Wear and surface roughness analysis of machining of Ti-6Al-4V under dry, wet and cryogenic conditions

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Abstract. Use of cooling media contributes in elevation of desired responses owing to its cooling and lubrication effects especially in case of hard to cut materials like Ti-6Al-4V. This study aims to analyze the effect of cooling media in addition to cutting speed on responses including tool wear and surface integrity during turning. Results highlighted the effectiveness of cooling system in particular that of cryogenic media. Use of cryogenic media and cutting fluid enhanced tool life max by 33% and 21% respectively. At lower cutting speed surface roughness was improved by 13% and 8% by cryogenic media and cutting fluid respectively.

Keywords: Ti-6Al-4V, Titanium, Machining, Cryogenic

1. Introduction

Use of cooling media is as old as the history of machining itself. From basic water cooled machining systems to state of the art cryogenic cooling, technology has evolved into different forms in pursuit of overall process optimization. Selection of cooling media for a specific manufacturing system merits necessary consideration as it accounts for about 15% of the total manufacturing costs [1]. Minimum quantity lubrication [2] and conventional high volume coolant [3] are widely used in different machining systems. Lately cryogenic media has served the purpose well by reducing the cutting zone temperature and lubricating the sliding surfaces reducing tool wear and surface roughness respectively. Added advantages include no extra disposal measures and ease of global availability [4].

Economy and productivity defines efficiency of any manufacturing system [5]. Prolonged tool life contributes towards economy whereas better surface finish improves product quality. Ti-6Al-4V is a widely used titanium alloy because of good corrosion resistance, high strength and hardness. Approximately 60% of all titanium alloys usage consist of Ti-6Al-4V [6]. On the other hand it is highly reactive at high temperatures associated with high cutting speeds [7] in addition to its low thermal conductivity. Low modulus of elasticity and high temperature strength also adversely effects tool life [8]. Tooling costs make up around 4% [1]of total cost which is a sizeable figure keeping in view the overall manufacturing volume. Surface integrity also holds position of central importance as any product not conforming to requirement will amount to waste and add up to inefficiency. Working with Ti-6Al-4V, Jerold and Kumar [9] found that liquid nitrogen (LN2) and carbon dioxide (CO2) both produced better surface finish and tool life than dry machining. Sun et al [10]reported improved
tool life turning Ti-6Al-4V under cryogenic conditions owing to reduced cutting zone temperature and shorter chip contact length. Cryogenic conditions also gave better tool life and improved surface roughness in milling operations [11]. Birmingham et al [12] concluded in his research that high pressure coolant and LN2 produced comparable results in term of tool wear which were much better than dry machining. Keeping in view the effectiveness of both wet and cryogenic machining present research was conducted by vesting the cutting condition (dry, wet and cryogenic) as an input variable with varying cutting speed.

2. **Experimental setup**

CNC turning centre (ML 300) was used in experiments as shown in Fig. 1. Cryogenic LN2 setup was established using cryogenic cylinder with 160 liters capacity. Efficient dual jet configuration [13] was used connected via cryogenic bifurcating valve and decanting pipe to the cylinder. Temperature around -196°C is reached with use of LN2 cryogenic media [14]. Ti-6Al-4V was selected as work piece with chemical composition as shown in Table 1. ML 300 internal cooling system was used for wet machining. Dry, wet and cryogenic experiments were carried out at each of the four conditions given in Table 2.

![Figure 1. Experimental setup with cryogenic arrangement](image)

### Table 1. Chemical Composition (wt. %)

|   | Ti  | V  | Al | Fe  | Cu  | Cr  |
|---|-----|----|----|-----|-----|-----|
|   | 89.44 | 4.2 | 5.7 | 0.15 | 0.003 | 0.0023 |

### Table 2. Design of experiment

| Condition | Inputs |               |               |               |
|-----------|--------|---------------|---------------|---------------|
|           | Feed rate (f) (mm/rev) | Cutting speed (v) (m/min) | Depth of cut (d) (mm) |
| 1         | 0.12   | 50            | 1             |
| 2         | 0.12   | 75            | 1             |
| 3         | 0.12   | 100           | 1             |
| 4         | 0.12   | 125           | 1             |
3. Response measurement and analysis

Tool wear rate was measured using flank wear by Eq. 1[15] which is an appropriate comparison as shown in Table 3. Higher negative value represents lower flank wear and vice versa. Surface roughness results as tabulated in Table 3 were determined using roughness tester TR 110. These results were further evaluated and compared as shown in Fig. 2.

$$R = \log \left( \frac{VB}{L_s} \right) = \left[ \frac{VB}{1000tV_c} \right]$$  \hspace{1cm} (1)

Table 3. Tool wear rate and surface roughness results

| Condition | Tool wear rate | Surface roughness |
|-----------|----------------|-------------------|
|           | Dry            | Wet               | Cryogenic        | Dry            | Wet          | Cryogenic        |
| 1         | -6.15          | -6.25             | -6.32            | 1.55           | 1.44         | 1.36           |
| 2         | -6.09          | -6.16             | -6.20            | 1.39           | 1.30         | 1.24           |
| 3         | -6.01          | -6.06             | -6.09            | 1.28           | 1.23         | 1.16           |
| 4         | -5.98          | -6.01             | -6.04            | 1.11           | 1.08         | 1.03           |

3.1 Tool wear analysis

Tool wear has a relationship of direct proportionality with cutting speed as evident in Table 3. As temperature acts as a catalyst in wear inducing mechanisms [16] tool wear increases with increasing speed as cutting zone temperature elevates as speed increases [17]. Use of cooling media has significantly reduced tool wear as highlighted in Fig. 2 (a) with tool wear improvement indicated at each condition. In particular, cryogenic media because of its extremely low temperature ensured reduced heat production as well as timely heat extrication resulting in improved tool life. It was observed that effect of cooling media abridged at speeds above 100 m/min because of the reduced penetration in the cutting zone at such higher speeds [18].

![Figure 2](image.png)

**Figure 2.** Comparison of cutting conditions (a) Tool wear rate (b) Surface roughness

3.2 Surface roughness analysis

Fig. 2 (b) compares surface roughness under varying cutting conditions. Surface roughness improves with increasing cutting speed because of the thermal softening of work piece. Both cryogenic and wet conditions produced better results than dry machining owing to the lubrication effect at the sliding surfaces interface [19]. As discussed earlier the benefits of cooling media is more pronounced at lower cutting speeds.
4. Conclusion

Present research carried out turning of Ti-6Al-4V under dry, wet and cryogenic conditions. Tool wear and surface roughness were the focus of attention under varying machining parameters. Following conclusions were drawn:

- Tool wear and surface roughness are highly dependent on cutting speed as the temperature increases with increasing speed.
- Cooling media has significantly improved tool life by swift extrication of heat produced and reducing cutting zone temperature. Use of cryogenic media and cutting fluid improved tool life by 33% and 21% respectively at lower speeds.
- Surface roughness was reduced due to the lubrication effect of cooling media. Surface finish improved by 13% and 8% using cryogenic and cutting fluid respectively. Improvements were more pronounced at lower cutting speeds.

Employment of cooling system has considerably improved productivity and economy of manufacturing system. However sustainability of the manufacturing system pose new challenges which needs deliberation. Future research includes the study of effects of varying feed rate and depth of cut in terms of productivity, economy and sustainability of manufacturing systems.

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