Wear and Corrosion Behaviour of Wire Electrical Discharge Machined Ti-6Al-4V alloy

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Abstract The objective of the current research work is to study the wear and corrosion behavior of Ti-6Al-4V ELI alloy. WEDM is preferred over conventional machining for Ti alloys, as they are hard-to-machine materials. Wear and corrosion tests were performed using wear and friction monitor (Ducom Model TR20-LE) and electrochemical workstation (Autolab PGSTAT204) respectively. SEM and EDS were also carried out on each sample for evaluating the surface morphology and to know the exact composition of the material. WEDM rough and trim-cut modes improve the surface hardness of Ti-6Al-4V ELI alloy and hence affects their c.o.f. and wear rates. The outcomes of the present research work promote WEDM trim-cut mode over rough-cut mode because it results in lower values of c.o.f., wear and corrosion rates.

Keywords: Ti-6Al-4V ELI alloy; WEDM; Coefficient of friction; Wear behaviour, corrosion behaviour

Abbreviations:
SEM- Scanning Electron Microscopy
EDS- Energy Dispersive X-ray Spectroscopy
WEDM- Wire Electrical Discharge Machining
COF- Coefficient of Friction
PDP- Potentiodynamic Polarization Curves

1. Introduction

Titanium based alloys because of their excellent corrosion resistance and top-notch biocompatibility; are potential candidates in biomedical industry as an implant material for orthodontic and orthopaedic applications [1-4]. TiO2 protective layer enhances cell attachment and osteointegration with the Ti based alloy implants [5]. Surface properties for instance chemical composition and surface roughness display a substantial role in enhancing the biocompatibility and cell/tissue adhesion of metallic implants [6,7].

WEDM can machine Ti based alloy implants quite economically and efficiently to produce complex shapes. In WEDM, recast layer phenomenon affects the wear behaviour, fatigue life and other functional properties [8-10]. This surface damage can largely be managed by using trim cutting after rough cutting operations because it produces surface with low crack density and low surface roughness [11-12] and hence improved corrosion resistance property [13-18]. An extensive survey of literature reveals that WEDM modified surface improved the bio-functionality, biocompatibility, osteointegration and cell attachment between implant and human tissues largely. This is because WEDM modified surface consists of nano and micro scale structures which promotes the cell attachment and bone formation leading to short healing time [19-21].
Wear is a crucial factor influencing the presentation and failure of biomedical devices. Surface morphology and lubrication conditions considerably affect their corrosive wear and corrosive rates [22]. It has been observed that wear and c.o.f. values are significantly lower in trim cut mode in comparison to rough-cut mode [23]. Ti alloys because of their good mechanical and chemical properties provides strong adhesion tendency of these alloys.

The main physical properties affecting the long-term durability of the metal-implants are morphology, surface roughness, wettability and surface free energy. Surface roughness of the implant surface serves as a physiochemical aspect that primarily affects the osteointegration of the tissue and the implant. Moreover, surface roughness is a favourable factor that increases cell adhesion and cell growth. A rough surface with a corrosive environment at a larger interfacial area, and consequently, an increase in surface roughness enhanced the corrosion process [24-26].

Above literature-review clearly indicates that only a few numerical studies have found in the literature that considered the effects of WEDM trim-cut mode for Ti-alloys. Therefore, the pretension of the current experimental opus is to analyse wear and corrosion behaviour of Ti-6Al-4V ELI alloy under two modes of WEDM which are trim-cut and rough-cut.

2. Experimental setup

2.1 Material Preparation

In the present experimental work, a cylindrical bar of 11 mm diameter and of 100 cm length Ti6Al4V ELI alloy is used and machined with WEDM Electronica Sprintcut and manufacturing by WEDM then polished by grit 800, 1000, 1200, 2000 grit paper and then grade-1 Al2O3 paste for getting polished surface. After the polishing of the sample, wear test is done on it and surface is observed using SEM before and after the wear test. Table 1 shows the chemical composition of Ti6Al4V ELI while figure 1 shows the EDS of Ti6Al4V ELI after WED Machining.

| Element | Shell | Weight % | Atomic % |
|---------|-------|----------|----------|
| Al      | K     | 6.19     | 8.03     |
| Ti      | K     | 80.71    | 58.99    |
| C       | K     | 8.77     | 29.40    |
| Fe      | K     | 0.05     | 0.03     |
| V       | K     | 4.22     | 3.03     |
| Pd      | L     | 0.05     | 0.02     |
| Sum     |       | 100.00   | 100.00   |

Table 1. Chemical configuration of Ti6Al4V ELI
Figure 1. T6Al4V ELI EDS after WEDM

2.2. WEDM Process Parameters and sample preparation

The present experimentation used CNC-WEDM (Sprint Cut) with copper wire electrode (ϕ: 250 µm). Samples were prepared by changing the conditions of discharge under WEDM’s rough and trim-cut modes. The objective of first cut i.e., rough-cut is to get rid of the maxima material while Trim cut mode aims to remove a very thick layer on rough cut WEDMed surface, thereby, minimizing the whitish layer or recast layer thickness and surface disfigurement. The process parameters listed in Table 2 were varied under different cutting conditions.

Table 2. WEDM Process Parameters

| Sr. No. | WEDM Parameters | Symbol | Units | Rough Cut (RFC) | Trim Cut (TRC) (Number of Trim Pass-2) |
|---------|-----------------|--------|-------|-----------------|----------------------------------------|
| 1.      | Servo voltage   | SV     | V     | 20              | 30                                     |
| 2.      | Pulse on time   | T<sub>on</sub> | µs    | 110             | 104                                    |
| 3.      | Pulse off time  | T<sub>off</sub> | µs    | 45              | 40                                     |
| 4.      | Peak current    | I<sub>p</sub> | Ampere | 250            | 120                                    |
| 5.      | Wire tension    | WT     | Grams | 500             | 900                                    |
| 6.      | Wire feed       | WF     | m/min | 2               | 6                                      |
3. Results and Discussions

3.1 Wear Analysis

The performance of wear behaviour of Ti based medical implants significantly affects their service life. Therefore, wear tests were performed on Ti-6Al-4V ELI alloy with variable surface integrity using cylindrical pins (ϕ 3.5mm, length 6mm). Figure 2(a) and 2(b) showed the SEM before and after the wear test. Furthermore, figure 3 recorded real time variation of c.o.f. for Ti-6Al-4V ELI alloy sample at 10.0 N and 600 seconds. During the sliding period of 30-40 seconds, there is an abrupt rise of c.o.f. and thereafter it decreases with the passage of time and attains the equilibrium condition. Pin prepared under rough cutting mode shows highest value of c.o.f. and reached the condition of equilibrium after the span of 300 seconds. Similar behaviour is observed from pin prepared with trim-cut mode and acquire equilibrium conditions after 100 seconds.

Figure 3 and figure 4 show the c.o.f. and wear rates under different WEDM cutting modes. Trim-cut surfaces show lesser value of wear rates in comparison to rough-cut surfaces due to the presence of higher percentage of rutile-TiO₂ phase and hence higher hardness. Table 4 summarised the c.o.f. and volumetric wear rate under rough and trim cutting modes.

Therefore, the present research work confirms that trim-cut surfaces of WEDM improves wear and fatigue defiance properties and hence promotes non-corrosive and biocompatible forefending layer that enhances their presentation and lifecycle of Ti-6Al-4V ELI Alloy for biomedical building blocks and gadgets.

![Figure 2. (a) SEM before wear and (b) SEM after wear](image-url)
Figure 3. Coefficient of friction versus real time plot at pin-on-disc wear test.

Figure 4. Wear rate analysis of various machined surfaces.

Table 3. Surface roughness of various machined surfaces

| Sample            | Surface Roughness ($R_a$) | Surface Roughness ($R_a$) |
|-------------------|---------------------------|---------------------------|
|                   | Before wear (µm)          | After wear (µm)           |
| Rough-Cut (RFC)   | 2.326                     | 0.54                      |
| Trim-Cut (TRC)    | 2.086                     | 0.56                      |
3.2. Electrochemical Corrosion Analysis

In the present section, electrochemical measurements were carried out for the duration of two hours. These measurements were obtained from the surface of polished and WEDMed samples and were being compared using potentiodynamic polarization (PDP) curves as shown through figure 5. These plots comparisons for different set of samples clearly showed more negative value of corrosion potential \(E_{\text{corr}}\) for polished surface in comparison to other WEDMed samples and its value changed between the range of \(-0.4612\) V to \(-0.23692\) V (Table 5). Similarly, for the current density \(I_{\text{corr}}\), the minimum and maximum values varies between \(7.09\times10^{-6}\) A/cm\(^2\) and \(3.14\times10^{-5}\) A/cm\(^2\) for polished and trim-cut surfaces respectively. As far as the corrosion rates were concerned, the minimum and maximum values range between \(0.2152\) mm/year to \(0.6921\) mm/year for trim-cut and rough-cut surfaces respectively. Due to the change in chemical composition and morphology, trim-cut surfaces showed lower values of corrosion rates and rough-cut surfaces showed higher values due to increased surface roughness values.

### Table 4: C.O.F and Wear rate of various machined surfaces

| Sample              | C.O.F | Wear rate (mm\(^3\)/min) |
|---------------------|-------|---------------------------|
| Rough-Cut (RFC)     | 0.385 | 67.51 x 10\(^{-2}\)       |
| Trim-Cut (TRC)      | 0.35  | 65.73 x 10\(^{-2}\)       |

### Table 5: Electrochemical parameters for potentiodynamic polarization curves

| Sample         | \(E_{\text{corr}}\) (V) | \(I_{\text{corr}}\) (A/cm\(^2\)) | Corrosion Rate (mm/year) |
|----------------|------------------------|----------------------------------|--------------------------|
| Rough Cut (RFC)| -0.23692               | 3.14x10\(^{-5}\)                | 0.6921                   |
| Trim Cut (TRC) | -0.28132               | 2.13x10\(^{-5}\)                | 0.2152                   |
| Polished Sample (PLC) | -0.4612          | 7.09x10\(^{-6}\)                | 0.2236                   |
Figure 5. Polarization curve for various machined surfaces

4. Conclusions

The current research work has to do with the wear and corrosion behaviour of Ti-6Al-4V ELI alloy. The conclusions noticed from the existing research work are

- Rough-cut sample due to higher thermal damage on machined surfaces results into higher $R_a$ values, whereas trim-cut modes produce improved surface properties of Ti6Al4V ELI. The $R_a$ values of machining samples under rough-cut and trim-cut samples are 2.326 µm and 2.086 µm respectively.
- Trim-cut mode experience lesser wear rate of $65.73 \times 10^{-2}$ mm$^3$/min in comparison to rough cut mode as $67.51 \times 10^{-2}$ mm$^3$/min respectively. This observation is due to higher percentage of rutile-TiO$_2$ phase and hence higher hardness in trim-cut surfaces in comparison to rough-cut surfaces.
- WEDM trim-cut surfaces improves wear and fatigue resistance properties and hence promotes non-corrosive and bio-compatible protective layer that enhances their service life and functioning of Ti-6Al-4V ELI alloy for biomedical practice.
- The corrosion rates for different set of samples vary between minimum and maximum values of 0.2152 mm/year to 0.6921 mm/year for trim-cut and rough-cut surfaces respectively. Trim-cut surfaces shows the least value of corrosion rate due to changes in chemical composition and morphology, while rough-cut surfaces show higher values due to increased surface roughness values.
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