Drilling of Ti6Al4V

A review

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***Abstract* - Titanium is light in weight, strong, highly corrosion resistant, biocompatible, and nonmagnetic. As titanium processes low specific gravity and high specific strength, titanium and its alloys are used mainly in aerospace, automotive, marine and petrochemical industries. Among all the alloys of titanium, Ti6Al4V is the most widely used alloy. Between the chip of titanium and tool face, high coefficient of friction exists which makes machining of titanium and its alloys difficult. After reviewing many research papers it was noticed that to improve drilling performance of titanium alloy high pressure supply of coolant is desirable. TiAlN coating for carbide tools is considered the most appropriate for drilling. Lower cutting speeds and peck drilling to be employed to achieve better tool life. Other important conclusions drawn from intense literature review have been summarized below. Several researchers have established co-relation amongst cutting parameters and chip morphology.**

***Index Terms* – Drilling, Machinability, Titanium Alloy, Ti6Al4V, Chip Morphology**

I. INTRODUCTION

Titanium is light in weight, strong, highly corrosion resistant, biocompatible, and nonmagnetic. As titanium processes low specific gravity and high specific strength, titanium and its alloys are used mainly in aerospace, automotive, marine and petrochemical industries. Among all the alloys of titanium, Ti6Al4V is the most widely used alloy, having chemical composition of 6% aluminum, 4 % vanadium, 0.25% (max) iron, 0.2% (max) oxygen and the remainder titanium. Titanium and its alloys are highly reactive with oxygen, nitrogen, carbon, and hydrogen. As Ti6Al4V has good fatigue and fracture properties, it is used in all product forms including forgings, bar, castings, foil, sheet plate, extrusions, tubing and fasteners. There are various Difficulties in machining titanium and its alloys like High strength at elevated temperature opposes the plastic deformation needed to form a chip, The chip obtained after machining titanium is very thin and possesses small contact area which causes high stresses on tip of the tool. [1] Table: 1 gives details of physical properties, thermal properties, and mechanical properties of Ti6Al4V.

Table: 1 Properties of Ti6Al4V

	Property Name	Description
Physical Properties	Crystal structure	HCP(<882.5^{0}C)
		BCC(>882.5^{0}C)
	Atomic Volume(m^3/kmol)	0.01
	Density(g/cm^3)	4.42
Thermal Properties	Melting point(^{0}C)	1667
	Thermal Conductivity (W/m-k)	7.2
	Specific Heat Capacity (J/g ˚C)	0.560
	Linear co-efficient of Expansion (inch/inch ^{0}F)	5 x 10^{-6}
Mechanical Properties	Hardness (HRC)	36
	Tensile strength (Ultimate) (MPa)	950
	Tensile strength (Yield) (MPa)	880
	Modulus Of Elasticity (GPa)	113.8
	Compressive Yield Strength (MPa)	950
	Poisson's ratio	0.342

Intense literature review had been carried out in order to meet the objectives of the project work literature review helps in giving proper guidance to select suitable machining conditions and other parameters. Drill material selection had been carried out using Table: 2.

II. MACHINABILITY OF TITANIUM AND ITS ALLOYS

P. D. Hartung et al [2] examined tool wear in titanium machining. Turning had been carried out using conventional C2 grade and C3 grade of cemented carbide tools. Most potential tool materials had been found rapidly dissolving or chemically reacting with titanium but tool material used here showed experimental evidence of the formation of stable reaction layer and were the most wear-resistant materials. A .R .Machado [3] studied on machining of titanium and its alloys. Usage of rotary tools and ledge tools along with ultrasonic assistance had been found very useful. Serrated chips had been achieved by machining titanium. The best grades in turning application are K20 (C2). WC/Co alloys having a Co content of 6% and WC grain size between 0.8 to1.4 micrometers appeared to be the optimum. All coated carbide tools showed higher wear rates than straight grade cemented carbides while turning application.

S. K. Bhaumik et al [4] carried out machining of Ti6Al4V with a WBN-CBN composite tool. WBN-CBN composite tools have been found economical to machine titanium alloys instead of PCBN and PCD which were used conventionally. E. O. Ezugwu et al [5] studied machinability of titanium alloys. Straight tungsten carbide and cemented carbide tools had been found the best. HSS tools such as M1, M2, M7, and M10 had been found suitable in machining titanium. Best results had been achieved with highly alloyed grades such as M33, M40 and M42. Cutting speed had the most considerable influence on tool life. At lower cutting speed tool life enhanced. Machining assisted with high pressure coolant supply had been found the most suitable one. A weak solution of rust inhibitor and water oil (5 to 10%) solution is the most practical fluid for high-speed cutting operations. Rahaman et al [6] studied machinability of titanium alloys. It had been concluded that about 80% of the heat generated while machining Ti6Al4V was conducted into the tool. To machine titanium alloys tools with high hardness, wear durability, hot hardness, good thermal resistance and high co-efficient of thermal conductivity are required. Klocke et al [7] calculated thermo mechanical tool load during high performance cutting of hard to cut materials. The effects of high pressure lubricant supply and cryogenic cooling with liquid nitrogen and carbon dioxide had been investigated. Improvement in cooling of the high pressure lubricant supply had been found beneficial.

Da Silva [8] investigated tool life and wear mechanisms in high speed machining of Ti6Al4V alloy. Segmented chips had been generated when machining with high pressure coolant supply. Long continuous chips had been generated when machining with conventional coolant flow. Mohammed Nouri et al [9] examined the Physics of machining titanium alloys. Interactions between cutting parameters, microstructure, and tool wear had been evaluated. Chips obtained after machining were mounted with epoxy so that they stood on their edge in order to make the cross-section after polishing straight across the length. Mechanical, thermal, metallurgical and physio-chemical aspects had been analyzed in depth. A decrease of cutting forces was noted for Ti6Al4V when cutting speed increased.

III. DRILLING OF Ti6Al4V

Ogawa [10] studied effects of high pressure supply of coolant in drilling of titanium alloy. High pressure supply of coolant was found to be effective on drill in high cutting speed that drill wear increased significantly under the conventional supply of coolant, Cutting temperature didn't increase remarkably even in drilling a deep hole as major cutting edges were cooled and chips were ejected smoothly. Dornfeld [11] analyzed drilling burr in titanium alloy Ti6Al4V. Drill geometry had been found affecting burr thickness and height. Helical point drill produced smaller burrs than split point drill. Larger helix angle and increased point angle both reduced burr height and thickness. Most drilling processes created a burr at both entrance and exit surfaces. The exit burr was much larger in size and the main concern. De Lacalle [12] performed drilling and turning of low machinability alloys using high pressure coolant. It had been observed that TiAlN coating was the most appropriate for drilling titanium. Cutting of titanium assisted by high pressure water jet system had been found effective. In this case cutting speeds were double the conventional speed with a good drill life.

D Saini et al [13] optimized drill life when drilling Ti6Al4V with HSS. Drilling with HSS long series drills of 10 mm diameter, a feed of 0.14 mm per revolution and cutting speed of 9 meter per minute had been observed to give smooth chip formation and flow through the drill flutes. A strategy involving regular full retractions of the drill and a few partial retractions allowing chip breaking had been found to successful drill deep holes. Cantero et al [14] drilled Ti6Al4V under dry conditions. Tool wear in drilling Ti alloy was found to be intense because of high cutting temperature. To machine Titanium alloys tool manufacturer recommend hard metal tools, moderate cutting parameters and abundant cutting fluids. M.Pirtini [15] analyzed forces acting during drilling operation and hole quality. Power and torque were proportional to the rotational speed. Thrust force, torque and power increased with feed. It had been observed that the hole quality was not predictably or significantly affected by the cutting conditions.

Zeilmann et al [16] studied drilling forces of Ti6Al4V with MQL. Lubricant was supplied with an external nozzle or internally through the tool. Feed force and torque were strongly dependent on feed. For machining drills coated with TiAlN was found to be the most suitable one. Coating did not influence the drill life significantly when MQL was supplied by external nozzles. Rui Li at al [17] carried out experiments of high through put drilling of Ti6Al4V. It had been found that balance of cutting speed and feed was essential to achieve long drill life and good hole surface roughness. Recommended feed for machining titanium was small. High tool temperature accelerated tool wear and limited drill life. The spiral point drill design resulted in low thrust force, torque, energy, and burr size. S.Sharif et al [18] analyzed performance of coated and uncoated carbide tools when drilling titanium alloy Ti6Al4V. The performance of uncoated WC/Co and TiAlN-PVD coated carbide twist drill had been investigated when drilling titanium alloy, Ti6Al4V. The results were similar for all cutting speeds tested, TiAlN coated drill significantly outperformed uncoated drill in terms of tool life and surface finish. Rahim et al [19] evaluated the performance of uncoated carbide tool in high speed drilling of Ti6Al4V. Folded wavy type chips and curly type chips had been produced under all cutting conditions. Higher percentage of aluminum content in super nitride coating recorded the lowest tool wear rate. Saw tooth chip formation had been observed at all cutting conditions.

F.R.Wong et al [20] studied the effect of drill point geometry and drilling technique on tool life when drilling titanium alloy Ti6Al4V. Peck drilling seemed to outperform direct drilling for both tools. Tools having greater point angle and helix angle performed better. Shyha et al [21] analyzed burr formation and hole quality in drilling titanium and aluminum alloys. Exit burr size was smallest when operating at the intermediate feed rate level.

Antoine Poutord et al [22] examined local approach of wear in drilling Ti6Al4V. Tool wear was highly influenced by drilling parameters and drill geometry. Increasing cutting speed or feed rate highly changed the tool lifetime. High feed and low cutting speed are desirable. Shetty et al [23] studied machinability on dry drilling of Titanium alloy Ti6Al4V.Chip morphology, micro hardness, burn thickness and surface roughness had been analyzed after drilling. Chip shape was the most important factor for the smoothness of a drilling process. Drilling process will be smooth if chips were shorter. Chip shape and chip thickness at low cutting speed were spiral cone chip with less thickness, easier to be ejected. As the cutting speed increased long ribbon like chips with increased length and thickness were achieved.

IV. THE EFFECTS OF DIFFERENT MACHINING CONDITIONS ON CHIP MORPHOLOGY

A. E. Bayoumi et al [24] investigated some metallurgical aspects of chip formation in cutting Ti6Al4V alloy. SEM image and chemical composition analysis showed no diffusion type phase transformation taking place in the machined chips while the X-ray diffraction technique identified some non-diffusion phase transformation occurring owing to the change in beta structure into alpha face during chip formation. J.Barry et al [25] investigated chip formation and acoustic emission in machining Ti6Al4V alloy. It had been concluded that the formation of saw tooth chips was a fundamental characteristic of the machining of Ti6Al4V alloy under conventional cutting conditions. Uday Dabade [26] analyzed surface roughness and chip cross sectional area during machining with self-propelled round inserts milling cutter. In this case inclination angle influenced machining the most. A.Daymi [27] analyzed effect of cutting speed on the chip morphology and the cutting forces for a bar of Ti6Al4V. Chips were cross-sectioned, polished, and etched in 4% nitric acid in ethyl alcohol. Conclusion

S.Sun et al [28] studied about characteristics of cutting forces and chip formation in machining titanium alloys. Chips obtained after machining had been mounted with epoxy so that they stood on their edge in order to make the cross section after polishing straight across its length. Bermingham [29] observed tool life, cutting forces and chip morphology in cryogenic machining of Ti6Al4V. The effect of cryogenic coolant on cutting forces and chip morphology was examined. Different machining parameters produced different chip morphologies. As the feed rate reduced and the depth of cut increased number of physical changes occurred in the chip including reduction in chip thickness reduced distance between serrations and increased shear band angle. Vikas Upadhyay et al [30] carried out comprehensive study of chip morphology in turning of Ti6Al4V.An attempt had been made to study the effect of cutting speed, feed rate and death of cut on saw tooth geometry in terms of peak height, valley height, tooth hight, segmentation degree tooth pitch, localized shear angle, to get better insights about the machinability characteristics of Ti6Al4V. From the experiments it had been observed that the most dominating parameter affecting peak, valley and tooth height was feed rate. From the intense literature review suitability of different tool materials can be compared as follows:

Table: 2 Suitability of material and tool performance evaluation for Ti6Al4V

Tool material	**Performance**	**Operation**
Tungsten Carbide & Cobalt(K20)	Best	Turning
Straight grade cemented Carbide	Good	Turning
PCBN	Good	Turning
PCD	Better than PCBN	Turning
WBN-CBN	Economical compared to PCBN & PCD	Turning
Coated carbides, Ceramics	Not Recommended	Turning
Straight tungsten carbide(WC/Co)	Superior	Turning
General purpose HSS tools M1,M2,M7, and M10	Suitable	Drilling
T5,T15,M33,M35, M40, and M42	Best	Drilling
NCr and TiCN coated carbide	Promising	Drilling
TiN coated carbide(K40)	Good	Drilling
TiAlN coated carbide	Best amongst all	Drilling

V. CONCLUSIONS

- It can be said that titanium and its alloys are widely used alloys for aerospace and other critical applications. For machining titanium alloys the best grades are those containing only tungsten carbide and Cobalt.
- HSS M33, M 40 and M42 are considered compatible.
- In order to improve the drilling performance of titanium alloy high pressure supply of coolant is desirable. TiAlN coating for carbide tools is considered the most appropriate.
- Drilling of titanium assisted by high pressure water jet system had been found effective.
- Spiral point drill design showed advantages of low thrust, torque, energy, and burr size.
- Lower cutting speeds and peck drilling to be employed to achieve better tool life.

VI. REFERENCES

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