micro EDM.
- is the significant contributor with 25.29% contribution and has the highest impact with rank 1 as shown in **Tables 5 and 7**, respectively, thereby resulting in reduced SR for the coated implant material enhancing its wear and corrosion resistance.
- The input process parameters of pulse-on time (T_{on}) and set voltage of spark gap (SV) impacted SR considerably on specimens of titanium alloy.
- The second experimental trial of combination of input parameters as per **Table 3** lead to attaining the lowest SR. Thus, resulting in reduction in wear along with enhancement of biocompatibility in terms of prolonged service life.
- The machined Ti6Al4V surface integrity consists of roughening brought on by the breakdown of the recast layer on the surface, surface microcracks, debris, and melted droplets, which can be seen from SEM image of **Fig. 5**.

Table 7 Response table for S/N ratios.

Level	Ton (μs) (A)	Toff (μ-s) (B)	FP (kg-pascal) (C)	WFR (m/min) (D)	WT (kgf) (E)	SV (volts) (F)	PC (Amp) (G)
1	0.00436	−0.93227	−2.03109	−0.58683	−0.36748	−0.37696	−1.03862
2	−1.17827	−2.31002	−1.05136	−0.92234	−0.83581	−0.97554	−1.80363
3	−2.50608	−0.43770	−0.59754	−2.17082	−2.47670	−2.32750	−0.83775
Delta	2.51045	1.87232	1.43355	1.58399	2.10922	1.95054	0.96588
Rank	1	4	6	5	2	3	7

Table 8 Summary of obtained model.

S	R-Sq	R-Sq (adj)
9.1096	93.77%	85.16%

- Except for the increased pulse duration, the process parameters for the electrode material cause an increase in the SR, MRR, and the wear of the electrode.
- The wear resistance and surface properties of Ti6Al4V alloy can be greatly improved by applying a TiAlN coating using the PVD process. This makes the alloy a valuable option for a variety of technological and manufacturing processes, especially when durability and effectiveness are crucial.

FUTURE WORK

Research on improving the wear and machining properties of difficult-to-machine materials, such as titanium alloys, is crucial since it affects several industries, including the aerospace, medical, and automotive ones. Future directions and consequences for this context's study include the following:

- Work can be done on creating reliable models, algorithms, and real-time monitoring systems to optimize cutting parameters, increase machining efficiency.
- Real-time tool wear monitoring and feedback control systems techniques can reduce tool wear in difficult-to-machine materials and improve machining precision.
- Develop credible models, algorithms, and real-time monitoring systems that can adapt to variations in the machining environment and parameters related to the material to maximize machining efficiency and tool life.
- To extend tool life and facilitate machining, more work needs to be done to regulate and improve the alloy's microstructure.

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CONFLICTS OF INTEREST

The authors have no conflict of interest to declare.

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