Analysis for Machining of Ti6Al4V Alloy using Coated and Non-Coated Carbide Tools

G. Dongre[1*], J. Shaikh[2],L. Dhakad[2], A. Rajurkar[3], P. Gaigole[4]

[1]Professor, [2]UG Students, [3,4]Assistant Professor
Vishwakarma Institute of Technology, Pune, India
{*ganesh.dongre@vit.edu*}

Abstract: The fundamental machining techniques were established long back. However, machining operations consume a large amount of money annually worldwide. Advanced engineering materials, such as ceramics, MMC, Titanium (Ti), Inconel and its alloys offer properties like high strength at elevated temperature, chemical and wear resistance. Therefore, these materials are being used in making components for aerospace, defence, nuclear, orthopaedic, and marine applications. However, these alloys are classified as a ‘difficult-to-cut’ due to their poor thermal conductivity, reactivity with tool material, high strength and low modulus of elasticity. Besides various measures to improve machinability of these alloys, the key areas of research focuses on selection of cutting tool material and its geometry, use of various machining environments and selection optimum processing conditions to improve tool life, metal removal rate and decrease cutting forces and surface roughness of the machined component. This paper focuses on machinability of titanium alloys under various machining environments such as – dry, flooded and mist jet cooling. The main objective of the paper is to understand the effect of change in machining environment on various aspects of machining of titanium alloys viz. tool wear, cutting forces, surface roughness and chip morphology. It is evident that the flooded and mist jet environments effectively cool the cutting zone and reduce the cutting forces and tool wear 30 and 40% respectively. On the other hand, flooded lubrication and mist jet cooling improves surface quality 20-30% as compared to dry condition machining. Based on this study, optimum conditions to improve machinability of Ti6Al4V alloys are presented.

Keywords: ***Ti6Al4V, mist jet cooling, coated and non-coated cutting tools, cutting force, tool wear and surface roughness***

1 Introduction

Advancements in the aerospace, nuclear and other industries require the enhanced in-service performance of engineering components. These requirements have resulted in the large scale development and use of heat-resistant and high-strength materials such as Ti6A4V alloys that offer unique combination of properties like high strength at elevated temperature, resistance to chemical degradation, and wear resistance [1]. Therefore, Ti6Al4V is being used in making components for aerospace, electronics, defence, paper and pulp, chemical processing, nuclear waste disposal, dental, orthopaedic, and sea water services. However, its ability to maintain these properties at elevated temperatures severely hinders the machinability of Ti-alloy, thus it is referred as difficult-to-cut material. The difficulty may lie in its physical and mechanical properties such as high strength and low thermal conductivity, which make the cutting forces and temperature very high and lead to a shorter tool life [2].

Despite lot of developments in this field, it is difficult to obtain close tolerances and high surface finish in machining of Ti-alloy components primarily due to its low thermal conductivity, which prevents the dissipation of heat from the tool and chip interface, in turn heats up the tool and results in lower tool-life. Excessive heat during machining catalyses a chemical reaction between the cutting edge and the chip producing crater wear, high hardness and extreme abrasive nature workpiece along with rapid cutting tool destruction. Titanium also has comparatively low elasticity modulus than steel. Therefore, workpiece has a tendency to move away from the cutting tool unless the proper backup is used.

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Also thin parts may deflect under tool pressures, causing chatter, tool wear and tolerance problems, tendency to work harden, so removing metal through a shearing action, rather than pushing it away, is crucial [3].This paper focuses on machinability of Ti-alloys under various machining environments such as – dry, flooded and mist jet cooling. The main objective of the paper is to understand the effect of change in machining environment on various aspects of cutting of Ti-alloys viz. tool wear, cutting forces, surface roughness and MRR. The machining system analyses effect of coated (Ti, Al_2O_3) and non-coated carbide tools on Ti grade 5 ($Ti6Al_4V$) alloy workpiece. In general, the focus of this paper has been on identifying suitable tool material for machining, arriving at parameters for their precise machining and achieving desired quality and properties on the newly machined surfaces.

2 Literature review

Many experimental works have been dedicated to understand the material removal mechanism and chip formation mechanism and its implications in Ti machining. These studies show segmented, but continuous chips often formed at high cutting speeds. In recent past, J. L. Evans et al. [4] has studied mechanical and thermal behaviour for machining $Ti6Al_4V$ with AlMgB14 and WC-Co tools. The tool geometry studies suggest that the round edged SCD tools gave a good cutting performance in the initial cutting stages. Also, the surface roughness was less than 45µm Ra and varied in the range of 12–15 µm. This is because the adhesive wear on the rake face and abrasive wear on the flank gradually increased with an increase in the cutting distance. Revankar et. al. [5] has analysed surface roughness and hardness in Ti-alloy machined with PCD tool under different lubricating modes. Various process parameters like lubricating mode, cutting speed, feed rate, nose radius and depth of cut were analysed.

M. Venkata Ramana et. al. [7] has presented work on optimization and effect of process parameters on tool wear in turning of Ti-alloy under different machining conditions. In this study, they presented machinability and chip formation mechanism. K Srinivasulu et. al. [6] has presented performance evaluation and selection of optimal parameters in turning of $Ti6Al_4V$ alloy under different cooling conditions. Intrinsic relationship between tool flank wear and operational conditions were investigated by Luo et. al. [8] while cutting metal using carbide inserts. Thamizhmanii and Hasan [9] evaluated machinability in terms of roughness, flank wear, cutting force and specific cutting pressure, The study was carried out for turning of hard martensitic stainless steel (AISI 440C) and hard alloy steel (SCM 440) by using CBN and PCBN inserts. Kurada S. and C. Bradley [10] divided the available methods for tool condition monitoring into two parts: direct and indirect sensors. Direct sensors measure the tool wear directly and they include vision, proximity and radioactive sensors.

Even though, lot of research work has been carried out in Ti6Al4V machining, still some gaps are needs to be addressed during machining of these materials. This may be effect of a change in cutting tool material geometry on machined surface characteristics has not been analysed adequately. At the same time, ready reference cutting data (feed, speed, depth of cut) is not available for recently developed materials and guidelines for selection of cutting tool material based on minimum tool wear are not mentioned clearly in the literature. Further, correlation of cutting force data with machining accuracy and surface integrity is not adequately studied and limited efforts to improve the cutting conditions using alternative methods like machining process optimization, use of different machining environment, hot machining, etc.

3 Experimental plan and Procedure

Fig 1 shows orthogonal cutting setup. The workpiece material is Ti grade 5 alloy Ti6Al4V (Ti-89.9%, Al-6.15 %, V-4.4%, C-0.05% and Fe-0.09%). The work material used has OD–73mm, ID–67 mm and 300 mm length. Al2O3 and TiN coated as well as non-coated WC triangular shaped tool inserts were mounted on PTLNR 2525 M12 (ISO designation) tool holder. For real time, precise force measurement data acquisition system was used (schematic shown in fig. 2).

Experiments were conducted in three types of cutting environments – (1) dry, (2) flooded lubrication system and (3) MQL (Minimum Quantity Lubrication) as shown in fig 3.

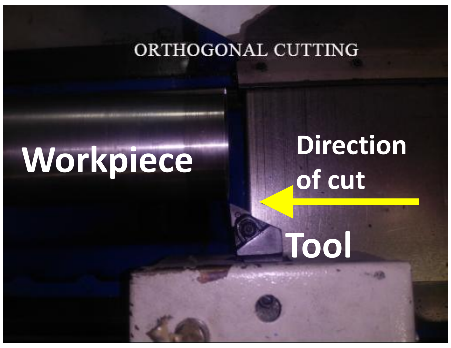


Fig. 1. Photograph of orthogonal cutting

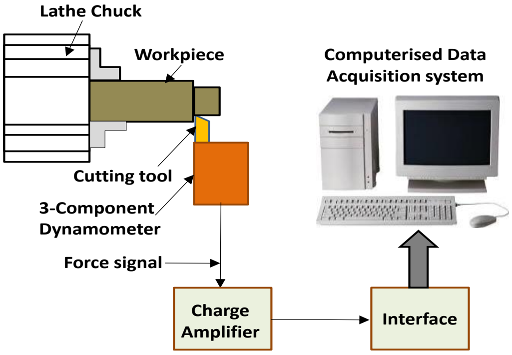


Fig. 2. Schematic of data acquisition system [12]

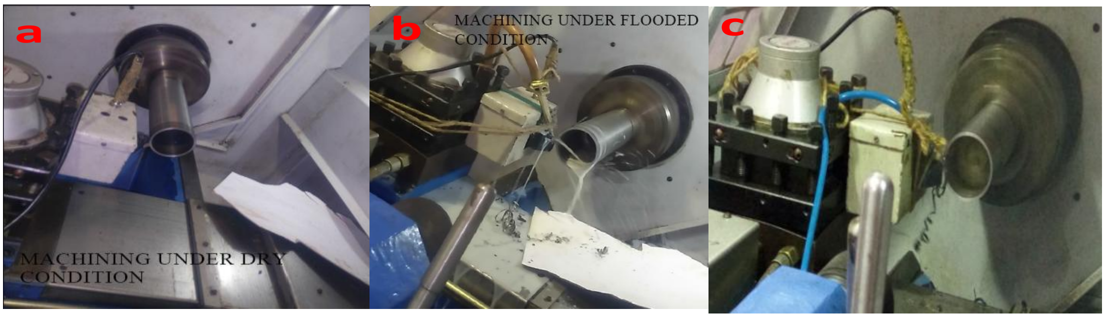


Fig. 3. Cutting environments: a) Dry machining; b) Machining under flooded condition; c) Mist condition

All trials were performed using Taguchi based design of experiments (L9 orthogonal array) where speed, feed, cutting length and insert type has been taken as control parameters (Table 1) and MRR, surface roughness, cutting forces and tool as response variables

Table 1 Control parameters and their levels

	Parameters	Values
1	Speed (rpm)	300, 650, 1000
2	Feed (mm/rev)	0.1, 0.15, 0.2
3	Inserts	Al2O3 & TiN Coated, Non coated
4	Cutting Environment	Dry, Flooded and Mist
5	Cutting Length (mm)	1.0, 1.5, 2.0

3.1 *Measurement of response variables*

Three components of cutting forces were measured - Thrust force, Feed force and Radial force. Force data was measured with respect to time and maximum values were recorded in table 2.

Fig. 4. a) Measurement of tool wear using Z microscope b) Typical results of tool wear using Z Microscope

Table 2 Experimental Results

Machining condition	Expt. No.	Speed	Feed	Inserts	Cutting Length	Force (kgf)			Ra Avg (µm)	MRR (mm^3/s)	Width (mm)	Thickness (mm)	Crater Wear (mm)	Flank Wear (mm)
						Thrust	Feed	Radial						
Dry	1	300	0.1	NC	1	114	281	75	0.67	55	3.52	0.28	0.1818	0.0861
	2	300	0.2	TiN	1.5	592	1122	331	0.5	141.43	3.72	0.44	0.1299	0.0949
	3	300	0.3	AL	2	846	1350	799	0.63	660	3.69	0.52	0.1392	0.1002
	4	450	0.1	TiN	2	547	499	181	0.42	146.67	3,38	0.24	0.082	0.0891
	5	450	0.2	AL	1	241	499	181	0.59	73.33	3.45	0.12	0.1392	0.0451
	6	450	0.3	NC	1.5	592	946	109	0.45	330	3.32	0.21	0.3822	0.078
	7	600	0.1	AL	1.5	80	548	164	0.38	247.5	3.21	0.08	0.0483	0.0946
	8	600	0.2	NC	2	432	326	67	0.39	440	3.42	0.42	0.2828	0.154
	9	600	0.3	TiN	1	121	548	99	0.6	330	3.12	0.25	0.201	0.07
Flooded	1	300	0.1	NC	1	63	364	78	0.35	82.5	3.5	0.28	0.0666	0.0762
	2	300	0.2	TiN	1.5	319	924	529	0.52	495	3.45	0.22	0.1176	0.1132
	3	300	0.3	AL	2	147	457	221	0.33	660	3.6	0.61	0.1188	0.0316
	4	450	0.1	TiN	2	138	411	345	0.43	440	3.48	0.34	0.0827	0.0872
	5	450	0.2	AL	1	31	103	46	0.23	330	3.46	0.5	0.0281	0.0613
	6	450	0.3	NC	1.5	103	472	261	0.52	495	3.44	0.63	0.1118	0.1063
	7	600	0.1	AL	1.5	113	37	69	0.29	495	3.38	0.29	0.1042	0.0928
	8	600	0.2	NC	2	22	93	68	0.47	660	3.52	0.39	0.2548	0.468
	9	600	0.3	TiN	1	138	243	261	0.91	330	3.6	0.58	0.1707	0.0928
Mist	1	300	0.1	NC	1	53	213	172	0.34	110.1	3.4	0.27		
	2	300	0.2	TiN	1.5	88	874	324	0.53	198.1	3.5	0.21		
	3	300	0.3	AL	2	124	914	40	0.46	188.7	3.6	0.68		
	4	450	0.1	TiN	2	58	759	56	0.42	264.2	3.88	0.4		
	5	450	0.2	AL	1	90	715	610	0.49	165.1	3.86	0.53		
	6	450	0.3	NC	1.5	120	826	340	0.62	330.2	3.64	0.69		
	7	600	0.1	AL	1.5	51	261	108	0.36	247.7	3.28	0.34		
	8	600	0.2	NC	2	68	94	471	0.62	330.2	3.42	0.43		
	9	600	0.3	TiN	1	53	97	767	0.31	165.1	3.56	0.63		

The surface roughness was averaged out of four readings and was measured using contact type roughness tester. Volumetric material removal rate was calculated as MRR. Tool wear was measured using Z-microscope with an accuracy of nano-meters (see fig 4). Width and thickness of chip after machining was measured using optical microscope. Table 2 covers all experimental results.

4 Results and Discussion

4.1 Analysis of surface roughness

Surface finish is an important factor to indicate the effectiveness of the machining process. A significant difference in variation of surface roughness under each machining condition was observed. It can be revealed that surface roughness decrease with increase in spindle speed.

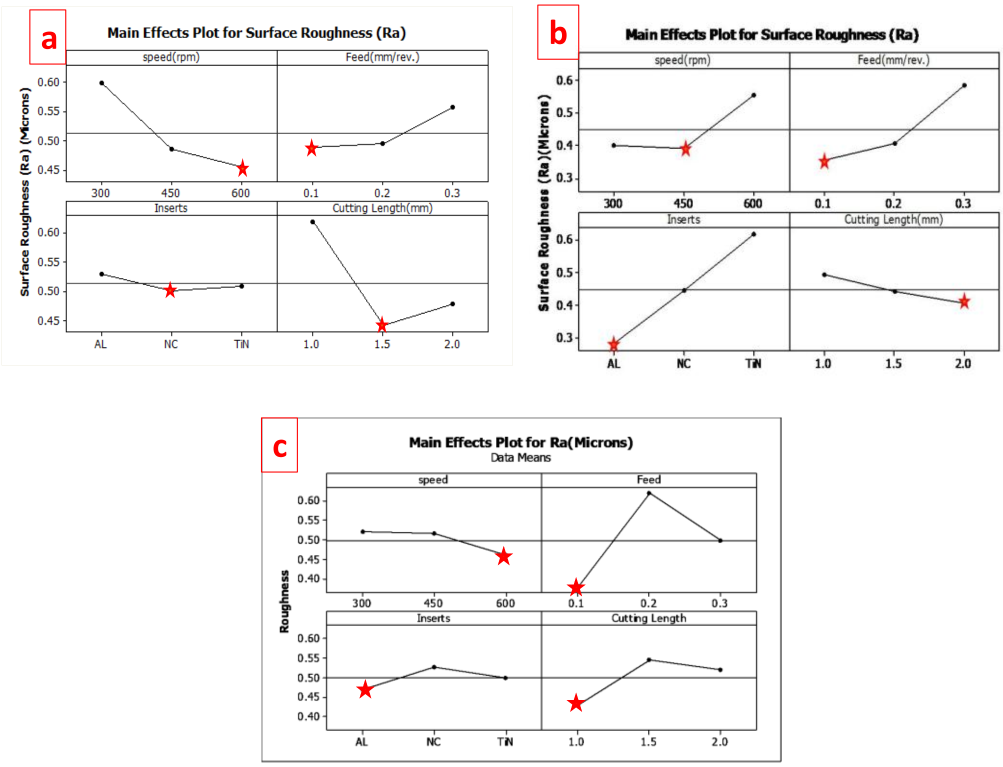


Fig. 5. Analysis of surface roughness under a) Dry, b) Flooded, c) Mist lubrication conditions

This has been shown in fig 5. Best surface finish has been recorded with the water-based emulsion (flooded lubrication) and followed by the MQL system. Although, both water-based emulsion and mist lubrication gave the lowest surface roughness, there was still slight difference in the variation of both. Water-based emulsion was acting as a better coolant compared to the mist lubrication (MQL). This could be due to the additives in water-based emulsion, which reduced the friction between tool tips and work surface. The surface finish obtained in presence of MQL was slightly worse than that with the flooded coolants because turning with compressed cold air is considered as dry cutting process. Compressed cold air did not have lubrication effect like conventional coolants. It has been categorically observed that feed rate was a dominant parameter for the surface roughness followed by cutting speed.

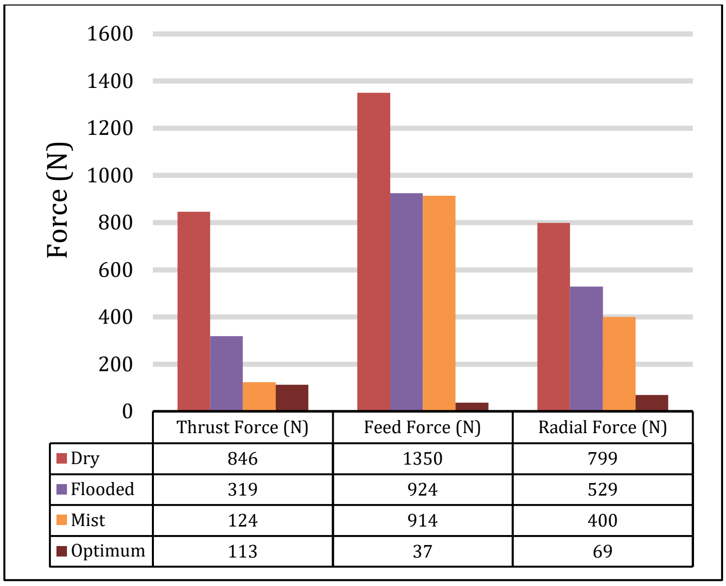
The optimum cutting conditions for surface roughness for various machining environments are shown in Table 3.

Table 3 Optimisation of surface roughness

Speed (rpm)	Feed (mm/rev)	Insert	Ra (µm)
For Dry Condition			
600	0.1	NC, Al_2O_3	0.38
For Flooded Condition			
450	0.1	Al_2O_3	0.23
For Mist Condition			
600	0.1	Al_2O_3	0.36

4.2 Analysis of cutting forces

Cutting forces are one of the important criteria that are used to evaluate the performance of the machining process. A comparative analysis of cutting forces is shown in fig 6. The lowest cutting force was obtained with the application of synthetic oil and compressed cold air combination mist. This could be due to the lubrication ability of the mist coolants. The conventional coolants did not reduce the friction between tool and chip. Therefore,abrasion of tool and chipping tend to increase the material adhesion resulting in higher force level.



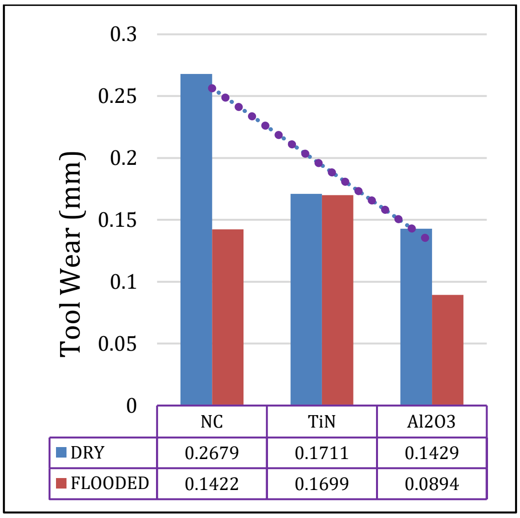
	Thrust Force (N)	Feed Force (N)	Radial Force (N)
Dry	846	1350	799
Flooded	319	924	529
Mist	124	914	400
Optimum	113	37	69

Fig. 6. Analysis of cutting forces under a) Dry, b) Flooded, c) Mist lubrication conditions

The mist provides adequate lubrication, which reduces the radial cutting forces. However, a higher magnitude of radial force was observed under dry and flooded machining environments. This is due to fact that the mist jet has ensured a large reduction in the friction between the rake face and the chip. Due to higher proportion of oil contents, lubrication capacity of the mist jet is higher than the other machining environments.

4.3 Analysis of Tool wear

Main cause of tool wear mechanism in machining titanium was found to be diffusion due to high temperature interface. There were two types of tool wears observed namely crater wear and flank Wear. Crater wear is always higher than flank wear in dry condition. On the other hand, flank wear is higher than crater wear for flooded lubrication condition. Usually, lower feed rate and lower cutting speed gives lower tool wear. At low cutting speed, worn flank encourages the adhesion of work piece of material. Analysis of tool wear (fig 7) reveals that flooded lubrication shows lower tool wear than dry machining conditions.



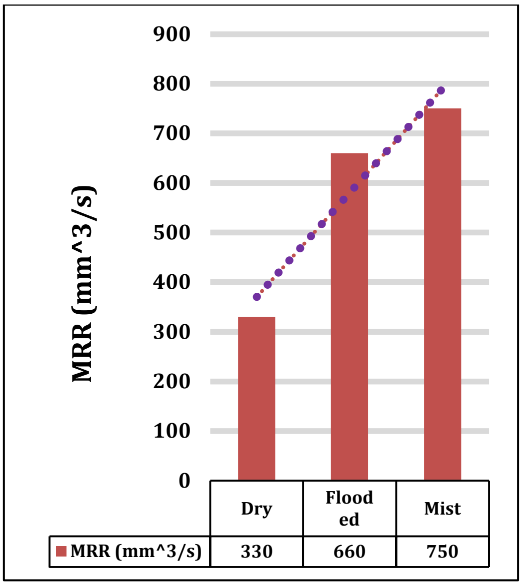
	NC	TiN	Al2O3
DRY	0.2679	0.1711	0.1429
FLOODED	0.1422	0.1699	0.0894

Fig. 7. Analysis of tool wear under a) Dry, b) Flooded, c) Mist lubrication conditions

This may be due to fact that cooling and lubrication abilities in flooded machining carry the chips away from the cutting zone. It causes a larger amount of heat to be taken away by chips. Thus, reduces tool wear during machining. While machining Ti6Al4V, continuous chips were formed which observed sliding friction with the tool face .Hence there has been temperature rise and also galling and welding on the tool face.

4.4 Analysis of MRR

Initially, MRR shows a decreasing trend for dry machining condition because initial cutting takes place due to shearing action and the heat is dissipated entirely to the tool and hence the material is not in plastic flow. However, MRR in flooded lubrication system is around 50 % higher than dry machining condition as shown in fig. 8. The reason for this is that the chip thickness decreases with the cutting speed under dry condition but under flooded lubrication the shear angle first increases with the cutting speed and then decreases with the further increase in the cutting speed. Due to this at high cutting speed, flooded lubrication makes it much easier to remove the work material.



	Dry	Flooded	Mist
🟥 MRR (mm^3/s)	330	660	750

Fig. 8. Analysis of MRR under a) Dry, b) Flooded, c) Mist lubrication conditions

5 Conclusions

The cutting performance of Mist lubrication machining is better than that of conventional dry and flooded lubrication machining.

Mist lubrication has improved tool life and also gives better finished surface.

The minimum cutting forces is achieved at lower cutting velocity and feed and using either mist or flooded lubrication system.

Moreover, mist lubrication gives 30-40% reduction in cutting forces as compared to conventional machining.

The minimum surface roughness of Ra value 0.3 μm is achieved for Mist lubrication machining condition, which 20-30 % times less than dry machining.

The crater wear and flank wear are reduced by 40-50 % by using flooded type lubrication than conventional dry machining.

At the same time 40-50% higher MRR is obtained by using both mist and flooded lubrication than dry machining.

The overall experimental results showed that the surface finish, cutting forces, and tool wear are related to the heat generated at the cutting zone and the friction between tool and work surface and to get better MRR, surface finish and minimum tool wear one must use effective lubrication method during machining.

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References

[1]. I E.O Ezugwu, J Bonney and Y Yamane, “An overview of the machinability of aeroengine alloys”, Journal of Materials Processing Technology, Volume 134, Issue 2, pp. 233-253.

[2]. S. I. Jaffery and P. T. Mativenga, “Assessment of the machinability of Ti-6Al-4V alloy using the wear map approach”, The International Journal of Advanced Manufacturing Technology, February 2009, Volume 40, Issue 7, pp 687-696

[3]. J. Paulo Davim, “Machining of Titanium Alloys Materials Forming, Machining and Tribology”, Springer, 2014

[4]. Deshayes, L., Evans, J. L., Ivester, R., Bhat, D. G., Batzer, S. A., and Whitenton, E. P., “ Mechanical and Thermal Behavior for Machining Ti-6Al-4V With AlMgB14 and WC-Co Tools” In ASME 2005 International Mechanical Engineering Congress and Exposition (pp. 503-512). American Society of Mechanical Engineers.

[5]. Revankar, Goutam Devaraya, Shetty, Raviraj, Rao, Shrikantha Srinivas, and Gaitonde, Vinayak Neelakanth, “Analysis of surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes”, Materials Research, 17(4), 2014, 1010-1022

[6]. Ramana, M. Venkata, G. Krishna Mohan Rao, and D. Hanumantha Rao. "Optimization and Effect of Process Parameters on Tool Wear in Turning of Titanium Alloy under Different Machining Conditions." Int. J. Mater. Mech. Manufacturing 2.4 (2014).

[7]. Ramanaa, M. Venkata, K. Srinivasulu, and G. Krishna Mohana Rao. "Performance Evaluation and Selection of Optimal Parameters in Turning of Ti-6Al-4V Alloy Under Different Cooling Conditions." International Journal of Innovative Technology and Creative Engineering, (ISSN: 2045-8711), volume 1.

[8]. Luo, X., Cheng, K., Holt, R., & Liu, X., “Modeling flank wear of carbide tool insert in metal cutting”, Wear, 259(7), 2005, pp. 1235-1240.

[9]. Thamizhmanii, Sivaprakasam, and Sulaiman Hasan. "Machinability of hard martensitic stainless steel and hard alloy steel by CBN and PCBN tools by turning process." Proceedings of the world congress on engineering. Vol. 1. No. 1. Proceedings of the world Congress on Engineering 2011.

[10]. Kurada, S., and C. Bradley. "A machine vision system for tool wear assessment." Tribology International 30.4 (1997): pp. 295-304.

[11]. Özel, Tugrul. "Modeling of hard part machining: effect of insert edge preparation in CBN cutting tools." Journal of Materials Processing Technology 141.2 (2003): pp. 284-293.

[12]. Ma, J., Duong, N. H., Chang, S., Lian, Y., Deng, J., & Lei, S., “Assessment of Micro-grooved Cutting Tool in Dry Machining of AISI 1045 Steel”, Journal of Manufacturing Science and Engineering, 137(3), 031001.