Experimental study on end milling parameters of Ti6Al4V Titanium superalloy in different cutting environment

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Abstract. Machining of super alloys becomes highly demanded in aerospace industries. Titanium alloys tend to fall under the above category due to its density ratio and high strength. Machining under dry conditions and conventional coolants were performing better under normal conditions. Also, disposal of contaminant coolants created a necessity to find an alternate to it. Cryogenic coolant is a recent sustainable green machining process which is considered as one of the efficient process to replace conventional coolants. In the study, Liquid nitrogen (cryogenic coolant) was utilized as a cryogenic coolant to endmill the Ti6Al4V titanium superalloy at varying investigative parameters depth of cut, feed rate and speed of spindle. This study was also focused on comparing cryogenic coolant with dry machining by measuring its surface integrity. Cryogenic milling has given beneficial results when compared to dry milling. Taguchi L9 technique was utilized for experiment design and corresponding ANOVA was done to find the most influencing parameter and optimized values. At higher speeds and feed rate (i.e.,5000 rpm and 0.6 mm/min) around 15% improvement was found in cryogenic milling when compared to dry milling. In environment and health of worker or machinist point of view, cryogenic machining leads to clean and green manufacturing without compromising the quality of output.

1. Introduction

Quality is a key word across all manufacturing process. In machining industry, quality of output is measured by the surface finish, better machining conditions and reduced tool wear. One good technique for providing better machining conditions is choosing a right coolant for the process.

Conventional coolants require a replacement as it depletes raw materials, creates environmental pollution, and increased machining cost. Many replacements are being researched by the machinists in which one of the efficient and user-friendly technique is cryogenic coolants. Cryogenics are minus degree gases which provides safe, non-toxic and green surrounding during machining. It also enhances surface integrity by providing better cooling and lubrication. It eliminates the secondary cooling process which is an advantage in cryogenic machining, as minus degree gases [1].
Pereira et al. evaluated the tool life improvement of 60% and better surface finish while using cryogenic CO$_2$[2]. Few research works explored the capability of cryogenic coolants in machining and found improvements in surface integrity, life of tool, material removal rate [3-4]. Usage of cryogenic coolants like Carbon di-oxide (CO$_2$) and Liquid Nitrogen (LN$_2$) has shown better rate of heat removal from machining area and thermal softening reduction of machining tools and inserts [5]. The heat absorption rate and layer formation of LN$_2$ provides good lubrication and cooling effect. Few works suggested that cryogenic coolant method as the efficient cooling method in the machining region due to its light density and spreading ability [6]. Titanium Ti-6Al-4V due to durability, it finds applications in making of aero and aerospace parts, parts of racing cars, marine applications and parts of gas turbines. Though widely used, being a hard-to-cut material its hardness, high temperature strength retention, machining at higher speed and feed rates becomes difficult [7-9]. Few previous researchers have intended to identify the optimum and better milling conditions for machining Ti-6Al-4V alloy. Kaynak, Y et al. [10] has stated that a very few amounts of research works have been studied to identify the performance of LN$_2$ cryogenic coolant on machining conditions of super alloys. Few suggestions from above literatures were identified as research gaps. Experimentally identifying the effects on important parameters like surface roughness, tool wear in super alloys is one of the major gaps.

This research work tends to fill the gap identified, making a comparative study in different cutting environment between no-coolant(dry) environment and cryogenic coolant (LN$_2$) in determining the optimal milling conditions for titanium Ti-6Al-4V super alloy.

2. Experiment

2.1. Material

Ti-6Al-4V rectangular bar of 100mm X 20 mm X 20 mm was taken in this study. Composition of chemicals to understand the alloy presence was studied and reported in Table 1.

| Elements | Ti  | Al  | V   | Fe  | C   |
|----------|-----|-----|-----|-----|-----|
| %        | 88.59 | 6.70 | 4.36 | 0.163 | 0.128 |

The milling tool used here is Trio solid carbide endmill cutter of 8mm diameter and 4 flutes. The tool has hardness of 54HRC for providing superior cutting for machining superalloy.

2.2. Properties of Cryogenic coolant used

The temperature at which the Liquid nitrogen was taken for the study was -165°C. The liquid dewar flask was used here as shown in fig.1 for better insulation.
Figure 1. Liquid dewar flask containing LN$_2$ for maintaining the temperature at -165°C.

The properties of LN$_2$ is given in table 2. They have high expansion ratio which helps in better spread-ability while passing it in the machining area [11]. Also, when exposed to higher temperatures they turn into gas rapidly. If the expansion ratio is low the volume will be expanded and in turn increases its pressure.

| Cryogen | Boiling point at 1 atm $^\circ$C ($^\circ$F) | Pressure maintained inside the flask in Psi | Density of LN$_2$ cryogen, g/L | Gas Density of LN$_2$ cryogen (at 30$^\circ$C), g/L | Expansion ratio of LN$_2$ cryogen | Type |
|---------|---------------------------------------------|---------------------------------------------|-------------------------------|-----------------------------------------------|-----------------------------------|------|
| LN$_2$  | -197$^\circ$C (-321)                        | 492                                         | 808                           | 2.25                                          | 710                               | Inert|

A special delivery was designed shown in fig. 2 for delivering the cryogenic coolant from the dewar flask. This delivery system helps to maintain and regulate the pressure. Also, a small insulation was provided on the pipe for avoiding escape of gases due to convection into the environment. The pipe also carries a flow control valve attached to a pressure gauge.
2.3. Parameters and their levels considered for the study

Generally, end milling depends on the controlled conditions like speed, feedrate and depth. Patil et.al. [12] and many other researchers have suggested the optimized levels for the controlled parameters. The fixation of levels was done based on tool and machine standards. Table 3 shown for the selected parameters level.

| Conditions               | Units     | Levels |
|--------------------------|-----------|--------|
| Speed of spindle (N)     | rpm       | 4000   |
|                          |           | 4500   |
|                          |           | 5000   |
| Feed rate (f)            | mm/rev    | 0.2    |
|                          |           | 0.4    |
|                          |           | 0.6    |
| Depth of cut(dc)         | mm        | 0.5    |
|                          |           | 0.75   |
|                          |           | 1      |

2.4. Experimental design

Taguchi technique was used here to ensure the variability of minimum experiments and for fixing the efficient experimental trial runs. The orthogonal array (L9) from taguchi technique were used here which has 8 degrees of freedom (DoF) and to examine the least trial runs. The experiments formed by Taguchi L9 which is shown in Table 4.

| Trial No. | N (rpm) | f (mm/rev) | dc (mm) |
|-----------|---------|------------|---------|
| 1         | 4000    | 0.2        | 0.5     |
| 2         | 4000    | 0.4        | 0.75    |
| 3         | 4000    | 0.6        | 1       |
| 4         | 4500    | 0.2        | 0.75    |
| 5         | 4500    | 0.4        | 1       |
| 6         | 4500    | 0.6        | 0.5     |
| 7         | 5000    | 0.2        | 1       |
3. Results and Discussion

The experimented values for both dry and LN$_2$ and obtained results for surface roughness

3.1. Surface Roughness

The computed values of the surface roughness of the experimental trials as shown in Table 5.

| Exp. No | N (rpm) | f (mm/rev) | dc (mm) | Ra $\mu$m, Dry | Ra $\mu$m, LN$_2$ |
|---------|---------|------------|---------|----------------|-----------------|
| 1       | 4000    | 0.2        | 0.5     | 0.31           | 0.35            |
| 2       | 4000    | 0.4        | 0.75    | 0.41           | 0.44            |
| 3       | 4000    | 0.6        | 1       | 0.25           | 0.24            |
| 4       | 4500    | 0.2        | 0.75    | 0.48           | 0.37            |
| 5       | 4500    | 0.4        | 1       | 0.30           | 0.25            |
| 6       | 4500    | 0.6        | 0.5     | 0.42           | 0.48            |
| 7       | 5000    | 0.2        | 1       | 0.56           | 0.30            |
| 8       | 5000    | 0.4        | 0.5     | 0.31           | 0.23            |
| 9       | 5000    | 0.6        | 0.75    | 0.30           | 0.25            |

Surface roughness of the experimented specimens was measured on basis of ISO 1302 standards, cut-off length of 0.25mm, length of sampling of 0.8mm, LC of 1micron and average of 3 readings were taken which is given the above table. The analysis done using taguchi technique is discussed below. Table 6 shows SN ratio response values for dry condition. MINITAB17 version was utilized to plot the responses.

| Level | N (rpm) | f (mm/rev) | dc (mm) |
|-------|---------|------------|---------|
| 1     | 10.242  | 7.100      | 11.295  |
| 2     | 8.095   | 11.549     | 9.140   |
| 3     | 11.692  | 11.380     | 9.595   |
| Delta | 3.597   | 4.450      | 2.154   |
| Rank  | 2       | 1          | 3       |
The feed rate is found to be more influential since the delta value is found to be high. The delta value is calculated based on difference S/N values obtained from chosen levels. In dry machining, the contact between tool and workpiece is very high since there is no external lubricating medium except the atmospheric air. So, convention of heat becomes stagnant which in turn affects the surface finish. This goes well with the previous research work [13] where in dry machining feed rate is influential.

Figure 3 shows the main effect plots for dry machined parameters. In which the peak points being the optimistic parameters. Table 7 shows the optimum machining parameters for dry machining. Confirmation test were done and the obtained optimum conditions and shown in same table. The variation is around 5% which is negligible.

![Main Effects Plot for SN ratios](image)

**Figure 3.** Main effect plot for SN ratio Vs Input parameters in dry environment.

**Table 7.** Optimum machining factors of dry machining.

| N (rpm) | f (mm/rev) | dc (mm) | Ra (µm) | Ra obtained from confirmation experiment (µm) | % of deviation |
|---------|------------|---------|---------|---------------------------------------------|----------------|
| 4000    | 0.4        | 1       | 0.5824  | 0.6628                                      | -5%            |

Table 8 shows SN ratio response table using cryogenic coolants. It is identified that most vital parameter is feedrate. The reason can be attributed to tool-workpiece interface at higher speeds which is a general concept. Figure 4 shows the SEM image of machined surface at dry cutting environment for the above optimized experiment.
Figure 4. Surface profile of dry-machined specimen.

Table 8. SN ratio response table while using cryogenic coolant LN₂.

| Level | N (rpm) | F (mm/rev) | dc (mm) |
|-------|---------|------------|---------|
| 1     | 60.41   | 56.21      | 58.22   |
| 2     | 61.43   | 62.23      | 61.74   |
| 3     | 62.35   | 65.75      | 64.24   |
| Delta | 1.94    | 9.54       | 6.02    |
| Rank  | 3       | 1          | 2       |
Table 9 shows the optimum machining parameters for cryogenic LN$_2$ machining. Confirmation tests were performed and the obtained optimum conditions and shown in same table. The variation is around 3% which is highly negligible.

**Table 9.** Optimum machining parameters for LN$_2$ machining.

| N (rpm) | f (mm/rev) | dc (mm) | Ra (µm) | Ra’ obtained from confirmation experiment (µm) | % of deviation |
|---------|------------|---------|---------|-----------------------------------------------|---------------|
| 500     | 0.6        | 1       | 0.1976  | 0.2536                                        | -3%           |

The above results adapt well with previous results obtained by Kramar et al. [14] studied the machining factors of hard to machine material and the result states that there is a change in surface integrity at high feeds [15]. Figure 6 shows the SEM image of the above optimized experiment. This specimen carries lesser tool-stripe marks across the machining area when compared to dry machining. This may be attributed to the better cooling and spreadability of cryo layer between tool-workpiece interface.
Figure 6. Surface profile of cryo-machined specimen.

Dilip et al. [16] has studied the feedrate influence when cutting a super alloy in similar LN2 coolant and LN2 shows good performance in high spindle speed and feedrate owing to its spread-ability during milling. Further, when comparing the optimized parameters of dry and LN2 condition, Taguchi predicted that the cryogenic condition may provide lower surface finish at higher speed and feedrate. We confirmed the above prediction by performing the confirmation experiment and found to be valid. Cryogenic machining outperformed dry condition in a large deviation as shown in table 7 and table 9.

3.2. ANOVA plot for Ra in both conditions
ANOVA calculates percentage response magnitude and experimentally analyzed variance. Table 10, Table 11 shows the contribution of factors by evaluating its variance. The control factors P-magnitude implies a 95% confidence. The feedrate establishes as a most significant factor with F-value of 32.54.

| Sources/parameters | DoF | Adj -SoS | Adj M-Sq | F-Val | P-Val |
|--------------------|-----|----------|----------|-------|-------|
| N (rpm)            | 2   | 0.868    | 0.443    | 21.36 | 0.237 |
| f (mm/rev)         | 2   | 0.193    | 0.126    | 32.54 | 0.782 |
| dc (mm)            | 2   | 0.623    | 0.153    | 28.91 | 0.136 |
| Error of experiment| 2   | 0.356    | 0.162    |       |       |
| Total value        | 8   | 2.030    |          |       |       |

Table 11. Summarization of model plotted of Ra in dry cutting condition.

| Std. R | R²  | Adjusted R² | Predicted R² |
|--------|-----|-------------|--------------|
| 179.757| 65.66%| 63.19%| 62.24%|

The significance of 62.24% implies that the factors taken are influencing in this work. This is agreeing well with the previous works done [6-7] predicted the key machining parameters. Table 12 and Table 13 shows the plotted values of ANOVA and summary model.
One of the conditions feedrate carries a F-value of 63.37 shown in Table 12, proves itself as the most significant factor, other parameters were found to be insignificant. Previous research works [14-15] suggested the cryogenic coolant has an advantage in BUE formation resistance at high speeds and better spreadability and light density, this works well in this study. The contribution in LN₂ coolant condition is feedrate with beyond 60% contribution above other parameters. The obtained result matches well with previous work [16-18]. In ANOVA, R² is found to be greater than 80%. The obtained results indicate the significance of parameters.

4. Conclusion

The experimental results and analysis and optimization are reported here to investigate the performance measures of Dry cutting and Cryo-LN₂-coolant on output machining integrity characteristics in endmilling of Ti-6Al-4V titanium superalloy are presented below

(i). For Dry condition:
- The factor which is most influencing for obtaining minimum Surface roughness is feedrate and it influences around 60% in this study
- The minimum Ra value is obtained at speed of spindle = 4000rpm, Feedrate =0.4mm/rev dₜ=1 mm which achieves surface roughness around 0.6628 µm

(ii). For LN₂ cryogenic environment:
- The factor which is most influencing for obtaining minimum Ra is feed rate contributing to Surface roughness around 65%.
- The minimum surface roughness is obtained at a speed of spindle= 5000 rpm, feedrate 0.6 mm/rev and depth-of-cut of 1 mm which achieves surface roughness around 0.1976 µm.

(iii). Though Dry machining has major advantage of cost-cut during machining, cryogenic works well at higher speed of spindle and feedrate providing better surface finish and surface integrity.

(iv). Overall, feedrate is most influencing parameter and cryogenic coolant is eco-friendly when equated with conventional coolants.
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