Machining of Ti-6Al-4V ELI Alloy: A brief review

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Abstract: Ti-6Al-4V ELI has similar properties as of Ti-6Al-4V (Grade 5) except it has higher
ductility as well as improved fracture toughness. It has the ability to withstand high temperature without losing properties, highly corrosion endurance and high strength to weight ratio. So it’s widely applicable in biomedical implants, aerospace industry, military application, automobile component and high pressure cryogenic vessels. During the machining of the titanium alloys, a lot of machining difficulty occurs due to its hardness, chemical reaction take place between tool and machine workpiece, high amount of heat generated at cutting zone. Cutting speed and cutting feed are predominant factors for cutting tool wear as well as the finished quality of the surface. Mainly flank wear (adhesion), notch wear and crater wear (diffusion) are identified during the machining. Cutting temperature indirectly influenced the surface quality of machined surface and tool wear. The high cutting speed with low feed rate is a most favourable combination for cutting force. For cutting insert, performance tool coating plays a significant role and coated inserts performed better than the uncoated tool at various cutting conditions. Machining under minimum quality lubrication is more favourable than flooded and dry scenario.

1. Introduction
Now a day’s due to advancement in cutting technology specially in the cutting tool, hard turning even at high speed successfully replaced the EDM and Grinding machining to improve the productivity. Ti-6Al-4V ELI (Grade23) comes under α + β categories of titanium alloys and ELI stands for an extra-low interstitial. Ti-6Al-4V ELI has similar properties as of Ti-6Al-4V (Grade 5) except it has higher ductility as well as improved fracture toughness. It has the ability to withstand at high temperature without losing properties, highly corrosion endurance and high strength to weight ratio. So it’s widely applicable in biomedical implants, aerospace industry, military application, automobile component (at high stress), and high pressure cryogenic vessels.

Table 1. Chemical content of Ti-6Al-4V ELI [2-14]

| Composition | C   | Si  | Fe  | Al  | N   | V   | S   | O   | H   | Ti   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Wt %        | 0.003 | 0.10 | 5.85 | 0.006 | 3.8 | 0.08 | 0.001 |      |      | Balance |
|             | 0.11 | 0.22 | 6.13 | 0.02 | 4.1 | 0.13 | 0.003 |      |      |       |
During the machining of the titanium alloys, a lot of machining difficulty occurs due to its hardness, chemical reaction take place between tool and machine workpiece, high amount of heat generated at cutting zone [1]. Figure 1 shows the schematic view of machining aspects and chemical content and physical and mechanical properties of Ti-6Al-4V ELI alloy shown in Table 1 and Table 2.

2. Application of machining methods

Hard turning is successfully replaced the EDM and Grinding for machining the very high hardness materials. During machining of this type of titanium alloy difficult to machine because of the high amount of heat produced at the cutting region which affected the machining process. However, selection of suitable cutting parameters and favourable cooling environments are the key aspects which affect the entire cutting process. Very few amounts of machining investigations have been found on machining Ti-6Al-4V ELI till date. Some studies were made considering both turning and milling cutting operation and its cutting details with responses studied has been arranged in Table 3.

| Reference | Author’s Name | Year | Machining Process | Process parameters | Response |
|-----------|---------------|------|-------------------|-------------------|----------|
| 1         | Sulaiman      | 2014 | Turning           | 120, 170, 220      | Tool wear |
| 2         | Sulaiman et al. | 2013 | Turning          | 120, 170, 220      | Optimized cutting parameters |
| 3         | Shin et al.   | 2013 | Turning           | 110               | Cutting Force, Tool life, and surface roughness |
| 4         | Ghani, Haron  | 2015 | Turning           | 120-200, 0.1-0.2   | Wear mechanism |
### 3. Application of Cutting tools and cooling techniques

The performance of the cutting insert also depends on the types of the coating applied to the tools, thickness of the coating, working temperature. When the working on the titanium alloy the tool wear gradually increased after the damage of the coating surface. Various researchers suggested that use only coated insert for machining of titanium alloy [1, 4]. Basically, two types of coating (CVD & PVD) used during the machining of hard materials. When machining hard materials high range temperature occurred at the cutting region this excessive temperature causes softening of materials and required low cutting force to cut the materials but the increment in the temperature causes of tool wear and also affected the machining performance [2]. Also applied cooling technique affected the machining performance.

![Diagram](image.png)

**Figure 2.** (a) Types of tool coating and (b) cooling condition
Table 4. Cooling Conditions and finding

| Reference | Author’s Name      | Year | Machining Process | Cooling Condition | Finding                                                                 |
|-----------|--------------------|------|-------------------|-------------------|-------------------------------------------------------------------------|
| 1         | Sulaiman          | 2014 | Turning           | Flooded           | Tool wear rapidly increase with cutting speed                           |
| 2         | Sulaiman et al.   | 2013 | Turning           | Dry               | Low tool wear at high turning speed with low feed rate                  |
| 3         | Shin et al.       | 2013 | Turning           | Dry               | Wear and force rapidly increase with an increase in cutting time.       |
| 4         | Ghani and Haron   | 2015 | Turning           | Dry               | Adhesion and diffusion.                                                 |
| 5         | Karkaos et al     | 2016 | Milling           | Dry               | To reduce the cutting force and satisfied surface finish working at high turning speed with low feed rate. |
| 6-9       | Ibrahim et al.    | 2013, 2011, 2009 | Turning       | Dry               | Cutting temperature has mainly affected the microstructure of workpiece surface. Surface integrity affected by tool wear. |
| 10        | Gusri et al.      | 2010 | Turning           | Dry               | Surface quality highly correlated with feed rate                        |
| 11        | Dilibabu et al.   | 2013 | Turning           | Dry and flooded   | Nose radius predominant factor for surface roughness                    |
| 12        | Haron et al.      | 2016 | Turning           | Flooded, MQL      | MQL performed better than the flooded cooling condition                  |
| 13        | Sargade et al.    | 2016 | Turning           | Dry               | Feed rate is predominant factor for Surface roughness and force.        |
| 14        | Sharif            | 2014 | Milling           | Dry               | Feed rate affected surface roughness and cutting force decrease with increase in speed |

Because when working in dry environment more heat engendered at the cutting area which causes of tool wear to eliminate this problem using a suitable cooling condition which is harmless for the environment and employed health such as MQL, Cryogenic etc. cooling condition [3, 5]. Sulaiman et al.[2] predicted the optimized cutting variables during turning of the Ti-6Al-4V ELI under wet cooling environment using RSM technique. Found that the speed and axil feed predominant factor for the tool life and roughness of the machined surface. According to the ISO 3685 performance of the cutting tool for Ti-6Al-4V ELI is acceptable. RSM give the optimized values of the input variables (v = 220 m/min, f = 0.1 mm/rev, d = 0.4 mm). Haron et al.[12] used a water based mineral oil in both MQL and flooded cooling environment and the result shows that in MQL cooling technique measured low wear at tool edge as compared to the flooded cooling condition. Figure 2(a, b) and Table 4 shows the types of cooling condition and tool coating used during machining Ti-6Al-4V ELI by various researchers.

4. Analysis of Tool Wear
During the machining friction between the tool and workpiece causes the garb in the tool this wear cannot eliminate but it can control by choosing appropriate cutting parameters and cooling condition.
A high amount of cost spent on the tooling section so it’s very important to investigate the cause of tool failure and wear mechanism during the machining processes. When machining at excessive cutting speed more heat appeared at cutting region due to low thermal conductivity causes of the rise in the temperature at a cutting zone which affected the performance of the cutting insert and the quality of the finished machined surface [2, 3]. Tool wear is affected the overall machining performance. During cutting operation tool wear appeared due to the friction between the tool and workpiece. Wear in cutting inserts depends upon the tool parameters, types of coating and cutting condition. At elevated temperature, a chemical reaction takes place between the tool and workpiece causes the wear in tools also chips affected the rake surface of the tools. Mainly flank wear (adhesion), notch wear and crater wear (diffusion) produce during the machining of Ti-6Al-4V ELI alloy [4, 5]. Sulaiman et al.[1] analysed the tool wear rate for an uncoated tool insert during high speed turning of Ti-6Al-4V ELI alloy in a dry environment. The rate of wear significantly increase from low to high cutting speed and the tool life is less at high cutting speed. The performance of the uncoated carbide insert is low in the dry cooling condition. Shin et al.[3] used Back propagation neural networks technique for detecting the wear at cutting edge and the effect of the input parameters when turning of Ti-6Al-4V ELI in dry condition used CVD coated cemented carbide tool insert. Found that the surface roughness has closed relationship with tool wear.

![Figure 3. Schematic of the geometry of the carbide insert used in this study [1, 2]](image)

Ghani and Haron [4] investigated the wear mechanism during the turning of Ti-6Al-4V ELI with coated (TiAlN/ AlCrN) and uncoated tungsten carbide tools under MQL cooling condition. Found that the flank wear at the flank face, notch wear and crater wear at rake surface cutting insert occur. Excessive temperature and high stress generated at the cutting area which cause of tool wear out. Adhesion and diffusion found that the predominant wear mechanism also chemical reaction takes place between the tool and workpiece materials causes of wear mechanism. Fig. 3 showed the geometry of an uncoated carbide cutting insert. Where $s = 0.13$ mm, $l = 12$ mm, $iC = 12.7$ mm and $rc = 0.8$ mm.

5. Analysis of Surface Roughness

Titanium alloy used in biomedical implants and biomedical implants where required satisfied surface roughness and integrity. Surface quality easily affected by the input parameters when machining on titanium alloy specially feed rate is the predominant factor for surface roughness. Due to the high hardness of Ti-6Al-4V ELI alloy and low thermal conductivity, a high amount of heat generated at the upper surface of the workpiece causes increased in the tool wear which damage the microstructure and surface integrity [5-12]. Karkaaloels et al.[5] predicted the surface roughness of Ti-6Al-4V ELI alloy in a milling operation. Aftermaths obtained that the feed rate is the predominant variable for affected the roughness of the finished surface of the workpiece. RSM method used to optimizes the input and output response and then compared the RSM and ANN models for more accurate prediction. Ibrahim et al.[6-9] investigated the microstructure alterations and surface integrity during turning of Ti-6Al-4V
ELI alloy in a dry cooling environment with coated carbide cutting insert. Found that when the temperature increases at cutting region it’s damaged the upper machined workpiece surface and affected the surface microstructure. Surface roughness increased with increase in the temperature. Gusrir et al. [10] investigated the surface quality of Ti-6Al-4V ELI alloy using CVD coated insert in the absence of cooling environment. Found that the roughness of the machined surface is more influenced by the feed. The changing in the microstructure and texture of the surface affected the surface quality. Also, a white layer with 2µm thickness found during machining at high speed with high feed rate. Dillibabu et al. [11] investigated the influence of the process variables on quality of machined surface during machining of Ti-6Al-4V ELI alloy with coated (PVD- TiAlN) coated carbide inserts in the dry and wet environment. According to the ANOVA analysed data showed that the insert nose radius is predominant factor for surface quality than the other process variable and applied the cooling condition. Ibrahim et al. [8] investigated the surface integrity using coated carbide inserts during machining of Ti-6Al-4V ELI in the dry cooling environment. Aftermath showed that the feed rate is the dominated factor for surface quality. Surface roughness curves subsist of three aspects at first stage give better surface quality after that regularly decrease in the surface roughness. Also found a white layer at finished surface when machining at (v = 95m/min, f = 0.35 mm/rev, d = 0.10 mm). There was no physical damage (tears and crack) of the coated carbide tools. Ibrahim et al. [9] predicted the surface integrity and the tool (PVD coated) insert during the working of Ti-6Al-4V ELI used dry cooling environment. The result showed that the tool life high at low cutting parameters values as compare to the high parameters values. Tool wear increased rapidly, gradually and extremely at the initial, second and final stage. Surface quality is better at the initial stage as compared to the second and final cutting stage. Because when the change in the nose radius increment in the tool wear and affected the roughness of the machined surface. Haron et al. [12] investigate the performance of the uncoated carbide and quality of the machined surface of the Ti-6Al-4V ELI alloy in wet and MQL coolant condition during high speed turning operation. The result showed that in MQL cooling condition better tool life (25% and surface roughness (30%) more than the wet (flooded) cooling condition.

6. Analysis of Cutting Forces
Calculating the cutting force is very complexity during cutting operation because during machining the input parameters affected the cutting force specially feed rate is the predominant factor for cutting force in turning operation. Various researchers suggested that low cutting forces required when machining with high cutting speed and low axial feed. Sargade et al. [13] investigated the roughness of the machined surface and cutting force when turning operation of Ti-6Al-4V ELI with PVD coated carbide insert in absence of coolant. Found that specially feed rate is predominant variable for surface roughness and cutting force. ANOVA and RSM technique used to predict the effect of input parameters and optimization for minimizing surface roughness and cutting force. Sharif et al. [14] investigated the effect on upper finished surface roughness and cutting forces during milling machining on Ti-6Al-4V ELI under dry condition using PVD coated (TiAlN+TiN) and uncoated carbide tools. The result showed that the cutting force is low at the increment in the cutting speed with the low feed rate for both the coated and uncoated cutting insert. Coated tool show the better performance than the uncoated carbide tool at each cutting condition.

7. Conclusion
Machining of Ti-6Al-4V ELI comes under alloy which is difficult to cut. However, selection of process parameters, cutting tools, and cooling process plays a major role in machining. This raised in temperature affected the whole machining performance. The effect of the cutting parameters shown as

- Generation of higher ranges of cutting temperature may cause the poor surface quality as well as declines the dimensional accuracy and tool life. Also, higher heat accelerates the work softening effects and causes the variation in the microstructure of the finished surface. This
change in the microstructure affected the surface quality. The cutting feed was predominant factor for surface roughness.

- Abrasion and diffusion are prime mechanisms involved in coated carbide tool failure. Damage to upper layers of the coating is identified at higher speeds. Cutting speed is predominant factor for tool wear. Tool wear can be controlled by the applied appropriate cooling condition for better cutting performance.
- The high cutting force required to cut the hard material. At high temperature, work softening appeared which reduces the shear strength of materials thus machining is easier but at the same time, this elevated temperature also accelerates the tool wear thus surface quality. The high cutting speed with low feed rate is a most favorable combination for cutting force.

8. Future research
Very few conventional machining work reported on Ti-6Al-4V ELI however further detail investigations are needed to study its machinability. Some points may be considered in future as follows:

- Applications of different kinds of cooling/lubrication techniques like minimum quantity lubrication, high pressure cooling, spray cooling, cryogenic cooling and nano fluids can be considered.
- Investigations on residual stresses, white layer formation, microstructure etc. can be considered for the betterment of overall machining process.
- Economic aspects can be considered

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