Surface roughness evaluation in machining titanium alloys using non-textured and textured cutting inserts

N. Abishekraj¹, T. Gowtham¹, V. Krishnaraj², R. Bibeye Jahaziel², B. Geetha Priyadarshini³
¹Under graduates, Department of Production Engineering, PSG College of Technology, Coimbatore, India.
²Department of Production Engineering, PSG College of Technology, Coimbatore, India
³Nanotech Research Innovation and Incubation Centre, PSG Institute of Advanced Studies, Coimbatore, India
E-mail: abishekraj6464@gmail.com

Abstract. Ti-6Al-4V alloy is well known for its difficulty in machining due to its ultimate hardness. The temperature generated at the tool-chip interface is typically high which results in poor surface finish and rapid tool wear. The current focus of work was to analyze the influence of response parameters such as cutting speed, feed rate and depth of cut on the surface roughness on the non-textured and textured cutting inserts. Response Surface Methodology (RSM) was utilized to generate the analytical relation between the process parameters and their interaction with the responses namely surface roughness. Analysis of Variance (ANOVA) was implemented to correlate with the significant factors and the correctness of the model. The machining was done experimentally using the textured and non-textured tools and the surface roughness was measured to analyze the influence of process parameters. It was found that the surface roughness was immensely reduced while using microtextured cutting tools.

1. Introduction
Titanium alloys are highly beneficial and used in various applications such as aviation, aerospace, and other fields due to its exceptional mechanical properties [1]. They have impeccable characteristics such as higher corrosive resistance, low thermal conductivity, and higher strength to weight ratio than most of the alloy steels. During the dry machining, the removal of the chip is difficult due to its poor thermal conductivity (7.1-7.3 W/m.K) and thereby it is required to have high cutting forces (value in range) which automatically reduces the tool life [2]. Henceforth, it is significant to increase the heat dissipation at the secondary deformation zone which contributes to the enhancement of machinability in the workpiece which in turn reducing the cutting cost.

Therefore, to reduce the heat dissipation during machining, many researchers have been using cutting fluids between the tool and the workpiece to overcome this problem. However, it indirectly affects the environment such as smoke emission which causes lung cancer for the workers. [3] This occurs due to the disposal of metalworking fluids (MWF).

The use of metalworking fluids facilitates the minimizing of friction at the secondary deformation zone by pushing out the minute particles and hence reducing the heat in the zone. Today, many researchers are eminently working on green manufacturing since there was more pollution and
harmful health effects by the usage of metalworking fluids [4]. In addition to this, these fluids are very hard to dispose of. Moreover, the process of recycling these fluids are very challenging since in almost countries standard regulatory compliances are mandatory [5].

Gravier et.al. [6] stated that corrosion behaviour was hugely related to the new surface conditions of copper in salt fog room temperature. Prakash et al. [7] stated that the rake angle and spindle speed influences the surface behaviour of work material. The researchers observed that the corrosion levels in salt fog conditions influence the surface roughness behaviour which increases with the reduction in rake angle and on the other hand the decreases resulted in high levels in cutting speed.

The cutting temperatures and shear stress on machining hard materials can produce high levels in the secondary zone and thus develops a micro-level coating on the workpiece, the area was affected due to the cutting forces and severe temperature. This process depicts that if there was no reduction in these parameters then there would be an occurrence of fatigue in the tool material which leads to poor surface finish. It happens because of the interaction among secondary deformation zone and a wavy profile was found due to the defect in the relative motion of the machine, removal of the chip and preheating of the work material [8].

Roughness value has an important dependency on the use of the component and can affect various parameters such as the optomechanical, thermolectric and magneto properties. Henceforth, there was still no reasonable assertion behind this effect that elucidates the effect of the roughness on diverse properties. Thus, a new method for hard turning was introduced that controls the cumulated merits of both the machining process. From the past process, it appeared to improve the quality of the machined surface. During this process, the efficiency of the product affects the surface roughness which was developed [9].

Analytical modelling was the better methods to evaluate the surface phenomena during various operation. The new ways required in forecasting the responses of the machining operation were very intricate, exhibiting a less uniform behaviour which also needs diverse parameters. The geometric methods were generally dependent on curve adjustments derived from the process [10]. The stated method has an effective role in predicting the attributes and link of the responses and combinations with the process. In addition to various expansion techniques, the most accurate and reliable was the Response Surface Methodology (RSM) mainly due to which their methodology was to analyse and clear the problems that are responsible for the effect of various responses and explains optimization of the parameters [11].

Aouici et al. [12] assessed the effect of the responses on the surface phenomena and cutting forces by the usage of design of experiments in dry machining of H11 grade steel material on cubic boron nitride tool. Yan and Li [13] stated that using a novel optimization method having an ideal interaction among reliable, productivity and standard mechanism was found during machining the steel grade work material. Davoodi and Eskandari [14] developed the model for coated cutting inserts and removal of the chip with the relation to the feed and spindle speed using RSM on machining malleable alloys. Kumar and Chauhan [15] modelled the surface phenomena on machining aluminium alloys with the ceramic composite. Artificial neural network and the multiple output optimization giving finer optimal conditions for various applications.

Chen pan et al [16] proposed that the hole pattern was highly reductive in the heat dissipation of the secondary deformation zone and also this affects the surface quality which was not sufficient to remove. Thus, the surface roughness in the other work material was found to be good. After laser engraving with the micro-hole pattern, the inserts were cleaned using acetone.

The current investigation was focussed on the influence of input variables on response factors such as feed rate, spindle speed, and depth of cut on machining titanium alloys using non-textured and textured cutting tools. The analytical forecasting models of the parameter was emphasized by implementing RSM. Analysis of variance helps to find the optimal parameters required and most influential part in the cutting parameters. Henceforth, experimental values of the surface roughness were analyzed for better understanding of the effect of input parameters with non-textured and textured cutting tools.
2. Experimental setup

2.1. Materials and Methods

The tool used for machining titanium alloy was Kennametal TCMT KC5025 AlTiN coated cutting tool. The holder utilized was STGCR2020K16. The insert geometry was orthogonal with rake angle 5°, corner radius 0.8mm, clearance angle 7°. The insert was engraved using a laser engraving machine using a hole- textured of diameter to about 40μm. In this investigation, the surface textures were made at the rake face of the insert. The textures were produced with an offset of 150μm away from the outer margin of the tool to regain tool strength at the tip. The dry cutting technique was used with the cutting-edge perpendicular to the direction of the cutting tool.

The composition rate of chemicals in the Titanium alloy was as mentioned below Table 1. Cutting velocity, depth of cut and feed were used as the input parameters while surface phenomena at the tool chip interface were selected as the responses.

| Table 1. Composition of Ti-6Al-4V alloy. |
|----------------------------------------|
| **Element** | **Mass (%)** | **Al** | **C** | **V** | **Fe** | **Ti** |
| Ti-6Al-4V  |      | 5.99  | 0.024 | 4.07  | 0.14   | 89.60  |
| ASTM F136  |      | 5.5-6.5 | 0.08Max | 3.5-4.5 | 0.25 Max | -     |

Figure 1 illustrates the SEM images of the micro-hole textured inserts and the pitch in the vertical direction was about 100μm and was approximately 80μm in the horizontal direction. The depth of the hole was about 50μm.

![Figure 1](image)

Figure 1. SEM images of the micro-hole textured inserts.

The surface phenomena of each machining trials were conducted using the Mitutoyo SJ201 surface roughness tester. The cut off length was set as 0.25 mm and a total of three readings were measured for each trial and the average was taken as the final reading. The experimental setup used as shown in Figure 2.
Figure 2. (a) Pinacho lathe centre for machining with micro-textured inserts.

Figure 2 (b) Mitutoyo surface roughness tester.

Table 2. Design of experiments with 3 level and 3 factors.

| Trail Experiment | Cutting velocity (m/min) | Feed Rate (mm/min) | Depth of Cut (mm) |
|------------------|--------------------------|--------------------|-------------------|
| 1                | 0.1                      | 60                 | 0.75              |
| 2                | 0.1                      | 80                 | 0.75              |
| 3                | 0.2                      | 60                 | 0.75              |
| 4                | 0.2                      | 80                 | 0.75              |
| 5                | 0.15                     | 30                 | 0.5               |
| 6                | 0.15                     | 80                 | 0.5               |
| 7                | 0.15                     | 60                 | 1                 |
| 8                | 0.15                     | 80                 | 1                 |
| 9                | 0.1                      | 70                 | 0.5               |
| 10               | 0.2                      | 70                 | 0.5               |
| 11               | 0.1                      | 70                 | 1                 |
| 12               | 0.2                      | 70                 | 1                 |
| 13               | 0.15                     | 70                 | 0.75              |
| 14               | 0.15                     | 70                 | 0.75              |
| 15               | 0.15                     | 70                 | 0.75              |

According to Taguchi design of experiments, maximum of 27 experiments was required to be performed, to minimize the cost of machining and production time, an alternative approach was used known as Box Benkhen design (RSM) technique to save the experimental trails. The current investigation was primarily focused on the responses which are cutting speed feed rate and depth of cut. The responses measured were surface finish. RSM method could help in analysing the response of
the process parameters on the surface phenomena at moderate levels. It had been minimized the experimental trails from 27 to 13. Additionally, it was very optimal to visualize the repeatability of the results obtained from the experiment with the last three trails which as the conformation trails. Table 2 illustrates the level of and responses for the design of experiments.

3. Results and Discussion

3.1. Response of input parameters on surface roughness

Figure 3a infers that higher the feed rate increases the surface roughness. If both the depth of cut and the feed rate was carried out at the moderate level, optimum surface roughness can be achieved. Due to the minimal movement of longitudinal feed and cross feed, the deviation in the amplitude gets reduced.

This was obvious from the experimental trail 9 where feed rate and depth of cut was at lower condition, the roughness decreases gradually and also from the graph, the surface roughness gets increased at the maximal level of feed rate and depth of cut. This could be found by the trial experiment 12. This occurs due to the shear instability in the chip removal process and henceforth produces a uniform and irregular tooth profile in the chip as shown in Figure 4a and 4b.

Figure 3. (a) Influence of feed and depth of cut on surface roughness. Figure 3. (b) Response of cutting speed and feed rate on surface roughness.

Figure 3b infers that increasing the feed rate maximises the surface roughness. This was primarily assertive that more feed rate causes more vibration in the tool. Henceforth, produces lower surface finish which was observed from the trail experiment 4. The plot shows that if the feed rate decreases, the good surface was observed from trails 12 and 9 respectively.
Figure 3c infers that the combination of a moderate increase in the cutting speed and depth of cut decreases the surface phenomena moderately. This shows that depth of cut and cutting speed was the most contributing factor in surface roughness which was confirmed by the trial 11 accordingly. This was proved by the ANOVA regression analysis from Table 3.

Table 3. ANOVA regression analysis for surface roughness.

| Source                        | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|-------------------------------|----|---------|---------|---------|---------|
| Model                        | 9  | 1.73658 | 0.19295 | 26.51   | 0.001   |
| Linear                       | 3  | 1.30090 | 0.43363 | 59.57   | 0.000   |
| Feed (mm/rev)                | 1  | 1.28963 | 1.28963 | 177.17  | 0.000   |
| Speed (rpm)                  | 1  | 0.00281 | 0.00281 | 0.39    | 0.561   |
| Depth of cut (mm)            | 1  | 0.00846 | 0.00846 | 1.16    | 0.330   |
| 2-Way Interaction            | 3  | 0.00625 | 0.00208 | 0.29    | 0.834   |
| Feed*Spindle speed           | 1  | 0.00498 | 0.00498 | 0.68    | 0.446   |
| Feed*Depth of cut            | 1  | 0.00122 | 0.00122 | 0.17    | 0.699   |
| Spindle Speed*Depth of cut   | 1  | 0.00004 | 0.00004 | 0.01    | 0.944   |

The influencing parameters are feed, speed, depth of cut, tool shape, nose radius chip formation, vibration, chip adheres to rake face, tool wear are the parameters affect the tool life as well as surface finish of work material to avoid that the optimum level of cutting condition should be needed.

The roughness Ra was calculated using the formula [17],

\[ R_a = \frac{0.0321 f^2}{r} \]

whereas, \( f \) is the feed rate of the tool (mm/rev)
\( r \) is the nose radius of the cutting tool (mm)
By using the equation, we get the surface roughness as:

\[ R_a = \frac{(0.0321)(0.12)}{0.8} \]

\[ R_a = 0.4013 \, \mu m \]

From the graph 5 shown below and the formula, it was clear that the surface roughness was directly proportional to the feed rate which had been correlated to the data from the experimental values.

**Figure 5.** Responses for surface roughness using micro-textured inserts.

### 3.2. Variation in surface roughness using non-textured and textured cutting tools

In comparison with the results of machining titanium alloys using micro hole textured tools and commercial tools, Figure 6 shows that the micro-hole textured tools were more significant in reducing the surface roughness. This can be derived from the fact that in texturing of tools the tribological behaviour of acts on the sliding region of rake face was significantly induced by textures. By bringing restrained peaks and valleys, the wear and friction properties could be enhanced. Lubricants could be used in the textures which tend to act as small reservoirs, producing in a decreased friction which significantly increased life of the tribological properties [18].

Moreover, the micro-hole acts as the reservoirs and hence the heat dissipation occurs rapidly in the interface. The convection heat transfer happens in the valley zone (textured) due to the atmospheric air aspiration. Also, the thermomechanical load reduced using the micro-textured tools [19]. Therefore, under dry cutting conditions, the effectiveness of lubrication was found to be better for the micro-textured tool as compared to the commercial tool and also improves the surface finish of the work material.
Figure 6. Comparison of Ra using textured and non-textured tools.

4. Conclusion
In this investigation, the Response Surface Methodology was utilized to elaborate and idealize the response of the input parameters on the surface phenomena while machining on titanium-based alloys. According to results obtained, the following interpretations were made.

- The contour plots using the factorial design helps to observe and investigate the influence of the response variables on the surface roughness. Besides, ANOVA illustrates that the feed rate was the primary contributing factor on the surface roughness with the contribution of 94.25%.
- Moderate cutting speeds with lower feed rates and larger depth of cut gives better surface finish when compared to higher feed rates and lower cutting speeds while machining Ti-6Al-4V alloys. Increased feed rates and lower cutting speeds produces poor surface quality.
- The comparison results of surface roughness using textured and non-textured tools shows that using micro hole-textured inserts was more significant with the reduction of 12.22%.
- Uniform tooth profile was found at lower feed rates whereas the serration of the chip was high at the higher feed rates.

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5. References

[1] Ezugwu E O and Wang Z M 2005, Titanium alloys and their machinability—a review, *Journal of Material Processing Technology*, **68** 262–274.

[2] Ezugwu E O, Bonney J and Yamane Y 2003, An overview of the machinability of aero-engine alloys, *Journal of Material Processing Technology*, **134** 233–253.

[3] Sun S, Brandt M and Dargusch M S 2009, Characteristics of cutting forces and chip formation in machining of titanium alloys, *International Journal Machining Tools Manufacturing*, **49**, 561–568.

[4] Klocke F and Eisenblätter G 1997, Dry Cutting, *CIRP Annals - Manufacturing Technology*, **46**, 519-526.

[5] Sreejith P S and Ngoi B KA 2000, Dry machining: Machining of the future, *J Mater Process Tech.*, **101**, 287-291.

[6] Gravier J, Vignal V and Bissey S B 2012, Influence of residual stress, surface roughness and crystallographic texture induced by machining on the ion behaviour of copper in salt-fog atmosphere, *Corros. Sci.*, **61**, 162–170.

[7] Prakash M, Shekhar S, Moon A P and Mondal K 2015, Effect of machining configuration on the corrosion of mild steel, *J. Mater. Process. Technol.*, **219** 70–83.

[8] Xie J, Luo M J, Wu K K, Yang L F and Li D H 2013, Experimental study on cutting temperature and cutting force in dry turning of titanium alloy using a non-coated micro-grooved tool, *Int. J. Mach. Tools Manuf.*, **73** 25–36.

[9] Rashid WB, Goel S, Luo X and Ritchie J M 2013, The development of a surface defect machining method for hard turning processes, *Wear* **302**, 1124–1135.

[10] B. Jabbaripour, M.H. Sadeghi, M.R. Shabgard and H. Faraji 2015, Investigating surface roughness, material removal rate and corrosion resistance in PMEDM of c-TiAl intermetallic, *J. Manuf. Process.*, **15** 56–68.

[11] Arruda E M, Brandão L C, Ribeiro Filho S L M and Oliveira J A 2014, Integrated optimization using mixture design to confirm the finishing of AISI P20 using different cutting strategies and ball nose end mills, *Measurement* **47** 54–63.

[12] Aouici H, Yallese M A, Chaoui K, Mabrouki T and Rigel J F 2012, Analysis of surface roughness and cutting force components in hard turning with CBN tool: prediction model and cutting conditions optimization, *Measurement* **45** 344–353.

[13] Yan J and Li L 2013, Multi-objective optimization of milling parameters – the trade-offs between energy, production rate and cutting quality, *J. Clean. Prod.*, **52** 462–471.

[14] Davoodi B and Eskandari B 2015, Tool wear mechanisms and multi-response optimization of tool life and volume of material removed in turning of N-155 iron–nickel-base superalloy using RSM, *Measurement* **68** 286–294.

[15] Kumar R and Chauhan S 2015, Study on surface roughness measurement for turning of Al 7075/10/SlCp and Al 7075 hybrid composites by using response surface methodology (RSM) and artificial neural networking (ANN), *Measurement* **65** 166–180.

[16] Chen Pan, Qinghua Li, Kaixing Hu, Yuxin Jiao and Yumei Song 2018, Study on Surface Roughness of Gcr15 Machined by micro-Texture PCBN Tools, *Machines* **6** 42.

[17] Ilhan asilturk and Mehmet cunkas 2011, Modelling and prediction of surface roughness in turning operation using artificial neural network and multiple regression method, *International Journal of expert systems with applications* **38** 5826-5832.

[18] Anil K C, Vikas M G, Shanmukha Teja and Sreenivas K V 2017, Effect of cutting parameters on surface finish and machinability of graphite-reinforced Al-8011 matrix composite, *IOP Conf. Ser.: Mater. Sci. Eng* **191** 1.

[19] Zhongfei Zou, Lin Hea, Hongwan Jiang, Gang Zhan and Jinxing Wu 2019, Development and analysis of a low-wear micro-groove tool for turning Inconel 718, *Wear*, **420-421** 163-175.