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# Tool wear analysis of turning Ti-6Al-4V under dry, wet and cryogenic conditions

Syed Husain Imran Jaffery[1], Muhammad Ali Khan[2,3*]

[1]Department of Mechanical Engineering, College of Engineering, Faculty of Computing, Engineering and the Built Environment Birmingham City University, UK;
[2]School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan;
[3]Department of Mechanical Engineering, College of Electrical and Mechanical Engineering (CEME), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan;

* Corresponding author. Tel.: +923335248284; fax: +0-000-000-0000. *E-mail address:* mak.ceme@ceme.nust.edu.pk

**Abstract**

Economy of a manufacturing system is symbolic of its wholesome efficiency. Machining of difficult-to-cut titanium alloys has persistently presented a challenge due to its high temperature strength, low thermal conductivity and poor modulus of elasticity. In addition to the loss of economy owing to accelerated tool wear, the machine downtime also degrades manufacturing system efficiency. In the present research, effects of machining parameters and cooling systems were analyzed in terms of tool wear, which is a key productivity index, during turning of Ti-6Al-4V. Machining environments including wet and cryogenic conditions as well as dry machining was employed for experimentation. It was seen that tool wear can significantly be reduced by use of correct machining parameters in combination with appropriate cooling system. Cryogenic condition was found to cause 23% and 12% lesser wear than corresponding dry and wet machining at 60 m/min. SEM imagery identified adhesion and diffusion dissolution as the main wear inducing phenomena. ANOVA results identified cutting speed as the most substantial factor affecting tool wear with contribution ratio of 52.96%. Tool chip contact analysis depicted the lesser contact area under the usage of coolant reducing tool wear.



*Keywords:* Ti-6Al-4V; Tool wear; Machining environment; Scanning electron microscopy; Analysis of variance

## 1. Introduction

Titanium alloys are extensively used in a wide range of industrial applications [1] including aerospace, marine and medical fields. Their excellent physical and mechanical properties constitutes them the preferred choice in various applications [2]. According to one estimate Ti-6Al-4V accounts for about 60% of global titanium usage owing to its high strength-to-weight ratio and exceptional corrosion protection [3].

| **Nomenclature** | |
|---|---|
| f | Feed Rate (mm/rev) |
| V | Cutting Speed (m/min) |
| ME | Machining Environment |
| R | Tool Wear Rate |

One of the limiting factor on its usage is the tendency of work hardening during machining [4]. This hard to cut status, in addition to low thermal conductivity, causes inflated tool wear. In addition, chemical reactivity adds to tool wear especially at elevated cutting temperatures. As cutting speed dictates the temperature of cutting zone [5] the productivity is limited due to curtailed cutting speeds. In today's manufacturing industry, productivity is one of the main goals of research endeavors [6]. A variety of methods are adopted to enhance productivity while maintaining economy. In order to avoid excessive tool attrition at higher cutting speeds different cooling systems are installed in various configurations. These include high pressure coolant [7], minimum quantity lubrication (MQL) [8] and cryogenic media [9]. As cooling system accounts for around 20% of aggregate manufacturing budget [10] there is a significant need for the cooling system to be economical and efficient. Various researchers have carried out tool wear analysis for improving economy under different machining environments. Damir et al.


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[11] conducted milling of hardened H13 tool steel under cryogenic and wet conditions. In addition to increased tool life, up to 37% improvement in material removal rate, with better surface integrity was reported. Moreover, cost reductions were estimated to be around 33%. Another recent work [12] analyzed tool life while milling Ti-6Al-4V under high pressure cutting fluid. A conventional tool was compared with an additively manufactured tool having similar geometry but with in-built supply lines. Tool life was found to increase up to 70%. Khan et al [13] conducted parametric studies of dry, wet and cryogenic turning. It was concluded that cryogenic cooling decreased tool wear by 30% in combination with other responses. Cooling condition had an overall significant impact on machining output. A noteworthy contribution to cryogenic machining of Ti-6Al-4V was made by analysing tool wear along with other responses [14]. Tool life was found to increase by 125% under cryogenic media in comparison with wet machining. Similar results were obtained in another related work [15].

## 2. Design of experiment

Turning operation for Ti-6Al-4V was conducted on CNC turning center (Model - ML 300). Three different machining environments (ME) were used including wet and cryogenic conditions in addition to dry condition. Additional setup as shown in Fig. 1 was installed for cryogenic machining. Add-on setup included cryogenic cylinder, decanting pipe, bifurcating valve and nozzles. Two nozzle setup (with 4mm diameter), one each directed on flank and rake face, was used for optimum performance [16]. Liquid nitrogen was selected as the cryogenic media owing to its effectiveness when used with titanium work material and uncoated carbide tool [17]. Liquid nitrogen was also the preferred choice due to its inert nature and global availability [18]. Pressure of 20 psi was maintained which accumulated a combined flow rate of 4 LPM. Wet runs were carried out using under flow rate of 6 L/min. Design of experiment is displayed in Table 1. Depth of cut was kept constant because of its insignificant nature as determined in published literature[9]. As per the recommendations of ISO 3685[19], depth of cut was kept as 1 mm for the selected insert (corner radius of 0.4 mm). The selected levels and range of these input parameters were based on literature [20], [21], concerned ISO standards [19] and tool manufacturer guidelines [22]. Uncoated tungsten carbide inserts (SANDVIK–CCMW 09 T3 04 H13) were used.

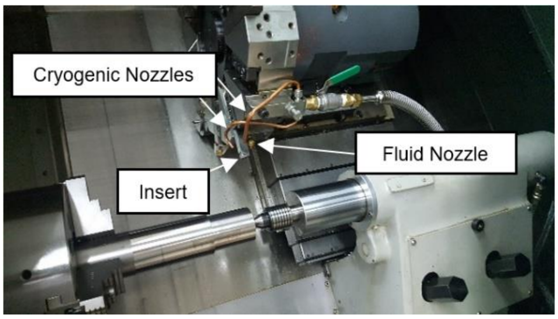


Fig. 1 Experimental operation

Table 1. Design of Experimentation

| Condition | Input | | |
|---|---|---|---|
| | $f$ $(mm/rev)$ | $V$ $(m/sec)$ | $ME*$ |
| 1 | 0.20 | 60 | 1,2,3 |
| 2 | 0.20 | 90 | 1,2,3 |
| 3 | 0.20 | 120 | 1,2,3 |
| *1 = Dry, 2 = Wet, 3 = Cryogenic | | | |

## 3. Tool wear measurement

In the present research tool flank wear is calculated for comparison as it represents substrate properties [23]. Eq. 1 is used to determine tool wear rate (R). It is pertinent to mention that $R$ remains constant during the entire cutting time for particular combination of machining variables. This is the precise reason for selecting R for analysis and not tool wear.

$$R = log\left[\frac{VB}{l_s}\right] = log\left[\frac{VB}{1000tV_c}\right] \qquad (1)$$

The Eq. (1) depicts logarithm ratio of two variables namely $VB$ (flank wear land) and $l_s$ (actual length of cut which is spiral length in turning)) or alternatively three variables $VB$, $V_c$ (cutting speed) and $t$ (cutting time). Hence it is the ratio the extent of flank wear to the length of workpiece that has effectively been in contact with the tool cutting edge or the length of travel of the tool on the workpiece surface. The flank wear is therefore expected to increase with the length of tool travel over the workpiece. R is therefore tool wear normalized against the tool-workpiece length of engagement. For a given set of cutting conditions, the tool wear rate per unit contact distance would remain constant as reported in past research [24]. A greater negative value of R represents lower flank wear and vice versa. Two trials were conducted for measurement of tool wear for each condition.

## 4. Result and analysis

Table 2 displays the average R of both trials measured at prearranged machining conditions. It can be noticed that cryogenic condition yielded the lowest tool wear at all three conditions as also can be seen in Fig. 2. A comparative pictorial representation of the tool wear at a particular condition ($f$ 0.2 mm/rev and $V$ 60 m/sec) is given in Fig. 3. Here, dry condition is seen to produce significantly large tool wear in comparison with wet and cryogenic conditions for the same duration of cutting time.

Table 2 Tool wear result

| Condition | $R$ | | |
|---|---|---|---|
| | Dry | Wet | Cryogenic |
| 1 | -5.74 | -5.92 | -5.98 |
| 2 | -5.65 | -5.81 | -5.85 |
| 3 | -5.56 | -5.67 | -5.73 |

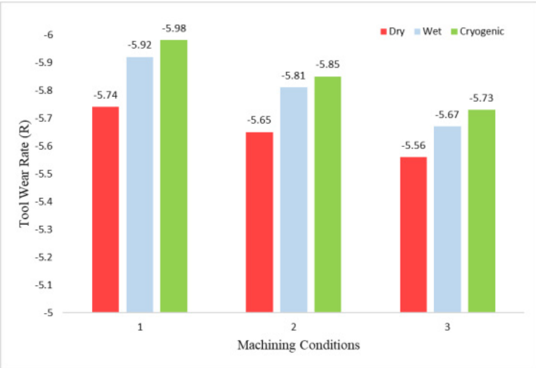


Fig. 2. Tool wear rate under different ME

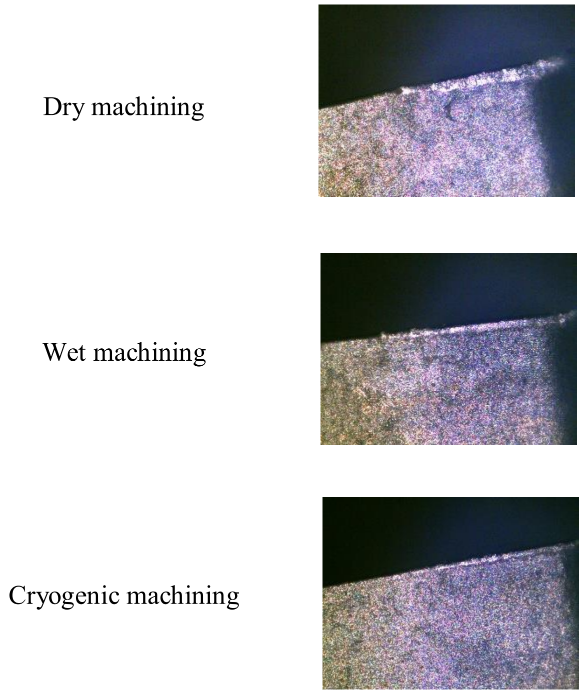


Fig. 3. Tool wear depicted at $f$ 0.2 mm/rev and $V$ 60 m/sec

Further, main effects plots were drawn and analysis of variance (ANOVA) carried out for conclusive examination. Fig. 4 shows the main effect plot of $R$ plotted against the input parameters. $R$ has a directly proportional relationship with speed. The elevated wear at elevated cutting speed values is because of the high cutting zone temperature. Tool wear mechanisms of adhesion and diffusion-dissolution primarily depends on temperature [25] causing accelerated tool wear. Titanium is known to smear onto materials during machining through adhesion as shown in Fig. 5. These adhered titanium layers then break off with flowing chips causing tool wear. Similarly, Cobalt which is the main binding element of insert tends to diffuse into the titanium adhesion and flowing chip further elevating tool wear. Machining environments including dry, wet and cryogenic conditions highly influenced the tool wear because of their cooling as well as lubricating effect. Wet cutting produced lesser wear than dry cutting because of cooling effect. However, cryogenic media had a more profound effect because of its immense cooling capacity (-197°C [26]). Also, cryogenic media tend to greatly limit the volume of heat produced in the cutting region. Table 3 displays ANOVA results for tool wear rate. Both, cutting speed and machining environment were found to be significant. It is shown that $V$ is the most effective input with contribution ratio $(CR)$ of 52.96% whereas $ME$ has $CR$ 45.82%.

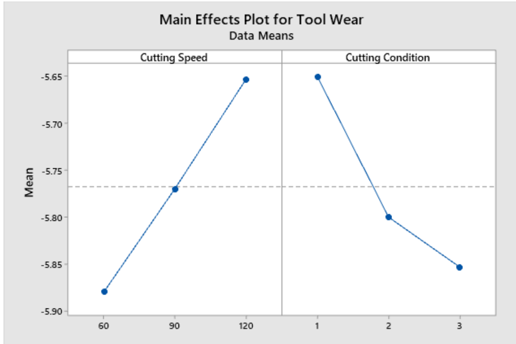


Fig. 4 Main effect plots

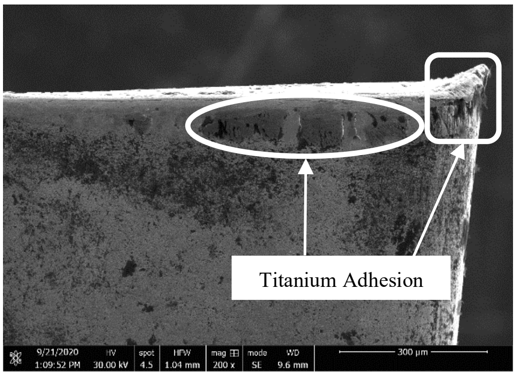


Fig. 5 Tool wear mechanism

Table 3. ANOVA for tool wear

| Source | DF | Seq SS | Adj MS | F | P-Value | CR (%) |
|---|---|---|---|---|---|---|
| $V$ | 3 | 0.077089 | 0.038544 | 86.73 | 0.001 | 52.96 |
| $ME$ | 2 | 0.066689 | 0.033344 | 75.03 | 0.001 | 45.82 |
| Error | 6 | 0.001778 | 0.000444 | | | 1.22 |
| Total | 11 | 0.145556 | | | | 100 |
| S = 0.0210819 R-Sq = 99.78% R-Sq(adj) = 98.56% | | | | | | |

Tool wear is further characterized using tool chip contact length $l_c$. The intimate contact between tool surface and workpiece chip is known as $l_c$ as shown in Fig. 6. $l_c$ is an important parameter; representative of machinability of materials [27]. $l_c$ depends on various factors like tool material/ geometry, machining variables including feed rate and cutting speed, and type of coolant used [28]. Tool wear during machining is directly proportional to $l_c$. A greater $l_c$ would mean higher tool wear owing to the greater contact area resulting in larger amount of heat transferred between the two surfaces. $l_c$ is known to increase at higher cutting speeds and feed rates[29]. On the contrary, $l_c$ is reduced under use of coolant [4]. This occurrence is due to the elimination of slip region (as indicated in Fig. 6) under the use of coolant. A lesser $l_c$ results in lower heat transfer and so causes lower tool wear. This aspect is ascertained by comparison of $l_c$ under the three used machining environments working with same feed rate and cutting speed as displayed in Fig. 7. It may please be noted that although cryogenic and wet machining has comparable $l_c$, nonetheless they have different coolant potential affecting aspects like cutting zone temperature and chip morphology.

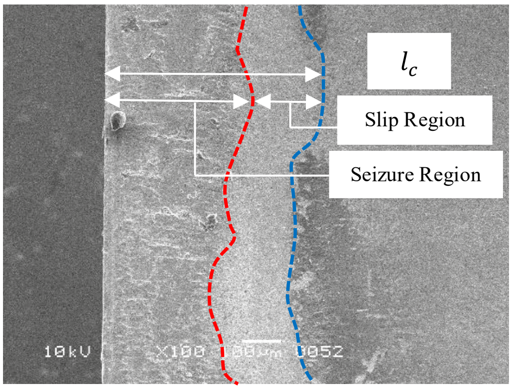


Fig. 6 Tool chip contact length ($l_c$)

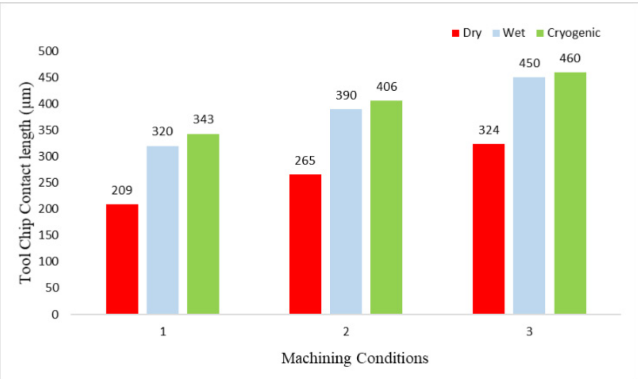


Fig. 7. Tool chip contact length under different ME

## 5. Conclusions

Present work examined tool wear during machining of titanium alloy Ti-6Al-4V under dry, wet and cryogenic conditions. Key takeaways are as follows:

- Tool wear rate is directly proportional with cutting speed. Elevated cutting zone temperature, at higher cutting speeds, expedites wear inducing phenomenon including adhesion and diffusion dissolution.
- Cooling media significantly reduces the tool wear. At 60 m/sec cutting speed, cryogenic machining yields 23% and 12% lesser tool wear than corresponding dry and wet machining, respectively.
- Cutting speed was found to be the most effective input with CR of 52.96% whereas machining environment had CR of 45.82%.
- Tool chip contact was found to reduce under use of cryogenic and wet machining resulting in lower tool wear.

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