# On Machinability of Titanium Grade 4 under Minimum Quantity Lubrication Assisted High Speed Machining

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**Abstract** The wonder metal Titanium and its alloys are prime candidate for various automotive, biomedical and aerospace applications due to their good strength-to-weight ratio, bio-compatibility and corrosion resistance. Titanium and its alloys are known as difficult-to-machine materials i.e. their machining is challenging. The experimental work reported in the present paper attempts to enhance the machinability of Titanium Grade 4 under the influence of minimum quantity lubrication at high speed conditions. In this work a total of twenty seven experiments has been conducted based on full factorial design of experiment technique. Cutting speed, feed rate, and depth of cut are varied at three levels each and the values of important MQL parameters are fixed. The effects of machining parameters on surface roughness are discussed. Machining at optimum combination of parameters resulted in precision finish with maximum roughness value 2.16 μm and maximum tool flank wear value 0.201 mm. The research results reveal the superiority of MQL over conventional wet cooling to successfully machine Titanium Grade 4 at high speed conditions with sustainability.

## 1. Introduction

Titanium is known as wonder metal and used in various biomedical, aerospace and industrial applications in commercially pure and alloyed forms [1-3]. The special characteristics that make titanium superior to other materials are biocompatibility, high strength to weight ratio, and corrosion resistance etc. But, it is also known as difficult-to-machine (DTM) material and its machining is challenging. It possesses poor machinability that results in excessive tool wear, high consumption of energy and resources, deteriorated work surface quality, and high machining cost [3]. Titanium Grade 4 is a reliable material for various industrial and bio-medical applications such as heat exchangers, vessels, condenser tubing, dental implants, surgical instrument etc. It undergoes extensive machining operations (i.e. turning, milling, drilling, and grinding etc.) while manufacturing products for the aforementioned applications. The high speed conditions (important to achieve high productivity) make the machining extremely difficult. Conventional wet cooling is not effective at high speed machining conditions especially for titanium and its alloys, because wet cooling cannot manage the extensive heat generated at high speed conditions and fails to do effective lubrication [3-6]. It results in extensive tool wear, deterioration in work surface integrity, and high machining cost with environmental footprints. There are some ways such as using sustainable cooling and lubrication; optimum machining parameters;

appropriate tool materials, geometries and coatings; and employing hybrid techniques etc. to make the machining of difficult-to-machine materials such as titanium and its alloys easy [3-6].

Sustainable cooling and lubrication techniques are very helpful to reduce the consumption of energy and cutting fluids as well as friction and heat generation in the tool-chip interface and thereby tool wear, and to maintain the work surface quality [5-7]. One of the important sustainable lubrication techniques is minimum quantity lubrication where tiny droplets of green lubricants mainly synthetic esters, vegetable oil, fatty acids and alcohols are sprinkled over the tool-chip interface in the machining zone [7]. A detailed literature review conducted by the authors reveals that there are many articles where MQL assisted machining of various materials have been reported [8-12], but there is a lack of research conducted on the MQL assisted high speed machining of titanium Grade 4.

The research work reported in this paper fills the gap and discusses the experimentation details, effect of machining parameters on an important machinability indicator such as surface roughness, and optimization to secure the best set of machining parameters for enhanced machinability of Grade 4 titanium.

## 2. Experimental details

Titanium Grade 4 at high speed conditions has been machined on CNC turning centre using rhomboid shaped carbide tool inserts. Producut make MQL device has been used to supply green lubricant which is a blend of natural, synthetic and sulphurized esters. The experimental setup used in the present work is shown in Figure 1.

Full factorial design of experiment methodology has been used to design the experiments at various combinations of machining parameters. The full factorial design includes all possible combinations of input parameters and hence the most appropriate experimental results [13]. Three important machining parameters namely cutting speed, feed rate and depth of cut at three levels each have been selected based on some preliminary experiments, machine settings and literature review. A total of twenty seven experiments have been conducted to analyze the effect of the aforementioned three machining parameters on machinability indicators i.e. maximum surface roughness and tool flank wear. The details of variable and fixed input parameters are given in Table 1.



**Figure 1.** Experimental setup
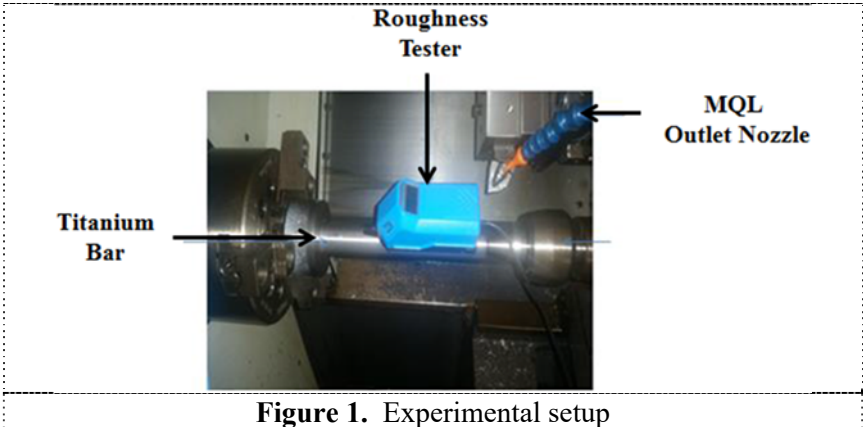
**Table 1.** Details of input process parameters

| Machining Parameters | Unit | Level | | |
|---|---|---|---|---|
| | | -1 | 0 | 1 |
| Cutting Speed '$V_c$' | m/min | 200 | 250 | 300 |
| Feed Rate '$f$' | mm/rev | 0.1 | 0.15 | 0.2 |
| Depth of Cut '$d_c$' | mm | 1 | 1.5 | 2 |
| MQL parameters | Flow rate 70 ml/hr | Air pressure 4 bar | Nozzle distance 30 mm | |

CP_Ti_Grade_4: Carbon- 0.012% + Iron-0.206% + Hydrogen- 0.0028% + Nitrogen- 0.0028% + Oxygen- 0.3 % + Ti- balance
Yield strength- 480 MPa

## 3. Results and discussion

Table 2 presents the values of average surface roughness and tool flank wear corresponding to all twenty seven set of experiments. Figures 2-4 depicts the effect of machining parameters mainly cutting speed, feed rate and depth of cut on maximum surface roughness. The statistical analysis of variance (ANOVA) study found feed rate and cutting speed as the most significant parameters affecting surface roughness and tool wear respectively.

**Table 2.** Experimental results corresponding to twenty seven combinations of machining parameters

| Expt. No | $V_c$ (m/min) | $f$ (mm/rev) | $d_c$ (mm) | Maximum Surface Roughness $R_{max}$ (µm) | Tool Flank Wear $T_w$ (mm) |
|---|---|---|---|---|---|
| 1 | 300 | 0.1 | 1 | 2,25 | 0,55 |
| 2 | 250 | 0.3 | 1 | 7,08 | 0,11 |
| 3 | 300 | 0.2 | 1 | 4,83 | 0,17 |
| 4 | 200 | 0.1 | 2 | 3,06 | 0,14 |
| 5 | 250 | 0.3 | 2 | 8,31 | 0,32 |
| 6 | 250 | 0.3 | 1.5 | 7,83 | 0,17 |
| 7 | 300 | 0.1 | 2 | 2,67 | 0,19 |
| 8 | 300 | 0.3 | 1 | 6,48 | 0,14 |
| 9 | 250 | 0.2 | 1.5 | 5,34 | 0,15 |
| 10 | 200 | 0.3 | 1.5 | 7,89 | 0,16 |
| 11 | 300 | 0.3 | 2 | 8,04 | 0,35 |
| 12 | 200 | 0.3 | 1 | 7,32 | 0,09 |
| 13 | 200 | 0.1 | 1 | 2,79 | 0,28 |
| 14 | 300 | 0.3 | 1.5 | 7,11 | 0,18 |
| 15 | 300 | 0.1 | 1.5 | 2,46 | 0,32 |
| 16 | 250 | 0.2 | 1 | 5,16 | 0,14 |
| 17 | 300 | 0.2 | 2 | 5,37 | 0,27 |
| 18 | 250 | 0.1 | 1.5 | 2,82 | 0,30 |
| 19 | 200 | 0.2 | 1 | 5,58 | 0,08 |
| 20 | 300 | 0.2 | 1.5 | 5,13 | 0,14 |
| 21 | 250 | 0.1 | 1 | 2,52 | 0,24 |
| 22 | 200 | 0.2 | 1.5 | 5,70 | 0,09 |
| 23 | 250 | 0.1 | 2 | 2,94 | 0,17 |
| 24 | 250 | 0.2 | 2 | 5,55 | 0,18 |

| 25 | 200 | 0.1 | 1.5 | 2,97 | 0,10 |
|----|-----|-----|-----|------|------|
| 26 | 200 | 0.2 | 2   | 5,79 | 0,09 |
| 27 | 200 | 0.3 | 2   | 8,46 | 0,47 |

As shown in Figure 2, increase in cutting speed leads to improve surface finish. High surface roughness at low speed is due to the formation of built-up edge on tool tip which deteriorates the work surface quality including surface finish [14-15]. At high feed rates, large amount of chips flow on the cutting edge of the tool which results in high friction that causes high roughness. Therefore, increase in feed rate increases surface roughness (See Fig. 3). As depicted in Figure 4, there is a straight line relationship between depth of cut and surface roughness i.e. increasing depth of cut leads to increase surface roughness. It is due to the fact that material removal is increased at high depth of cut which contributes to increase the cutting force, and high cutting forces cause fracture of tool particles that form voids on the surface being machined and hence increase the surface roughness [16].
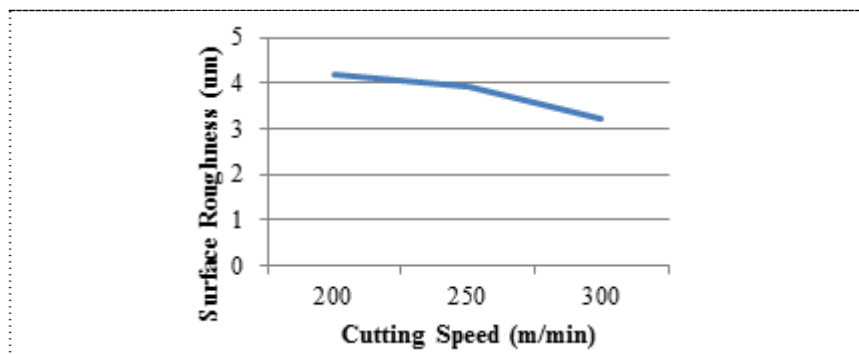

**Figure 2.** Effect of cutting speed on maximum roughness.
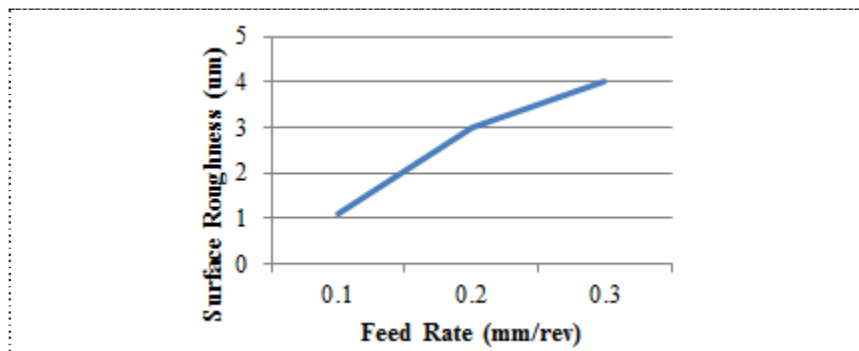

**Figure 3.** Effect of feed rate on maximum roughness.
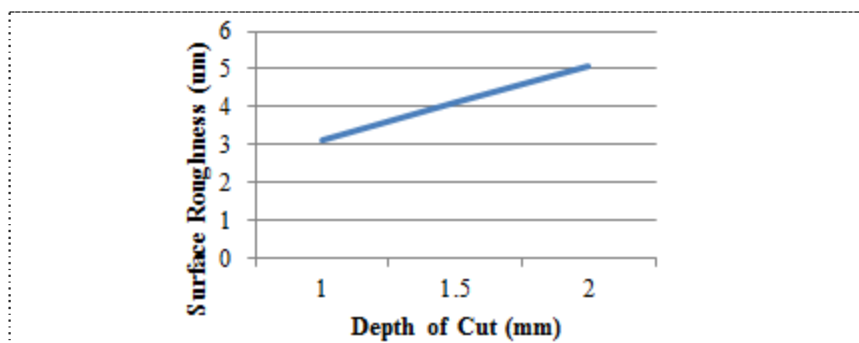

**Figure 4.** Effect of depth of cut on maximum roughness.

Similarly, the effects of machining parameters on other machinability indictors such as tool wear, energy consumption, and cutting forces have been investigated and reported elsewhere. After a detailed analysis of the results, it has been found that the variation trends of all machinability indicators are different and a trade-off exists that requires multi-performance optimization to simultaneously secure the best values of all machinability indicators at single set of machining parameters.

A statistical optimization technique Desirability analysis [17] with 'smaller the better' type of desirability function has been used for multi-performance optimization. Table 3 presents the optimum values of input machining parameters as well as responses predicted by desirability and the actual values obtained by confirmation experiment conducted at the optimal parameters. The results of the confirmation experiments validate the predictions and ensure significant improvement in surface finish and reduction in tool flank wear at a single set of machining parameters. Figure 4 depicts the SEM image of flank wear of the tool used to machine titanium grade 4 at optimum parameters.

**Table 3.** Results of confirmation experiments for optimization

| Optimal parameters | Predicted optimal responses | | Optimal responses at confirmation expt | |
|---|---|---|---|---|
| Machining condition | $R_{max}$ (µm) | $T_w$ (mm) | $R_{max}$ (µm) | $T_w$ (mm) |
| Cutting speed-Feed-Depth of cut 250-0.1-1 | 2.546 | 0.307 | 2.158 | 0.201 |
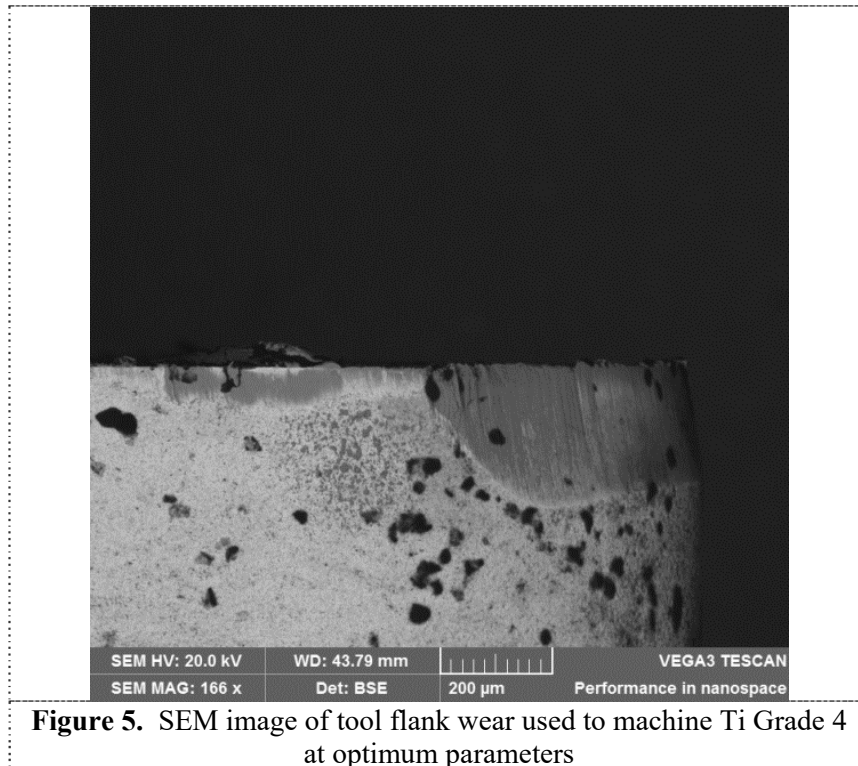


**Figure 5.** SEM image of tool flank wear used to machine Ti Grade 4 at optimum parameters

## 4. Conclusion

This paper reports various important aspects of a detailed investigation conducted on the MQL assisted high speed turning of titanium grade 4. The following conclusions can be drawn from this investigation:

- Increasing feed rate and depth of cut increase the surface roughness, whereas increasing cutting speed decreases the roughness.

- Machining at optimum parameters i.e. cutting speed- 250 m/min, feed rate-0.1 mm/rev, and depth of cut- 1 mm resulted in optimized values of maximum surface roughness- 2.16 μm and tool flank wear- 0.201 mm.

- Tool flank wear value 0.2 mm is under the recommended ISO limit (0.6 mm).

- Cutting speed and feed rate were found to be the most significant parameters.

A comparative study of titanium grade 4 machining in different cooling and lubrication conditions, MQL assisted machining of other titanium grades, and life cycle analysis of the titanium machining process etc. are the possible scope for future research in this area.

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