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A comprehensive review on machining of Ti6Al4V

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Abstract - *Since last century there is a phenomenal development in aerospace grade and high strength to weight ratio material. Titanium alloy – Ti6Al4V showed very good property and is a first choice of material among the industries for aerospace application. Although there have been great advances in the development of cutting tool material, but still it is great challenge to machine Ti6Al4V efficiently for machinist because of its inherent characteristics. This article provides comprehensive review on the machining of Ti6Al4V with detailed insight on the main problems associated with the machining of titanium as well as tool wear and the mechanisms responsible for tool failure. It was found that the straight tungsten carbide (WC/Co) cutting tools continue to maintain their superiority in almost all machining processes of titanium alloys, whilst CVD coated carbides and ceramics have not replaced cemented carbides due to their reactivity with titanium and their relatively low fracture toughness as well as the poor thermal conductivity of most ceramics. This seminar also discusses new generation special machining methods, such as rotary cutting tools and the use of ledge tools, which have shown some success in the machining of titanium alloys. A number of literatures on machining of titanium alloy with conventional tools, advanced cutting tool materials, high speed machining and in different cutting conditions like cryogenic cooling, hot machining, high pressure cooling, MQL is reviewed. This research article provides good summary on machining of titanium alloys and can be helpful to review and understand the machinability of titanium alloys and selection of the machining process.*

Keywords: *Titanium alloys, High speed machining, MQL, nanofluid, Flood cooling, Dry machining*

I. INTRODUCTION

Titanium and its alloys are used extensively in aerospace because of their excellent combination of high specific strength which is maintained at elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. They are also being used increasingly in other industrial and commercial applications, such as petroleum refining, chemical processing, surgical implantation, pulp and paper, pollution control, nuclear waste storage, food processing, electrochemical and marine applications [1]. Ti6Al4V is witnessing a focus shift of market trends from military to commercial and aerospace to industrial applications.

The Ti-6Al-4V comprises about 45% to 60% of total titanium production.[1] They have become established engineering materials available in a range of alloys and in all the wrought forms, such as billet, plate, sheet, strip, hollows, extrusions, wire, etc.

Despite the increased usage and production of titanium and its alloys, they are expensive when compared to many other metals because of the complexity of the extraction process, difficulty of melting, and problems during fabrication and machining. On the other hand, the longer service lives and higher property levels counterbalance the high production costs. Near net-shape methods such as castings, isothermal forging, and powder metallurgy have been introduced to reduce the cost of titanium components. However, most titanium parts are still manufactured by conventional machining methods. For the manufacture of gas turbine engines, turning and drilling are the major machining operations, whilst in airframe production; end milling and drilling are amongst the most important machining operations. [1,2]

The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of the materials. Titanium is very chemically reactive and, therefore, has a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool-work piece interface, which affects the tool life adversely. Additionally, its high strength maintained at elevated temperature and its low modulus of elasticity further impairs its machinability [1,2,3].

Yang et al. [4] mentioned that "now the expansion of the titanium market will be even more dependent on reducing the cost." This can be achieved best if the machinability of titanium and its alloys can be improved because machining is almost always involved if precision is required and is the most cost effective process for small volume production.

In 1955, Siekmann [5] pointed out that "'machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips".

II. TITANIUM ALLOYS – DIFFICULT TO MACHINE

Tool life, surface finish, and power required to cut are three main parameters that define machinability. Ti6Al4V is considered as difficult to machine by traditional methods because of its following inherent properties.

1. High strength at elevated temperature. It opposes the plastic deformation required to form a chip.
2. Poor conductor of heat. Heat, generated during cutting, does not dissipate quickly. That increase tool tip temperature and reduce tool life.
3. Titanium's chip is very thin. It causes high stresses on rake surface of the tool and increase power consumption.
4. Observed high tool-tip temperatures of up to about 1100°C [3,6]
5. Strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. It adversely affect tool life and caused galling, welding, and smearing of the cutting tool.
6. Low modulus of elasticity. It demands rigidity of the machine tool and increase cost of machining.
7. Chances of loss of surface integrity.

Therefore, industries cope up the machining difficulties while machining Ti6Al4V by taking due care of such challenges posed by inherent characteristics of alloy.

Titanium alloy form serrated chip and have thus been classified as 'catastrophic shear chips' whereas most materials can form a continuous chip with relatively uniform thickness. Shear to form the chip occurs on a particular shear plane when the stress built up by the relative tool motion exceeds the yield strength of the material. The energy associated with this deformation is converted immediately into thermal energy and because of titanium's poor thermal properties large temperature rises occur. This in turn causes the effect of temperature softening locally and thus the strain continues in the same plane instead of moving to a new plane in the colder material. As deformation proceeds the deforming shear plane rotates, thus becoming larger until the increased force due to this rotation exceeds the force needed to plastically deform colder material on a more favorable plane. This process has been referred to as 'catastrophic thermoplastic shear' and results in a cyclic process producing a saw-tooth chip form.[2] Komanduri and Turkovitch [7] have suggested that the conditions of segmentation vary according to the microstructure and that no conspicuous serrated chip is observed in alpha alloys. According to Sun et al [8], with increasing alloy content and, hence, increasing beta phase, this effect is more pronounced. Author has also confirmed the presence of a very thin 'flow zone' (also called a 'seizure zone') between the chip and the tool. After comparing the structure in this zone and across the chip, he concluded that the mechanisms of catastrophic thermoplastic shear also occur in the secondary shear zone of the chips.[8]

III. Machining of Titanium Alloys

Virtually all types of machining operations, such as turning, milling, drilling, reaming, tapping, sawing, and grinding, are employed in producing aerospace components.[9] For the manufacture of gas turbine engines, turning and drilling are the major machining operations, whilst in airframe production; end milling and drilling are amongst the most important machining operations. The researcher's investigation on machinability of titanium alloys in different cutting conditions is summarized in succeeding discussion.

3.1 High speed machining

Ezugwu stated that the most effective way of increasing the metal removal is to increase the cutting speed, with tools that can retain hardness and strength at higher temperature so that they are suitable for the high cutting speeds. [9] Increase in depth of cut and feed rate for higher material removal leads to increased cutting forces and poor economics of cutting.
high speed machining is preferred in industries because it resulted in to high material removal rate increased productivity, improved machine tool hour rate, lower cutting force, better chip disposal, excellent surface finish and dimensional accuracy. For the difficult-to-cut materials like titanium alloys, the demand for high speed machining is increasing in order to achieve high productivity and to save machining cost.[9]

Fang et al. [10] performed a comparative and experimental study of high speed machining of Ti-6Al-4V and Inconel 718. For both the materials as the cutting speed increases, the cutting force, the thrust force and resultant force decrease, however the force ratio increases. For both materials as the feed rate increases the cutting force, the thrust force, the resultant force as well as the force ratio all increase. The cutting force and thrust force in machining Inconel 718 are higher than those in machining Ti-6Al-4V.

Velaquez et al. [11] conducted extensive experimental study of the surface integrity and the sub surface microstructure during high speed machining in orthogonal cutting of Ti-6Al-4V alloy. They have shown through X-ray phase analysis that there is no phase transformation in the near surface region with cutting speed. However there is a large plastically effected zone below the machined free surface whose thickness increases with cutting speed.

Kitagawa et al. [12] has concluded that cutting temperature and tool wear in the high-speed machining of aerospace materials, such as Inconel 718 and Ti-6Al-4V-2Sn alloys, have been examined by means of cutting experiments and numerical analysis. They investigated that TiC-added alumina tool is better over silicon nitride within a speed range from 250 to 500 m/min, where the tool temperature reaches around 1200 °C. Moreover they concluded that measurements in local tool temperatures at the tool-chip interface and the tool interior have revealed that maximum rake temperature is lower for intermittent cutting than for continuous cutting by approximately 15%.

3.2 High pressure cooling

High temperature is produced during machining of Ti6Al4V because of poor thermal conductivity.

(about 15 W/m°C) The high temperature produced at tool workpiece interface resulted in to a shorter tool life and a poor surface quality. Ti6Al4V machining can be improved by minimizing tool tip temperature by way of high pressure jet water cooling instead of flood cooling. Many researchers has worked in this direction. Their major contribution is discussed overhere.

Machado et al. [2] has reported that improved coolant penetration to the cutting interface by high pressure cooling reduces the temperature of the cutting tool that in turn reduces diffusion wear rate which resulted in to improved tool life by up to 300% achieved when machining Ti-6Al-4V alloy using.

M Rehman et al. concluded that high pressure coolant produces better lubrication and better cooling effect in the chip tool interface. Thus the coefficient of friction and thereby the cutting force is reduced. The cooling effect eliminates the welding of the tool and chip and improves the tool life as well as the surface finish. It is observed that the high-pressure coolant jet eliminates the welding of chip with tool by breaking and flushing the chips. Maximum flank wear has been found to be the prominent failure mode when machining with both conventional and high-pressure cooling. High-pressure coolant seems to be very effective while machining at low feed rate.[3]

Nandy et al. [13] used neat oil and water soluble oil for high pressure cooling and studied its effect and concluded that tool life on high pressure cooling with water soluble oil improved by 250% then in conventional wet. High pressure cooling with neat oil did not provide substantial benefit in tool life and productivity. Chip breaking is more pronounced while cooling with high pressure water soluble oil than neat oil. Cutting forces are also reduced significantly under high pressure cooling environment. Author also studied the effect of coolant pressure, nozzle diameter, impingement angle and spot distance in high pressure cooling with neat oil in turning of Ti-6Al-4V alloy. Coolant pressure was varied between 0.5 to 12 MPa and it was found that coolant pressure of 10 MPa with brass tipped nozzle of diameter 0.8 mm, impingement angle of 20° and zero spot provide best chip breaking with minimal tool damage.

M. Mia et al [14] has studied the effects of duplex jets HPC on machining temperature and machinability of Ti-6Al-4V by using TiCN/Al2O3/TiN coated cemented carbide are evaluated. They concluded that tool performance is improved under duplex HPC as the tool life is prolonged by 55–60% compared to dry turning. Tool wear analysis by SEM images revealed that adhesion, rubbing, nose wear and built-up-edge for dry cutting, and crater wear and chipping for HPC aided machining were prominent wear mechanisms. Overall, wear behavior under HPC has been found satisfactory. Moreover author investigated that chip formation has been found insensitive to HPC as in the broader sense no significant difference is noticed

3.3 Dry machining

Carcinogenic nature and the toxicity of the cutting fluids seriously degrade the quality of the environment in machine shop. It advocates for dry machining which in contrast the conventional myth of use of lubrication during machining for better surface finish, productivity and tool life. Experiments made on dry machining of Titanium alloys, brief summary with results is discussed below.

A. Ginting stated that 'until now dry machining of titanium alloys was not widely investigated. This is probably due to the fact that these materials are still considered as difficult-to-cut materials.'[15]

Ribeiro et al. [16] carried out turning tests for Ti-6Al-4V alloy with conventional uncoated carbides under dry condition, they concluded that best cutting conditions are close to the suitable conditions for the tool manufacturer and it is possible to work in more severe conditions than the manufacturer's conservative conditions. They also concluded that it is possible to work with low amount of cutting fluid or preferably in dry condition.

Ibrahim et al. [17] investigated the surface integrity of Ti-6Al-4V-ELI alloy when machined with coated cemented carbide under dry condition and showed that surface roughness value recorded with coated carbide tools was lower at high feed rates. Moreover the concluded that surface roughness values are mostly affected by feed rate and nose radius. White layer or plastically deformed layer was found when machining at cutting speed 95m/min, feed rate 0.35mm/rev and depth of cut 0.1mm and at the end of tool life.

3.4 Minimum quantity lubrication

As discussed in previous section that carcinogenic nature and toxicity of cutting fluid create unhygienic shop floor ambient. Cutting fluid costs is also considered as 18%-20% of total machining cost. However dry machining do not provide encouraging results. Therefore researchers has identified newer method of lubricating cutting zone which is economical, eco friendly and better than dry machining is Minimum Quantity Lubrication (MQL). In MQL technique the cutting fluid is supplied in ml/hr instead of l/min as in conventional flood cooling. The flow rates are selected in such a way that its application does not result in dispersion of mist, contributing towards a cleaner environment manufacturing. In MQL, air and lubricant are mixed to obtain the mixture to be spread on cutting zone. Following is the summary of research of major contributors in field of MQL machining of Ti6Al4V.

Wang et al. [18] concluded that at higher cutting speed and feed rate, MQL. seems to be more effective than flood cooling. In interrupted cutting, MQL is more effective than dry cutting and flood cooling.

Settineri and Faga [19] investigated that turning with MQL gives better performance as compared to wet turning and AlSiTiN is found to perform better than TiCN coating.

Brinksmeier et al. [20] experimented MQL technique in machining of titanium alloys and showed that reduction in forces results in improvement in surface quality and tool life by 20%. In milling of titanium alloys tool life in terms of travel length is determined for dry machining, MQL (Synthetic esters), MQL (Synthetic esters and phosphorus additives), MQL (Synthetic esters high additive) and overflow (emulsion 7%) and is observed that high additive products lead to increase in tool life compared with emulsions in overflow condition.

Sadeghi et al [21] studied the use of vegetable and synthetic ester oil in MQL grinding of titanium alloys. They found that 60ml/h quantity of lubricant and delivery pressure of 4 bar is most appropriate as compared to flood cooling considerably reduces perpendicular and tangential forces.

Lee et al. [22] carried out nanofluid MQL meso-scale grinding process using nano diamond particles. They concluded that the normal and tangential components of the grinding forces in the case of nanofluid grinding process were reduced by 33.2% and 30.3% respectively when compared with the case of dry air grinding

2.5 Novel Machining Techniques

Conventional cutting fluid poses challenges to the environment and application of same is questioned many times. Therefore cryogenic machining was experimented for better cooling at cutting zone as economical and eco friendly alternative. There is comparatively less research in this area, however summary of their work is as follow.

Hong et al. [23] machined Ti6Al4V with cryogenic cooling and concluded that the flooding LN2 yielded very good results compared to dry cutting; unfortunately the tool life was just close to the conventional flood cooling.

Venugopal et al. [24] studied the effect of cryogenic cooling and investigated that benefit of cryogenic cooling is substantial at cutting speed of 70m/min. for a tool life criterion 300μm dry, wet and cryogenic cooling gives tool life of 5 min, 7 min and 12 min respectively. Cryogenic cooling by liquid nitrogen enables substantial improvement in tool life through reduction adhesion-dissolution-diffusion tool wear.

Hong et al. [23] has suggested that new economical cryogenic machining approach also eliminated the buildup edge problem because the cold temperature reduces the possibility of chip welding to the tool and the focused LN2 jet helps to clean the edge. Author also worried about ways to deliver LN2 with a low flow rate, because it is technically challenging even for the cryogen industry. The flow rate reduction in this study was enabled through the evolution in the delivery line design. [23]

Matteo Strano et al. [25] has confirmed in his research that cryogenic machining is able to increase the tool life, even with respect to wet cutting. Besides, the results showed that not only cutting forces are reduced but also a small, albeit significant, reduction can be achieved in the coefficient of friction at the tool–workpiece interface.

Increased material temperature improves its ductility and softness. Both improved properties are favorable for machining. Hot machining provides reduction in cutting forces, improves surface finish and longer tool life. However one has to take while machining. Similar to cryogenic machining very few researchers has worked on hot machining.

Maity and Swain [26] had developed experimental set-up for hot machining and investigated that tool life is improved and cutting forces were decreased significantly.

Ginta et al. [27] concluded that work piece preheating significantly increase the tool life of uncoated WC-Co carbide inserts in full immersion end milling of Titanium alloy. Induction heating was utilized for preheating of work piece. Tool life increase was 325% with preheating of 650°C compared to experiment at room temperature.

O. A. Shams et. al. [28] has used laser beam and plasma torch to produce more intense localized heating compare to that by induction coil in his experiments. They investigated that the laser technique offers very controllable process heating compared to other techniques. Laser-assisted machining (LAM) also largely reduces cutting forces leading to better surface finish. Thus, laser-assisted technique is recognized to be more cost-effective and productive for improving machinability of titanium alloys than rest of the heating techniques.

Economy of machining is influenced by cutting fluid consumption, recycling and disposal of waste fluid. Cutting fluid carries on an average 16-20 percent of total cost of machining. Various factors' like, machining process, work piece material, cutting tool material, process parameters, cost of cutting fluid, surface finish, environmental effect and occupational health hazard derive the selection of cutting fluid. Lubrication and cooling requirement during machining process can be determined by the type of machining process, method of applying cutting fluid (flood, mist, manual, high pressure), rigidity of the system, work piece material and its hardness and microstructure, cutting tool material, geometry and coating and process parameters i.e. speed, feed, and depth of cut. [29] It is well known that no one type of fluid can provide best lubrication and cooling qualities simultaneously for any machining process. Lubrication and cooling effects are adversed, if we increase one effect by changing the composition of cutting fluid the other will decrease. Nano fluid can balance these two effects to a certain extent. Water is the best coolant whereas oil is the best lubricant. So, nanofluid must be formulated in a way that it can optimize cutting requirements i.e. cooling and lubrication as well as non cutting requirements like corrosion inhibition, favorable fluid residues, nonflammability, filterability, nontoxicity, disposability and recyclability. Application of nanofluid as cutting fluid is rarely experimented.

Shen [30] experimented and concluded that the application of nanofluid in MQL grinding was evaluated for the first time. It is concluded that nanofluid are not able to provide superior cooling capacity in MQL grinding process. However, the suspension of nanoparticles can improve the tribological properties of the base fluids, which can help lubricate the grinding zone. Therefore, the research of application of nanofluid in MQL grinding should focus on the advanced lubrication properties. Shen also shown for the first time that lubricant oils with novel MoS2 nanoparticles significantly reduces the tangential grinding force and friction between the wear flats and the workpiece, increases G-ratio and improves the overall grinding performance in MQL applications.

Dinesh Setti et al. [31] has concluded in his research that application of nanofluid leads to the reduction of tangential forces and grinding zone temperature. The cooling effect is also evident from the short C-type chip formation. Authors further added that MQL application with Al2O3 nanofluid helps in effective flushing of chip material from the grinding zone, thereby solving the main problem during the grinding of Ti–6Al–4V.

Srikant et al. [32] has noted in his experimentation with CuO nano particles based nano fluid that the tool tip temperature reduced significantly during application of nanofluid

IV. Conclusion

Titanium and its alloys are considered as difficult to cut materials due to the high cutting temperature and the high stresses at and/or close to the cutting edge during machining. The high cutting temperature is due to the heat generated during machining, the thin chips, a thin secondary zone, a short chip-tool contact length and the poor heat-conductivity of the metal, whilst the high stresses are due to the small contact area and the strength of titanium even at elevated temperature.

As a basic rule, a cutting fluid must be applied when machining titanium alloys. The correct use of coolants during machining operations greatly extends the life of the cutting tool. Chemically active cutting fluids transfer heat efficiently and reduce the cutting forces between the tool and the workpiece.

High speed machining with flood cooling and hig pressure coolant technique produces better lubrication and better cooling effect in the chip tool interface. That reduced the cutting force, improved surface finish and economics of cutting. However adverse environment effect of cutting fluid mist and excess cost of cutting fluid is major concern of these methods.

Discussed few novel machining techniques like Minimum quantity lubrication technique, Cryogenic cooling during machining, Hot machining and use of nanofluid as cutting fluid are looks promising and also address two major concerns of machining – economy and ecology of cutting. However breakthrough and rigorous research is required before industrial application of such techniques.

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