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# Assessment of machinability of Ti6Al4V alloy under dry conditions.

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# Assessment of Machinability of Ti6Al4V Alloy Under Dry Conditions

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**Abstract.** Titanium alloys pose significant challenges during machining, necessitates a thorough investigation into the impact of process parameters on machining Ti6Al4V alloy. This study investigates into the machinability of Ti6Al4V alloy under dry machining conditions using uncoated tools. The experimental design studiedthe effect of process parameters on the cutting power, surface roughness and material removal rate during dry machining of Ti6Al4V alloy. Utilizing Taguchi design of experiments, unified cutting experiments were conducted under dry conditions employing uncoated tools. The study findings revealed that optimal cutting parameters lead to improved cutting energy consumption, reduced tool wear, and enhanced surface finish and material rates. Analysis of Variance (ANOVA) and regression modelling were employed to obtain an objective function capable of predicting the best cutting conditions. ANOVA showed that cutting speed is the main factor for an increase in the cutting power with major contribution of 73 % whereas feed rate is the key factor for surface roughness with the contribution of 80 %. These results help to gain the advantages of dry machining under optimal conditions, facilitating clean production with minimal energy consumption and improved surface quality.

## 1 Introduction

Machining is an integral part of the manufacturing industry which accounts for over 60% of power consumed in the sector, achieving sustainable manufacturing requires reducing the amount of energy used in machining[1]. The machinability of Ti6Al4V alloy presents some challenges, especially regarding cutting power and material removal rate. Carbide tools were found to be the most widely used cutting tools due to their comparatively hardness and toughness in the machining of Ti6Al4V and its alloys [2]. Dry machining Ti6Al4V alloy with uncoated tools is challenging due to te alloy's tendency to harden, generate heat, and conduct heat poorly[3].Selecting appropriate tools and machining processes is crucial for balancing productivity and tool life while minimizing heat generation. Dry machining is employed where cutting fluid use is limited or avoided due to environmental concerns. The alloy`s exceptional properties, such as its excellent combination of high strength-to-weight ratio, corrosion resistance, and low density make it a desirable material of choice for aerospace, automotive, and biomedical sectors. However, its low thermal conductivity and low modulus of elasticity result in short tool life and poor surface finishing respectively [4], [5].

Understanding the effect of process parameters stands as a critical factor in many manufacturing studies [6], [7], [8]. For instance, the effects of high cutting speed led to high temperature, too high feed rates result in high material removal rate, and deeper cuts influence high cutting forces [9]. It was reported that machining Ti6Al4V alloy at a high speed of 125 m/min results in high cutting power and wear rates, due to a bigger contact length [10] Studies show that factors that determine the cutting power are type of material remove, level of final surface required, material removal rate, and cutting parameters. Other results show that a decrease in feed rate led to an increase in cutting power, cutting speed, and depth of cut [11]. It was observed that in dry machining of Ti6Al4V alloy with an uncoated insert the cutting power and surface roughness were reduced as cutting speed and MRR increased [12].It was reported that Taguchi models in turning Ti6Al4V alloy were effective in estimating the surface roughness and cutting power. The ANOVA result shows that cutting power and surface roughness was observed to decrease by 89.3% and 94.45% respectively and depend on feed rate at optimal cutting parameters of 50 m/min, 0.20 mm/rev, and 1.0 mm [13]. Another result shows that an uncoated insert depends on low cutting speeds for a better result, but a low feed rate leads to high cutting power [4]. The result in turning of the Ti6Al4V alloy with different inserts shows that surface integrity is independent of tool geometry and cutting conditions [14].

A lot of studies have been reported on how to understand the effects of cutting conditions on machining responses [15], [16], [17]. There are still several areas that need to be filled to fully understand how cutting parameters affect material removal rate, cutting power, and surface roughness throughout the machining process. This research focuses on the

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Taguchi design and use of ANOVA to find the optimal cutting conditions that balance the multiple objective's functions, to better understand the effects on the cutting power, surface roughness, and material removal rate in dry machining environment with Ti6Al4V alloy. In many industrial applications, these optimal values can help to create more effective and efficient machining operations.

## 2 Experimentation section

### 2.1 Materials and Methods.

This research used a rod of Ti6AL4V alloy as a workpiece material for dry machiningexperiments. Cutting experiments were conducted on a rod of Ti6AL4V alloy under a dry machiningenvironment using uncoated tools. A length of cut of 75 mm was chosen and a fresh uncoated Tungsten carbide cutting insert was used for each run.

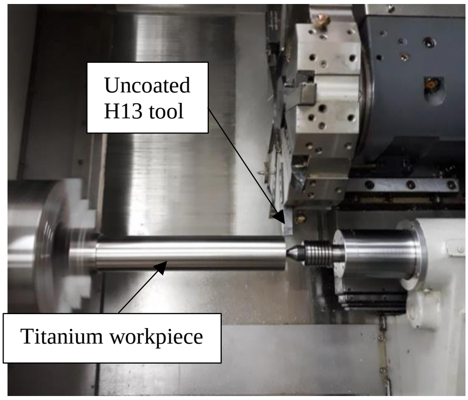


**Fig 1.** Experimental setup for turning Ti6Al4V alloy.

Machining experiments were carried out using CNC machine with a spindle power of 18 KW and maximum rpm of 8000. The setup is shown in Fig 1 with the details of the tools and arrangement of the tool and workpiece. A full factorial Design ofexperiment was used to perform dry machiningat various combinations of cutting speeds and feed rates. Depth of cut was kept constant at 1mm. The ranges and levels of the cutting parameters are shown in Table 1.

**Table 1.** Design of Experiments for dry machining

| Cutting Parameter | Range |
|---|---|
| Cutting speed (m/min) | 50 |
| | 75 |
| | 100 |
| | 125 |
| | 150 |
| Feed (mm/rev) | 0.12 |
| | 0.16 |
| | 0.20 |
| | 0.24 |
| Length of cut (mm) | 100 |

### 2.2 Measurement of cutting power.

Energy consumption in each experimental run was recorded using a power meter attached to the machine's control panel, following a previously established approach. It measures the difference of power between the idle power state and the actual cutting state using Eq. 1

$$\text{Cutting Power} = P_{\text{actual cut}} - P_{\text{air cut}} \qquad (1)$$

Where P actual is the machine power recorded when cutting was done.
P air is the power recorded when the machine was activated with a machining run performed in air.

### 2.3 Measurement of Surface roughness.

Surface roughness was measured using a portable surface tester and five readings were made after each machining run. The average value of surface roughness (Ra) is tabulated in the following sections.

## 3 Results and Discussion

### 3.1 Effect on cutting power.

Energy consumption is a key concern in modern manufacturing setups, influenced by various factors including cutting parameters, tool geometry, and the workpiece material. Cutting power also depends on the cutting forces which in turn can also affect the surface roughness and tool wear condition [4]. Results from the experiments are shown in Table 2.

**Table 2.** Responses from experimental tests

| Sr. # | Cutting speed (m/min) | Feed rate (mm/rev) | Ra | Cutting power (KW) |
|---|---|---|---|---|
| 1 | 50 | 0.12 | 1.08 | 0.095 |
| 2 | 50 | 0.16 | 1.56 | 0.12 |
| 3 | 50 | 0.2 | 2.26 | 0.15 |
| 4 | 50 | 0.24 | 2.54 | 0.17 |
| 5 | 75 | 0.12 | 1.26 | 0.16 |
| 6 | 75 | 0.16 | 1.71 | 0.22 |
| 7 | 75 | 0.2 | 2.21 | 0.27 |
| 8 | 75 | 0.24 | 2.9 | 0.315 |
| 9 | 100 | 0.12 | 1.04 | 0.225 |
| 10 | 100 | 0.16 | 1.54 | 0.29 |
| 11 | 100 | 0.2 | 2.88 | 0.36 |
| 12 | 100 | 0.24 | 2.4 | 0.43 |
| 13 | 125 | 0.12 | 1.05 | 0.285 |
| 14 | 125 | 0.16 | 0.92 | 0.37 |
| 15 | 125 | 0.2 | 1.1 | 0.47 |
| 16 | 125 | 0.24 | 2.52 | 0.56 |
| 17 | 150 | 0.12 | 1.03 | 0.35 |
| 18 | 150 | 0.16 | 0.84 | 0.46 |
| 19 | 150 | 0.2 | 1.48 | 0.57 |
| 20 | 150 | 0.24 | 3.01 | 0.61 |

Cutting power increases with the increase in the MRR (Fig 2a), which in turn is the product of cutting speed feed rate and depth of cut. The effect of cutting parameters on cutting power is illustrated in Fig 2b. It was observed that cutting speed significantly influences power, increasing with higher cutting speeds. This result agrees with the published trends for specific energy consumption in machining of Ti6Al4V alloy [9, 12]. This is because the chip load increases at the chip tool interface when the cutting speed increase from low speed regime to a relatively higher speed. The effect of tool wear at high speed could even further fluctuate the process dynamics, cutting forces and energy consumption requirement. This highlights the need to consider the machine tool dynamics, chatter, and vibration as well as the tool stability into account when machining hard to cut materials. In the current study the tool wear was monitored and remained within the limits prescribed by ISO 3685.

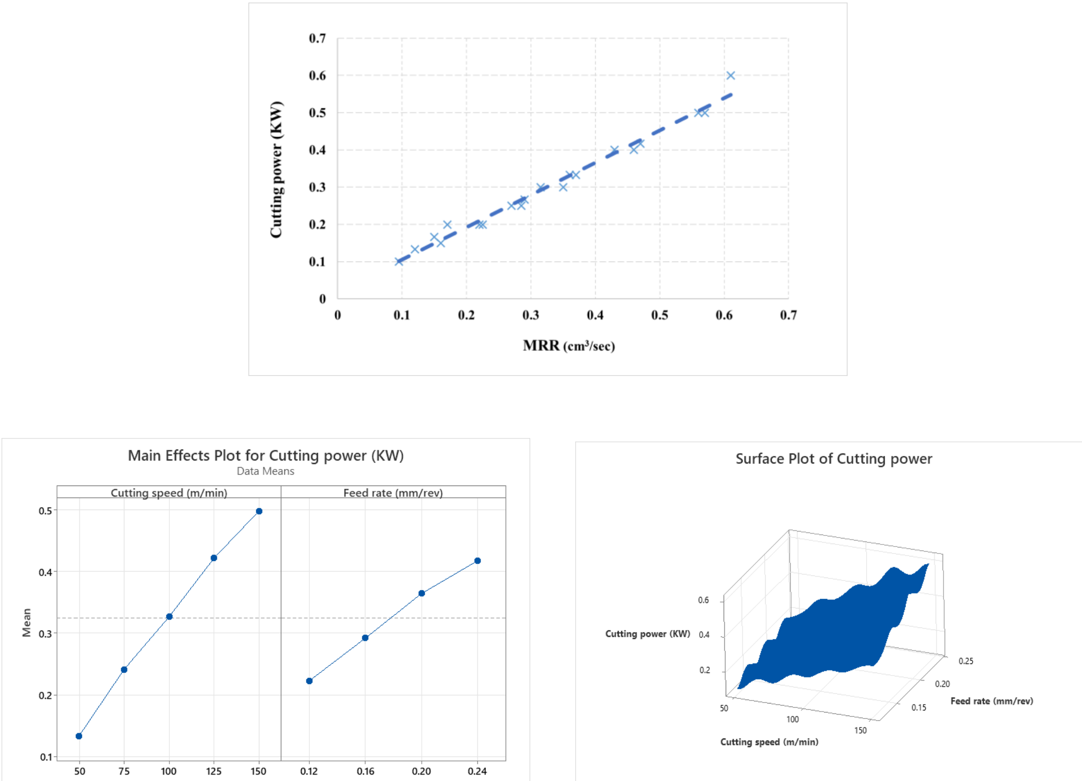


**Fig 2.** Cutting power against (a) MRR (b) speed and feed (c) surface plot

ANOVA analysis in Table 3 further confirms the significance of both factors. However, cutting speed emerges as the primary factor affecting cutting power in Ti6Al4V alloy machining.This is attributed to the increased power requirement for driving the spindle and efficiently shearing the material at higher cutting speeds. However, when cutting power is normalized over material removal rate, specific energy can be estimated, representing the energy consumed per unit volume of material removed [10]. These findings highlight the importance of considering cutting power in machining analysis. However, it should be examined in conjunction with other responses such as material removal rate, surface roughness, and tool wear to achieve optimal machining outcomes.

**Table 3.** Analysis of Variance for Cutting Power

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Cutting speed (m/min) | 4 | 0.657371 | 72.75% | 0.657371 | 0.164343 | 160.14 | 0.000 |
| Feed rate (mm/rev) | 3 | 0.213378 | 23.61% | 0.213378 | 0.071126 | 69.31 | 0.000 |
| Error | 32 | 0.032840 | 3.63% | 0.032840 | 0.001026 | | |
| Lack-of-Fit | 12 | 0.032608 | 3.61% | 0.032608 | 0.002717 | 234.25 | 0.000 |
| Pure Error | 20 | 0.000232 | 0.03% | 0.000232 | 0.000012 | | |
| Total | 39 | 0.903589 | 100.00% | | | | |

### 3.2 Effect on surface roughness.

Surface roughness measurements for all cutting conditions are presented in Table 3 above. Figure 3 illustrates the mean data and reveals that surface roughness initially increases with the rise in cutting speed up to 75 m/min, then decreases until 125 m/min, and finally starts to increase again after 125 m/min. This fluctuation can be attributed to the wear of the cutting tool under different cutting conditions. Studies have indicated that cutting conditions transition from low to moderate and high wear during titanium machining [5], [10], resulting in an initial increase in surface roughness from 50 to 75 m/min, followed by a decrease as moderate wear is reached. Subsequently, in the high tool wear zone, surface roughness increases again. On the other hand, surface roughness increases with the increasing feed rate. The optimal surface condition was achieved at a speed of 125 m/min and a feed rate of 0.16 m/min, consistent with the recommended feed and speed by the tool manufacturer. Statistical analysis (Table 3) revealed that feed rate is the most influential parameter for controlling surface quality and should be carefully selected for dry machining of Ti6Al4V.

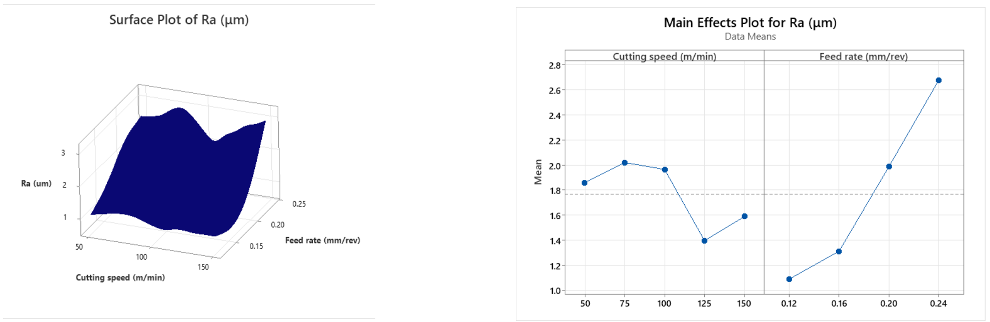


**Fig 3.** Surface roughness plotted against speed and feed.

**Table 4.** Analysis of Variance for Surface roughness

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Cutting speed (m/min) | 4 | 1.7863 | 9.34% | 1.7863 | 0.44657 | 7.68 | 0.000 |
| Feed rate (mm/rev) | 3 | 15.4792 | 80.94% | 15.4792 | 5.15973 | 88.77 | 0.000 |
| Error | 32 | 1.8599 | 9.72% | 1.8599 | 0.05812 | | |
| Lack-of-Fit | 12 | 1.7788 | 9.30% | 1.7788 | 0.14824 | 36.56 | 0.000 |
| Pure Error | 20 | 0.0811 | 0.42% | 0.0811 | 0.00406 | | |
| Total | 39 | 19.1254 | 100.00% | | | | |

A regression model (Eq. 2) was developed that can predict the surface roughness of the output part with respect to the cutting conditions. This relationship can estimate the surface roughness within less than 5 % error and thus is very useful for machining Ti6Al4V alloy using uncoated tools.

$$Ra = -0.207 - 0.00465 \text{ Cutting speed (m/min)} + 13.54 \text{ Feed rate (mm/rev)} \qquad (2)$$

It is important to mention here that the effect of tool wear on the roughness and energy was not considered but the tool condition was monitored as per ISO standard and a fresh insert was used for each run. Studies have shown that tool wear may affect other machining responses, but this will be considered for future analysis.

## 4 Conclusions

This study investigated dry machining of Ti6AL4V alloy using H13 uncoated tools, varying cutting speed and feed rates. The following conclusions can be drawn from the study:

1. Cutting speed plays a crucial role in limiting cutting power and energy consumption during the machining process.
2. Feed rate is a significant parameter for controlling surface quality.
3. ANOVA and surface plots are effective tools for controlling process parameters and understanding the relationship between cutting parameters to achieve the best results for dry machining Ti6Al4V alloy.
4. The findings suggest that dry machining can achieve optimal surface quality with notable energy consumption and material removal rates.
5. Dry machining of Ti6Al4V alloy at low cutting speeds 50 m/min and feed rates of 0.12 to 0.2 mm/rev will save a lot of cutting power for future industrial application.

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