A Brief Review on Machining of Ti-6Al-4V under Different Cooling Environments

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Abstract. Ti-6Al-4V is an alpha beta titanium alloy which has high strength to weight ratio. It has excellent corrosion resistance, high toughness and low density, which makes it most suitable for applications in automobile, aeronautical, architectural, petro chemical and various medical equipment industries. Due to its high pressure load, high heat stress, poor thermal conductivity, varying chip thickness it is termed as hard to machine material. As it is a hard to machine material so many researchers are taking keen interest to study the effects of different machining aspects and machining environments on the machining performance of Ti-6Al-4V alloy. The present paper presents a comprehensive review on important aspects associated to machining of Ti-6Al-4V alloy using different cooling environments and machining tools. Experimental and theoretical observations for tool wear, surface roughness, machining force, tool life and machining temperature using different types of cutting inserts under distinguish cooling environments are also been discussed.

1. Introduction

In the present days titanium alloys are the most tempering metal alloys among all the other alloys because of its excellent corrosion resistance, fracture toughness, low density and superior strength to weight ratio. Ti-6Al-4V alloy is one of the most popular titanium alloy which is widely used in aerospace industry, marine engineering, medical and chemical industries due to its excellent physical and chemical properties [1]. Ti-6Al-4V alloy is considered as a difficult to machine material because of its low thermal conductivity and high chemical reactivity. Due to its low thermal conductivity, the heat generation during machining operation is very high which badly affects the machining performance and life of the tool [2]. As machining plays a major role in the manufacturing industry, so many researchers investigated on the different machining operations and cooling environment to enhance the machining performance of Ti-6Al-4V alloy. To overcome the above machining barriers, dry turning operation has been introduced which provides improved results regarding surface quality and maximizes the tool life. The most frequently used coated tools are CVD coated carbide, PVD coated carbide, ceramic, CBN and PCBN tools. Using coated tool provides a longer life of the tool, better surface finish and lower machining temperature as compared to uncoated tools [3]. So for the reduction of frictional force and competent removal of heat from the machining zone the use of coolant plays a vital role. During MQL technique the coolant is directly applied over the machining...
zone which provides easy removal of heat from the tool-workpiece interface. MQL technique not only removes the heat generated during machining but it also provides better machining performances than that of dry machining condition [4]. Due to heat generation at the machining zone, the surface quality of the workpiece gets hampered. To prevent these phenomena cryogenic cooling is being introduced. As using cryogenic cooling the heat generation at the machining zone is very less so the change in microstructure is negligible as compared to other cooling environments. Using cryogenic cooling technique with MQL environment provided the best surface finish and longer tool life among other cooling environments [5].

In the present paper, efforts have been made to present a brief literature review on machining operation of Ti-6Al-4V alloy using different coated insert under different cooling environments (dry, cryogenic and MQL). Fig. 1 presents the aspects of study covered in the present review work and Table 1 describes the chemical constituent of Ti-6Al-4V alloy.

![Figure 1. Schematic view of machining aspects of Ti-6Al-4V alloy](image)

| Workpiece (Ti-6Al-4V alloy) | Cooling Environment | Machinability Aspects |
|-----------------------------|---------------------|----------------------|
|                     | Dry                | Tool wear            |
|                     | MQL                | Surface Roughness    |
|                     | Cryogenic          | Tool life            |
|                     |                    | Machining force      |

**Table 1. Chemical constitution of Ti-6Al-4V alloy [14]**

| Content | C   | Fe  | N   | O   | Al  | Si  | V    | H    | Ti   |
|---------|-----|-----|-----|-----|-----|-----|------|------|------|
| Composition % | 0.1 | 0.3 | 0.05 | 0.15 | 5.5-6.8 | 0.15 | 3.5-4.5 | 0.015 | Balance |

2. Cutting performance analysis in various cooling environments
In present days, due to the growing demand for cost effective and eco-friendly machining process, green machining technique came into huge existence. Green machining technique mostly involves dry machining, MQL, spray cooling, compressed air cooling and cryogenic cooling environment. Many researchers investigated the role of dry, MQL and cryogenic cooling environment during machining operation of grade Ti-6Al-4V alloy.

2.1. Dry machining environment
Due to the growing demand for machining of hard and tough steels, dry turning operation came into existence because of its better machining performances while turning difficult to machine materials. Dry turning operation is used to machine harder materials using mostly coated insert without application of lubricants or coolants [6]. Mamedor and Lazoglu experimentally observed that predicting the amount of heat generated between tool and workpiece interface is very critical as it directly affects the tool wear, residual stress and dimensional accuracy of the machined workpiece [7]. Hau and Shivpuri studied the chip morphology and segmentation during machining of Ti6Al4V alloy. During machining, the formation of the chip was found highly affected by crack initiation. Discontinuous chips were obtained at low machining speed but at higher machining speed chips obtained were serrated [8]. Nouari and Makich investigated on the effect of material microstructure on the wear of the tool surface. It was experimentally observed that wear on the tool is highly affected by microstructure and machinability of the workpiece. Low machinability causes severe and premature
wear of the tool surface during dry machining operation [9]. Khanna and Davim found that machining and feed forces are mainly affected by feed rate and machining speed has a major impact on machining tool temperature [10]. Ramesh et al. studied that feed is the most affecting factor for surface finish followed by the depth of cut and machining speed [11]. Chowdhury et al. discovered that by applying self-lubricating TiB$_2$ PVD coating on the cutting tool surfaces, the life of the cutting tool can be greatly increased. The surface finish using this type of coating was found better as compared to uncoated and TiAlN coated insert [12].

2.2. Minimum Quantity Lubrication

A huge amount of heat is being generated during dry turning operation at the machining zone due to the friction between tool and work specimen surface. So to achieve improved surface quality and minimize the heat generation, the use of coolant becomes very necessary. Thus MQL technique is used to fulfill all the demands which were not achieved during dry machining operation [13]. Sadeghi et al. conducted experiment to study the machining performance of MQL during grinding operation. Lower machining force and surface roughness were generated under MQL environment. As compared to flooded cooling environment, MQL significantly reduced the perpendicular and tangential forces [14]. Hegab et al. found that using multi-walled carbon nanotubes dispersed in vegetable oil reduced the flank wear and power consumption by around 45% and 11.5% respectively [15]. Nam and Lee experimentally found that using nanofluid MQL significantly reduces the drilling torque, drill tool wear and thrust forces but its effect is more prominent at low feed rate [16]. Rahim and Sasahara proposed that as compared to dry machining, MQL machining provide lower thrust force, machining temperature and better tool life. The machining performance of palm oil lubricant was found better as compared to synthetic ester during MQL machining [17]. Hassanpour et al. found that during micro milling under MQL environment, the machining speed is the prime factor affecting both machining force and surface quality [18]. The different types of the machining operations used by the various researchers and its effect on the machining performance are mentioned in Table 2.

| Ref | Cooling Condition | Speed m/min | Feed mm/rev | Depth of cut mm | Response |
|-----|-------------------|-------------|-------------|----------------|----------|
| 9   | Dry               | 20,35,65    | 0.1         | 1              | Cutting force, tool wear |
|     |                   | 80,80,280   | 0.06,0.13,0.21 | 0.5,0.75,1     | Surface roughness, chip morphology |
| 14  | MQL               | 20,30,40    | 0.002,0.005,0.007 | 0.03          | Grinding force, Surface roughness |
| 17  | MQL               | 60          | 0.1         | 10             | Tool life, machining force and temperature |
|     |                   |             |             | 2.30           | Tool life, Tool wear |
| 22  | Cryogenic         | 80          | 0.15        | 2.30           | Tool wear, surface quality |
| 25  | MQL               | 63,79,99   | 0.2         | 0.25           | Surface roughness |
| 30  | Dry               | 80,100,120  | 0.05,0.075,0.15 | 0.1,0.25,0.40 | Surface roughness |
| 44  | Cryogenic         | 80          | 0.2         | 0.25           | Flank wear, machining temperature |

2.3. Cryogenic environment

Cryogenic environment further decreases the heat generated at the machining zone and the work specimen microstructure is hardly affected during the machining operation. So using cryogenic
environment allows high speed machining even using higher machining parameters [19]. Ti6Al4V alloy is widely used in biomedical applications. As machining of this alloy is very difficult so researchers used cryogenic cooling method using liquid N\textsubscript{2} as cooling fluid [20]. Sadik et al. observed that cryogenic cooling system using CO\textsubscript{2} decreases the development of thermal cracks by hindering the chipping of machining edge. Better surface finish and longer tool life were obtained using higher flow rate of coolant [21]. As the cost of liquid N\textsubscript{2} cooling fluid is very expensive Sarto et al. used gaseous N\textsubscript{2} as cooling fluid. It was observed that gaseous N\textsubscript{2} as cooling fluid at – 150 degree centigrade provide a significant reduction in flank and rake wear which was found very close to the cooling effect of liquid nitrogen coolant [22].

3. Performance analysis of different cutting fluids
Machining fluid plays a vital role in increasing the machining performance and productivity during any machining operation. The main role of machining fluid is to bring down the machining temperature, provide lubrication and remove chips from the cutting zone [23]. Titanium alloy also finds its place in the aeronautic industry. Using compressed cold air for turning operation displayed better result over dry turning operation [6]. Phapale et al. observed that during high pressure machining, the lubricating fluid produce enough lubrication near the tool and workpiece interface which results in lower overall effect on phase change during machining [24]. Ramana found that using sunflower (vegetable oil) as cutting fluid in flooded machining and MQL machining displayed better performance than dry machining condition [25]. Imbrogno et al. proposed that using liquid N\textsubscript{2} as cutting fluid during turning operation of titanium alloy provide better surface finish than dry turning process [26]. Deiab et al. have found that using vegetable oil as a coolant in MQL displayed better results as compared to synthetic coolant in terms of surface finish and tool wear. Thus it can be used as an alternative to synthetic cooling fluids [27]. Krishnamurthy studied the impact of ethanol blend metal removal fluid and cryogenic cooling system for enhancing the cutting performance of Titanium alloy. Around twenty five percent reductions in machining force, reduction in surface roughness and very less material transfer between workpiece tool interfaces were obtained using cryogenic cooling [28]. Nath et al. investigated the consequences of water soluble metal working fluid at the different concentration on the life of the tool, chip morphology, surface finish, machining force and friction coefficient during machining of Ti alloy using ACF spray system. The coolant used was water soluble MWF S-1001 [29]. Summary of investigation on cutting fluids during machining operation is presented in Table 3.

Table 3. Summary of types of coolant and its effects on machining performances

| Ref | Cutting Fluid       | Speed m/min | Feed mm/rev | Depth of cut mm | Responses                                    |
|-----|---------------------|-------------|-------------|-----------------|----------------------------------------------|
| 22  | Liquid N\textsubscript{2} | 80          | 0.2         | 0.25            | Tool wear, surface roughness                  |
|     | Blaser B-COOL 9665  | 90          | 0.3         | 1               | Tool wear                                    |
| 24  | Sunflower oil       | 63,79,99    | 0.2,0.27,0.34 | 0.6,1.6       | Surface roughness                            |
| 25  | Liquid N\textsubscript{2} | 70,110,150 | 0.2         | 1               | Machining temperature and forces, surface roughness |
| 26  | Rapeseed oil        | 90,120      | 0.1,0.2     | 0.8             | Tool wear, surface roughness, energy consumption |
| 27  | MWF S-100           | 80          | 0.2         | 1               | Machining temperature, tool life              |
| 29  | Liquid CO\textsubscript{2} | 80          | 0.15 mm/tooth | 2 and 30      | Tool life, tool wear                         |
| 37  |                     |             |             |                 |                                              |
4. Performance analysis of different cutting tools

Machining of titanium alloy is very difficult due to its high chemical reactivity, less thermal conductivity, low modulus of elasticity and high hardness. So various types of cutting tools are used while cutting operations of titanium alloy depending on the requirement and machining conditions [24]. Tool with CVD coating displayed better results when compared to tool with PVD coating because of its greater toughness and tool wear resistance. Surface roughness and wear of the tool surface were found less using CVD coating tool as compared to PVD coated tool [25]. Ramana et al. have found that uncoated tool can only be used during machining at lower machining speed, feed and depth of cut whereas a coated tool can be used at high machining speed and depth of cut [30]. Armendia et al. compared the different machinability aspects of different titanium alloy using WC-Co tool during turning operation. Adhesion of the workpiece material on the tool surface was noticed during high speed machining which resulted in the formation of built up edge [31]. Analysis of wear of the tool was done by Ramesh et al. during turning operation of commercial aerospace titanium alloy using RCMT 10T300–MT TT3500 round tool. The experimental results acknowledge that feed was the most prominent factor which alters the surface finish [11]. During rough turning operation of titanium alloy by using TiB2 coated tool there was an improvement in tool life by nearly 60% when compared to the uncoated tool and more than 70% when compared to TiAlN coated tool. Due to the self-lubricating property of the coated layer the decapitation of the heat generated at the tool workpiece interface was better which resulted in better surface finish [12]. Koseki et al. investigated the damage of cutting tools coated by physical vapor deposition during turning of a titanium alloy. Degradation of the coating on the rake face of the tool was contributed to fracture with no plastic deformation and damage of the coating was caused by the force exerted by the adhered materials on the grain boundary on the damaged coating surface [32]. Ayed et al. found that the machining with HP assistance is appreciable and tool life can be increased up to 9 times with a pressure of 100 bar. It also had been noticed that, pressure beyond 100 bar produces scratches on the workpiece surface [33]. According to W.F. Sales et al. experimental outcomes confirmed that flank and crater wear are the primary wear mechanism in machining Ti6Al4V alloy, using PCD insert under cryogenic, hybrid and flood machining condition. Cryogenic coolant supply condition encountered lower forces during machining [34].

5. Analysis of Surface roughness

Surface roughness is an important index for machinability of any cutting operation. As in every manufacturing industry surface finish is given maximum priority, many researchers investigated on machining parameters which affect the surface roughness of the work specimen [35]. During turning operation of titanium alloy, it was experimentally observed that that surface roughness is mostly affected by feed rate. It was observed that up to certain machining time surface roughness decreases with increase in feed rate but after some time it increase with increase in feed rate [6]. Kumar et al. experimentally found that nose radius of the machining tool plays the most significant role which affects the surface roughness of the workpiece [5]. Ramana et al. investigated the effect of machining fluid and different lubrication process on surface roughness during turning operation of titanium alloy. Surface roughness was found least in case of MQL condition as compared to the dry and flooded conditions [25]. Ramana and Aditya experimentally observed that feed rate mostly affect the surface roughness followed by machining speed and depth of cut. When surface finish was compared during machining using uncoated and PVD coated tool, the performance of PVD coated tool was found better at higher speed and the performance of uncoated tool was better at lower machining speed [30]. Deiab et al. found that surface roughness is less while machining is done at a lower feed rate and it slightly increases with increase in machining speed. Flooded cooling was only found efficient in producing good surface during machining at low feed and to achieve lower surface roughness at higher feed the cryogenic condition proved to be the best condition [27]. Experiment was conducted by Nath et al. to study the effects of different concentration of metalworking fluid on surface roughness using ACF spray system during machining of titanium alloy. Minimum surface roughness and best surface finish
were obtained at 10% MWF concentration [29]. Due to increase in cutting edge radius the formation of built up edge takes place, this protects the tool surface from flank and crater wear and results in very low surface roughness. Experimental investigation suggests that turning operation of titanium alloy at machining speed of 62 m/min resulted in very low surface roughness value [36].

6. Analysis of Tool wear

In machining problems, tool wear is a critical aspect and a detailed analysis behind the growth of wear should be studied. Dry turning of Titanium alloy is a very difficult process as the tool wear is very high. It was experimentally obtained that dry turning at a speed range of 60-70 m/min is the most suitable speed to achieve good surface with low tool wear [37]. During machining of titanium alloy, the wear of the tool mainly occurred due to the stress shear at primary and secondary shear zones. At higher cutting speed the formation of built-up edge was found more as compared to machining operation carried out at lower speed [38]. While using CVD carbide insert during turning operation of TiGr5 alloy following results were obtained: Formation of adhesive and abrasive wear at the flank wear, flanking occurred on the rake face, flank wear was prominent on the nose radius, welding of chip and wore out of tool coating at the machining tool [39]. Khan and Maity experimentally found that while turning operation of Titanium alloy, less wear of the tool was observed using cryogenically treated carbide insert as compared to untreated carbide insert [40]. Sun et al. studied the role of cryogenic compressed air on wear of the tool during machining operation of titanium alloy. Experimental results displayed reduction in both depths of crater and machining edge. Due to effective cooling of machining zone using cryogenic compressed air huge decrease in flank wear was achieved with resulted in longer tool life [41]. Analysis of tool wear was done by Arrazola et al. during turning operation of titanium alloy on CNC Lathe. It was observed that adhesive of chip material on the tool surface happened when turning of titanium alloy. Researchers found that workpiece material adhesion on tool was prime factor which decreases life of the tool. Both crater wear and flank wear took place during turning operation of titanium [42]. Zhang et al. have found that during machining of titanium alloy flank wear was the most important criteria which affect the life of the tool because diametric accuracy is highly affected by flank wear of the tool [43]. Sartori et al. compared the tool wear produced during machining operation of titanium alloy using cryogenic and dry turning methods. Reduction in abrasive wear on both flank surface and cutting edge were found using cryogenic cooling. Cryogenic cooling method displayed better surface finish and longer tool life as compared to dry turning [44].

7. Conclusion

In this review paper efforts are being made to present a brief description of machining operation of Ti6Al-4V alloy using different machining operation in different cooling environment (Dry, MQL and Cryogenic). This paper also depicts the effect of different machining parameters and cooling environments on Tool life, machining temperature and surface roughness of the work specimen. Due to the growing demand for eco-friendly and cost efficient machining process, many researchers are taking a keen interest in new cooling environments so the comparison between different cooling conditions are presented in this review paper.

- Machining operation under MQL environment resulted in better surface finish, lower tool wear and longer tool life as compared to dry machining condition. Cryogenic cooling environment displayed maximum cooling effect at the machining zone during high speed machining operation and best cooling condition was achieved under hybrid (Cryo + MQL) environment for short machining time.

- Tool with CVD coating displayed better results when compared to tool with PVD coating because of its greater toughness and tool wear resistance. Surface roughness and wear of the tool surface were found less using CVD coating tool as compared to PVD coated tool.
Nose radius of the machining tool was found as an important factor which directly affects the surface quality of the finished product. Surface roughness was found least in case of MQL condition as compared to the dry and flooded conditions. The surface roughness was found to be less while machining was done at lower feed rate and it slightly increased with increase in machining speed.

Researchers found that work piece material adhesion on tool and work piece were most affected mechanism which decreases life of the tool. Both crater wear and flank wear took place during turning operation of titanium. Reduction in abrasive wear on both flank surface and cutting edge were found using MQL and cryogenic cooling environments.

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