High Speed Machining of Ti-alloys- A critical Review

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***Abstract* - Titanium alloys are widely used in many applications such as Aerospace, Automotive, Biomedical, Marine, Mining and Oil Industries. Titanium elucidates many engineering challenges for its effective utilization. The tool wear, material removal rate, surface finish and overall cost in titanium machining are major challenges. In order to meet these challenges conventional high speed machining may be one of the solutions to produce more durable and quality products. The present paper discusses to find the most efficient combination of tool, machining parameters, milling strategy, workpiece materials, etc. for the particular application. The work carried out by various researchers is studied in the field of conventional machining of titanium alloys considering only turning and milling operation and important findings are narrated.**

Keywords - Titanium alloys, Machinability, Milling, Turning.

I. INTRODUCTION

Today in this modern era, titanium (Ti) alloys are used in making products for Aerospace, Automotive, Biomedical, Marine, Mining, Railway, Oil and Piping Industry. Since 100 years, research on machining of Ti-alloys was considered to be extremely difficult even though there are up's and down's between years for different reasons taken into consideration. Experiments using different methods such as statistical approaches, mathematical modeling using software's and optimization techniques is extensively carried out till date. From past six years there is a tremendous progress in machining of the Ti-alloys for different applications. Machining of Ti-alloys can be done by conventional processes such as Milling, Turning, Drilling, Tapping, Grinding and Sawing and also by non- conventional processes such as Electric Discharge machining, Water Jet machining, Ultrasonic machining and chemical milling. In Conventional Machining (CM), "hogging" is very light i.e. the material removal rate is less as the spindle speeds are low and the amount of cutting time will be high. In CM, as low cutting speeds are present the cutting tool requires much force in order to cut the workpiece leading to high heat generation at tool-workpiece interface and tool deteriorates quickly.

High speed machining (HSM) is one of the procedures expected for shorter lead and production times, lower costs, delivering efficiently and better quality build products. HSM in practice has been carried out by enhancing the spindle designs, control systems and tools [1]. Productivity and efficiency of the machining process can be improved by varying feed rates in accordance with cutting velocity leading to high chip-removal rates with small tool diameters. Salomon assumed a cutting speed which varies by a factor of 5-10 times than in CM resulting in decrease of chip tool interface temperature [38]. HSM is also defined to be high productive rate, high cutting speed (v), high rotational speed (n), high feed (f), high speed and feed. HSM is not only simply high cutting speed and feed essentially it is a process where the operations are performed with very specific methods and production equipment like machining components of all sizes from roughing to finishing, recognizing it as High Productive Machining. Lower cutting forces are involved in HSM ensuing stress free components, burr free edges, high-quality surface finish as well as productivity increment [2&3]. Like all steels and aluminium grades have identical machining characteristics, Ti-alloys of different grades i.e. commercially pure and various alloys do not have same machining characteristics. Ti inhibits dissipation of heat with in the workpiece itself because of low thermal conductivity.

However, there are many challenges in HSM such as material cost, tool cost, cutting geometry, depth of cut, feed rate, tool wear, tool life, spindle speed, high temperatures, heat affected zones, workpiece surface integrity and different grades of work piece materials.

In present paper, the work carried out by various researchers with different methodologies in the field of machinability of Ti-alloys is discussed. The study of HSM of Ti-alloys by conventional machining approaches like milling and turning are considered and important findings are sorted. To find the most efficient combination of tool, machining parameters, workpiece materials, turning & milling strategy for the particular application, specific analyses are considered. The most effective metal removal rates are only achievable with selective harmonized set of cutting material, edge geometry, coating, coolant and milling strategies.

II. Ti-ALLOYS CLASSIFICATION AND PROPERTIES

According to the major phase or phases in the microstructure of the Ti- alloys different grades are distinguished which are classified into four categories such as Alpha(α), Near-Alpha, Alpha+Beta (α+β), and Beta (β) [4,5&6]. Ti has a hexagonal close-packed crystal structure (α-phase) at room temperature and body centered cubic (β-phase) at 888^0C as shown in fig.1. Titanium properties are defined by grain shape and size effect behaviour that leads to change in crystal structure from α to β and β to α. Ti-alloys have different mechanical, physical, thermal, chemical, electrical and optical properties for various grades obtained by the addition of alloying elements.

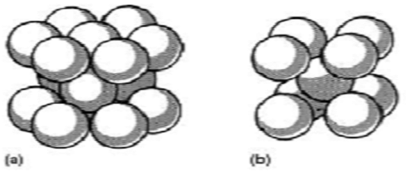

Fig.1 Appearance of Crystal structures of Titanium at the atomic level. (a) Hexagonal; close Packed (b) Cubic, body centered [7]

Ti-6Al-4V being the most commonly used Ti-alloy accounting for over 60 % of the total production. Specific and different mill processing methodologies are required to produce these alloys possessing unique properties for given application. Ti-alloys have high melting point, low modulus of elasticity, high intrinsic shock resistance, high electrical resistivity, high ballistic resistance to density ratio and essentially nonmagnetic.

In Alpha (α), Near-Alpha Ti-alloys: higher creep strength, non-heat treatable, improved weldability, medium strength, good corrosion resistance and good notch toughness are some of the characteristics. By adding definite alloys like aluminium and interstitials like oxygen, nitrogen, and carbon could stabilize the alpha phase i.e. by raising the temperature of Ti-alloys at which it will be altered entirely to the beta phase is known as beta transus temperature. In Alpha+Beta (α+β) Ti-alloys: heat treatable, good forming properties, medium high strength, good creep strength are some of the characteristics. In Beta (β) Ti-alloys: high strain rate sensitivity, higher density, fast heat treatment response, enhanced fabricability, low ductility, very high strength, superior short-time strength are some of the characteristics achieved by adding stabilizers to endorse beta phase. Most alloying additions will stabilize the beta phase by decreasing the temperature of transformation (α to β) such as vanadium, niobium, copper, iron, manganese, tantalum, molybdenum and chromium. Alpha phase is strengthened by many elements among which zirconium behave as neutral solute in Ti-alloys having little effect on transformation temperature. Exceptional strength characteristics and oxidation resistance at elevated temperatures (316-593 ^{0}C) are achieved by possessing excessive aluminium content for this group [6&7]. The most important characteristics of Ti-alloys are excellent for their combination of elevated strength to density ratio i.e. comparatively low density just about half the weight of nickel, steel and copper alloys, high strengths, fracture toughness and high structural efficiency. Although titanium is approximately 60% more dense than aluminium, it is twice as strong as common aluminium structural alloys. In addition to their static strength advantage, Ti-alloys have much better fatigue strength than other light weight alloys such as those of Al & Mg. Ti-alloys have lower thermal conductivities and lower thermal coefficient of expansion than the commercially pure material. In the Ti-alloys from α to β phases, decrease in the thermal conductivity can be seen which leads to less dissipation of heat at tool-workpiece interface and consequential loss of surface integrity due to tool damage while machining. It has got exceptional corrosion and erosion resistance to sea water, chlorides, oxidizing media and sour. Ti-alloys have short radioactive half-life, they are non-allergenic, non-toxic, biocompatible and consisting of fantastic cryogenic properties.

From the above information it can be noted that for Ti-alloys of different grades from α to β phases, machining is very difficult for β phase rather than other phases because of their increased hardness.

III. HSM OF Ti - ALLOYS IN TURNING OPERATION

Narutaki, Murakoshi, Takeyama [8] performed turning tests on alloys Ti-6Al-4V (α+β) & Ti-5Al-2.5Sn (β) with cutting speeds 0.5 to 5.0 m/s, depth of cut 0.5 mm, feed 0.1 mm/rev and cutting fluid of soluble type and found that for both the work pieces, natural diamond tool exhibited an excellent cutting performance compared to other tools like straight tungsten carbide (WC-K10), cemented TiN, pure aluminium oxide type of ceramic, coated TiC, CBN tool and sintered diamond. Cutting force for Ti-alloy was claimed to be about one half of that of a carbon steel (0.45%C) and cutting temperature to be about 250^0C higher than that of carbon steel because of low thermal conductivity and low density of Ti-alloys.

CheHaron, Jawaid, & Abdullah [9, 10, & 11] carried out turning operation on Ti-6Al-2Sn-4Zr-6Mo and Ti-6Al-4V under dry cutting condition using uncoated cemented carbide tools with surface speed 100, 75, 60 & 45 m/min at constant depth of cut 2.0 mm with feed rates

0.25 & 0.35 mm/rev. The effects of chip-breaker geometry, grain size of the tool, and workpiece surface integrity was investigated. They observed that (i) Wear mechanisms like plastic deformation, diffusion, attrition, abrasion and chipping. (ii) Excessive chipping on the flank edge and flank face wear at higher cutting speeds and feed rates was the major tool failure mechanism. From the experimental results, inserts with fine grain size and a honed edge were found to have a longer tool life. Wear rate for insert 883 with grain size of 1.0 µm was lesser than insert 890 with grain size of 0.68 µm due to increase solubility of WC into Ti-alloys. From the result it was claimed that both inserts gave better tool life at a feed rate of 0.25 mm/rev under all cutting speeds but both tools are not recommended at feed rate of 0.35 mm/rev for machining Ti-6246 under all cutting speeds. During dry cutting conditions after prolonged machining resulted in rigorous tearing and plastic deformation of the machined surface on Ti-6Al-4V.

Zoya & Krishnamurthy [12] performed turning on Ti-4.5Al-4.5Mn utilizing Polycrystalline Cubic Boron Nitride (PCBN) tools. The machining performance was evaluated in terms of surface finish, cutting temperature, cutting force, chip strain and specific cutting pressure. Good surface finish was achieved at 185 m/min and a stable cutting performance at 220m/min. Critical temperature of 700^0C was observed to be good for tool life and cutting speed recommended for the machining was 185±220 m/min. Finally they have concluded that machining process was thermally dominant.

Ezuguwa, Dasilvaa, Bonneya, & Machado [13] performed turning operation on Ti-6Al-4V with various coolants fed at higher cutting speeds upto 250 m/min using different PCBN tool grades and also with uncoated carbide tools at a speed of 150 m/min. The performance of cutting tools were determined by measuring surface roughness of machined surface, failure modes of tool, cutting force, tool wear and feed force. From the comparison, uncoated carbide tools outperformed than PCBN tools. Under the considered cutting conditions, decrement in tool life was resulted because of increased PCBN content of the cutting tool leading to notch wear formation.

An, Fu, & Xu [14] observed significant reduction in cutting temperatures, improvement in tool life, acceptable chip morphology and good machined surface quality using cold water mist jet (CWMJ) during turning process of (TC9) Ti-6.5Al-3.5Mo-2.5Sn-0.3Si with uncoated carbide tools at cutting speeds of 38, 60,75, 120 m/min, at a feed rate 0.1 mm/rev and depth of cut 0.5 mm. Hydrodynamic tests, turning tests, heat transfer tests were carried out to evaluate the cooling effects of CWMJ. Results indicated that CMJ had better cooling effects as compared with other two cold air jet and flood cooling methods.

Klocke, Krame, Mann, & Lung [15] used whisker reinforced ceramics and cemented carbide for machining Ti-6Al-4V on longitudinal external turning process applying cryogenic cooling (CO_2 & LN_2) and high-pressure lubricoolant supply. To analyse the mechanical load on the cutting edge with conventional flood cooling and high pressure lubricoolant supply they have calculated the ratio of cutting force to tool-chip contact area considering tool wear, tool temperature, cutting force and specific tool load. Slight notch wear and uniform flank wear were observed during conventional flood cooling. Flank wear can be reduced up to 45 % and the formation of notch wear could be avoided by using the high pressure lubricoolant supply reducing the thermal wear mechanism that was observed majorly at high cutting speed. With the high pressure lubricoolant supply it was difficult to determine the effect of concentration of cutting forces on the cutting edge. Further it was concluded that reduction of the chipup curl radius leads to decrease in tool-chip contact area because of direct lubricoolant flow into the wedge between tool and chip. Lower temperature was observed in the primary shear zone because of enhanced pressure by almost 15% increasing the cutting force slightly.

Rahman, Sun, Wang & Dargusch [16&17] applied laser assisted machining (LAM) technique to investigate the behaviour of the beta Ti-alloy (Ti-6Cr-5Mo-5V-4Al) using uncoated tungsten carbide tool with cutting speeds from 9.5 to 200 m /min, feed rate 0.054 to 0.8 mm/rev at a constant depth of cut 1 mm utilizing four different laser powers 400W, 800W, 1200W, and 1600W. LAM technique increased material removal rate by reducing the yield strength of the material which in turn reduced the cutting forces required to machine the workpiece. In order to explore the advantages /disadvantages of LAM over CM, the experiments were conducted under LAM conditions and compared with CM. They have observed that under both CM and LAM conditions the cutting forces were linearly proportional to the changes in the feed rate. Magnitude of these cutting forces in LAM was found significantly lower than that of CM within a certain range of cutting parameters. Maximum benefit was achieved at cutting speeds between 25 and 100 m/min using laser power of 1200W and at feed rates of 0.15-0.25 mm/rev. They also observed that using too high laser power i.e. 1600W at cutting speeds below 5 m /min results in chip pile up which can aggravate tool wear. A laser power range of 1200-1600W was found to be effective in reducing cutting forces during LAM with moderate to high cutting speeds ranging from 25 to 125 m/min.

Nabhani [18] conducted turning tests on rolled and annealed TA48 (Ti-5Al-4Mo-(2-2.5) Sn-(6-7) Si-2Fe max: 0.015H, 0.5O, 0.05N) using PCBN, Polycrystalline Diamond (PCD) & Coated WC at a surface sped of 75 m/min, feed rate 0.25 mm/rev, depth of cut 1.0 mm without cutting fluid. They investigated tool/workpiece interaction, wear rate, and performance using quick-stop tests. Plastic deformation of carbide tools under compressive stress was observed close to the cutting edge at high temperatures. The performance of carbide tools was not effective as the coated layers were rapidly removed during machining, leaving the tungsten carbide substrate open to cratering. The PCBN and carbide tools had the same wear mechanisms, while the lowest wear rate and best surface finish was observed in PCD when compared with other two inserts. From the quick stop technique, between the rake face and the underside of the emerging chip a layer was formed on all three cutting tools which had a fundamental effect on cutting and wear mechanism. Based on the results obtained, PCD was found to give a better surface finish, longer tool life and more manageable swarf than other tools and hence for machining Ti-alloys, it is considered as commercially successful cutting inserts.

Arrazola et.al [19] used uncoated cemented carbide tool for turning operation on Ti-6Al-4V and Ti555.3 with conventional cooling method. For critical aeronautical applications Ti-6Al-4V has been replaced by Near Beta Ti-alloys like Ti555.3. Investigation was done to understand tool wear mechanism. From the analysis of variables such as cutting forces, chip geometry and tool wear, they found (i) it was very difficult to machine Ti555.3 alloy compared with Ti-6Al-4V alloy at higher speeds up to 90 m/min. (ii) A correlation between component forces, mechanical properties of work material and tool wear (iii) adhered material layers composed of Ti and TiC was existed on the tool's rake face for both Ti-alloys by the diffusion process.

Rahman, Sun, Wang & Dargusch [20] used uncoated WC tool for tuning Ti-10V-2Fe-3Al (β-alloy) with cutting speeds from 5 to 75 m/ min with a constant feed rate of 0.19 mm/rev and secondly varying with 0.05 to 0.28 mm/rev under dry cutting conditions at constant laser power 1200W. Increase in cutting pressure was observed when the cutting speeds were increased upto 50 m/min without laser assistance where thermal softening was dominated by strain rate hardening, while pressure decreased as the cutting speed crossed 50 m/min. Periodic segmented chips were produced from continuous unsegmented chips due to increase in speed leading to reduction in cutting forces and flow stress where plastic deformation is confined to adiabatic shear planes. When both alloys were compared, it was found that the machinability of β-alloy was about 1/3 of α in CM and α+β in LAM. They observed that high strength-high temperature Ti-alloys were less responsive to LAM than traditional operation.

Dandekar, Shin, & John Barnes [21] performed turning operation on Ti-6Al-4V with carbide tools using LAM and hybrid machining. By varying MRR and tool material, the machining parameters like surface roughness, cutting forces, microstructure, tool wear and specific cutting energy was investigated to know the effectiveness of the two processes. Hybrid machining improved the machinability of Ti under cutting speeds from low to high (150-200 m/min) and LAM improved the machinability under cutting speeds from low to medium-high (60-107 m/min). Tool life improvement was observed in hybrid machining with TiAlN coated carbide tool upto cutting speeds of 200 m/min over CM.

Rosemar, Machado, Ezugwu, Bonney, & Sales [22] used PCD tools in turning of Ti-6Al-4V at cutting speeds 175, 200, 230, 250 m/min, depth of cut 0.5 mm, feed rate of 0.15 mm/rev in wet cutting condition. Investigation of the tool performance was done under different tribological conditions and dominant wear mechanism using high lubricity emulsion where 6% concentration at low pressure flow rate from the overhead direction and high pressures (7, 11 and 20.3 MPa) directed against the chip flow direction on the tool rake face. Significant improvement in tool life was obtained with high pressure coolant supplies and best result at the highest (20.3 MPa) relative to conventional coolant supply. Flank and nose wear were found to be the dominant failure modes, attrition and adhesion were dominant wear mechanisms. Long continuous chips were formed with conventional coolant flow while segmented chips were generated at high pressure coolant supply.

IV. HSM OF Ti - ALLOYS IN MILLING OPERATION

An inherent feature of the milling process geometry is the fact that the chip section is not constant, but varies periodically, the law of variation depending upon depth and width of cut, helix angle of the cutter, diameter of cutter, spindle speed, feed rate and the number of teeth on cutter. To predict the cutting forces in face milling, orthogonal machining theory can be applied along with cutting conditions and knowledge on work material properties [23]. Some of the research work in the prescribed areas is presented below.

Jawaid, Sharif, & Koksal [24] used PVD-TiN and CVD-TiCN/Al_2O_3 coated carbide tools for face milling of Ti-6Al-4V with different cutting speeds like 55, 65, 80, and 100 m/min, feed rates 0.1 and 0.15 mm per tooth, axial depth of cut 2 mm and radial depth of cut 58 mm and evaluated cutting performance with respect to wear mechanisms, tool life and failure modes. They observed that excessive chipping & plastic deformation at the cutting edge, flaking and/ or chipping on the rake face and claimed that non-uniform flank wear exhibit dominant wear pattern by both PVD and CVD tools. Initial wear mechanisms for both of the coated tools were formed because of adhesion of work material at the cutting edge, galling on the rake face and coating delamination. Diffusion and attrition wear mechanism were responsible for the flake and rake face wear on both the coated tools. Severe flaking and/or chipping of the inserts at both the rake and flank faces were observed because of the thermal cracks formation while machining. CVD coated tool were found to outperform the PVD coated tool.

Elmagrabi, CheHassan, Jaharah, & Shuaeib [25] performed dry slot milling tests on Ti-6Al-4V with coated and uncoated carbide cutting tools at various cutting speeds of 50, 80 and 105 m/min, feed rates of 0.1, 0.15 and 2 mm/tooth and depth of cuts 1, 1.5 and 2 mm respectively. Performance of the cutting tool was determined by tool life and the quality of the surface finish. From the observations PVD coated carbide tool was concluded to have a better tool life with a maximum of 11.5 minutes and surface roughness is more sensitive to the feed rate and depth of cut.

Abele & Frohlich [26] reviewed the work carried out by different researchers. They observed that if any elemental changes were done in the procedure then machining parameters will have strong influence on stability, process safety and operating efficiency. While machining the Ti-alloys the following common problems faced by scientists, researchers and machinists listed as (i) high thermal stress at the cutting edge due to the low heat dissipation by the chips and the work piece, (ii) Tool failure by chippings due to high cutting forces an self-induced chatter, (iii) Friction and chatter enhanced due to lower effective clearance angle, high cutting forces, low excitation frequencies caused by relatively low rotation speeds, (iv) Wear by diffusion due to high reactivity of Ti weakens the cutting material resulting in tool life failure, (v) Hazard of exoergic reaction of Ti chips with atmospheric oxygen. With the help of different experiments and scientific studies to conclude that efficient high speed milling of Ti-alloys is possible

Zhenchao, Yang, Yao, & Ren [27] performed high speed milling of Ti-alloy (α+β) TC11 using 10 mm uncoated cemented carbide under constant machining parameters like cutting depth 0.2 mm, feed 0.05 mm/tooth and cutting width 10 mm. TC 11 composition consists of Ti-6.42Al-3.29Mo-1.79Zr-0.23Si-0.025C-0.096O-.003H-0.0077Fe-0.004N. To improve component fatigue life and machinability, they have investigated on microstructure, surface integrity and residual stresses under the effect of cutting conditions like milling speed and cooling method. They have concluded that for high speed milling of Ti-alloy using uncoated cemented carbide tool the best cooling methodology was emulsion liquid cooling.

Wang, Rahman & Wong [28 & 29] carried out high speed milling (slot milling process) using new binderless cubic boron nitride (BCBN) inserts on Ti-6Al-4V with cutting speed 350 m/min, depth of cut 0.05, 0.075 and 0.1 mm, feed rate of 0.05, 0.075 and 0.1 mm/tooth at a high spindle speed of 15,000-30,000 rpm. Maximum flank wear was observed at the nose seemed to be the limiting factor that controlled the tool life in all cases. Hence, the average flank wear of 0.40 mm was choosen as the tool failure criterion. At a cutting speed of 350 m/min, depth of cut 0.075 mm and feed rate 0.05 mm/tooth the tool life was about 20 min for BCBN, whereas for same cutting conditions the tool life of PCBN tools was only about 1 min. From the analyses based on the SEM and EDX, it was suggested that adhesion of workpiece, attrition and diffusion-dissolution were the main wear mechanisms and non-uniform flank wear was the dominant wear pattern of the BCBN tool. Based on the comparison for tool life under all cutting conditions upto 400 m/min with excellent mechanical properties, the BCBN appears to become a new cutting tool material for high-speed machining of Ti-alloys with superior cutting performance.

Ginting & Nouari [30] used uncoated cemented carbide tools under dry cutting conditions of ball-end milling of the aerospace Ti-ally Ti-6242S with cutting speeds in the range of 60, 75, 100, 15 and 150 m /min. The axial and radial depths of cut were kept constant at 2.0 and 8.8 mm and feed rate values of 0.1 and 0.15 mm/tooth were selected in the experiment. SEM analysis was carried out on the worn tools and noted that flank wear and excessive chipping on the flank edge were the main tool failure modes. Experimental work was conducted under dry cutting conditions to conclude that the alloyed carbide tool (WC 69.8 wt%, Co9.50 wt%, Ti/Ta/Nb-C 20.70 wt%) in ball end mill configuration is best suitable for end milling of Ti-6242S with cutting speed 150 m/min, feed rate of 0.15 mm/tooth, axial depth of cut 2 mm and radial depth of cut 8.8 mm. For both feed rates, the results demonstrate that higher the cutting speed the better is surface finish in terms of failure mode. Localized flank wear VB_3 at the tool leading edge as the main wear mode determining the tool life followed by the brittle fracture such as cracking, chipping and flaking. Further FEM simulation was proposed to be helpful to calculate the contact parameters, modeling of chip formation and to understand the tool wear mechanisms.

Sharif, Jawaid, & Koksal [31] used two similar PVD-TiN coated carbide inserts during face milling of Ti-6Al-4V at various cutting speeds of 55, 65, 80 and 100 m/min with a feed rate of 0.1 mm/tooth, axial depth of cut 2 mm and radial depth of cut 58 mm. Tool life and tool failure characteristics were examined at the above cutting conditions. Edge geometry had significant effect on the tool performance; excessive chipping at the cutting edge and chipping/ flaking on the rake face were found to dominate the failure modes on both tools under most cutting conditions.

Su, He, Li, & Li [32] used coated cemented carbide tools in high speed end milling of Ti-6Al-4V under various cooling conditions like dry, flood coolant, nitrogen-oil-mist, Compressed cold nitrogen gas (CCNG) at 0^0C and 10^0C, Compressed cold nitrogen gas and oil mist (CCNGOM) to find the optimal cooling/lubrication condition for improving the tool life and observed flank wear to be the dominant failure mode under all the cooling conditions. Experiments were carried out and the best tool life was achieved at the CCNGOM condition. From the analysis based on SEM, diffusion wear and thermal fatigue wear were claimed to be predominant wear mechanisms of the coated tools under the cooling conditions. Excessive chipping at the cutting edge and fracture on the flank face was found responsible for tool failure under flood coolant condition.

Lopez, Perez, Lorente, & Sanchez [33] performed milling operation on Ti-6Al-4V using coated NCr and TiCN on HS steel and other hard metal tools at cutting speeds 15-100 m /min, feed rate of 0.03-0.15

mm/tooth and depth of cut 3-5 mm. To increase the productivity of the milling process they investigated on tool influence as to its geometry and coatings for the above considered parameters. TiCN and NCr coated tools developed high flank wear in the cutting edges, notch wear at the depth of cut level and burr formation. Uncoated hard metal mills exhibited similar wear behaviour, burr formation initiated at 100m/min cutting speed as a consequence of the wear on the tool flank. Major difficulties faced while performing machining was low thermal conductivity and its reactivity with the hard metal. Good results were found while machining with TiCN coated tools than NCr.

Edmund, Schuller, & Smith [34] used CVD Al_2O_3 coated on a tough carbide substrate and multilayered PVD TiN/TiCN coated on the same type of substrate for two operations face milling (75%) and end milling (25%) on Ti-6Al-4V. They have investigated on MRR stiffening of the machine system using vibration analysis tools and the harmonizer, lowering manufacturing cost correlated by machining the part twice as fast or to halve the milling run time, significant reduction of polishing and deburring time about 8 hours. From the systematic cutting tests of various geometries of face mill inserts, round and thick with coated carbide substrate were found to be the most effective inserts because of positive radial and axial rakes resulting in reduce cutting force and heat generation than square, triangular and rectangular parts. When cutting with an end mill or face mill, the self-excited vibration or “chatter” between the tool and the workpiece was suggested to be avoided to achieve high MRR which otherwise will create large forces damaging the machine system, cutting tools and poor surface finish. Twice-as-fast metal removal rates in heat treated Ti-alloy (Ti-6Al-4V) was claimed to be possible by stiffening the machine system, deeper cuts, and new carbide end-mill and face mill tools by using ample coolant pressure to ensure that the cuttings are not recut. HSM of Ti was found difficult apart from performing light finishing cuts using small radial and axial depth of cut in the 0.127 to 0.254 mm. Adequate tool life of 30 minutes for carbide end mills and tool life of 25 to 45 minutes was found possible when using coated carbide inserts.

Yanga, Brandtand & Sun [35] developed a 3-D transient finite element model for a moving Gaussian laser heat source to predict the depth of the heat-affected zone (HAZ) and temperature distribution in Ti-6Al-4V alloy workpiece. The temperature profile and depth of HAZ strongly depend on the parameters of laser beam. Close agreement was shown between the thermal model simulations and the results produced by experimental work.

Huang, Li, Sun, & Ge [36] used solid cemented carbide end mill for down milling operation on Ti-6Al-4V by varying cutting speeds from 80 to 360 m/min, constant feed per tooth 0.08 mm/tooth, axial depth of cut 20 mm and radial depth of cut 0.5 mm under dry cutting conditions. Machining chatter was investigated with variable pitch end mill through signal analysis method and compared at stable and unstable milling processes and found that chatter occurs because of milling speeds and impact forces that increases strain hardening grate of the workpiece and thermal softening with increasing milling temperature. Optimal cutting speed was achieved at 160 m/min achieving good machined surface quality and smaller milling force at this cutting speed.

Niu et.al [37] performed end milling using JHP 70 HPM Tribon end mill on Ti-alloys, Ti-6Al-4V (ASTM Grade 5) and Ti-6Al-4V extra Low Interstitial (ELI) (ASTM Grade 23) in Beta Annealed (BA) and Mill Annealed (MA) heat treatment conditions with three different cutting speeds 50, 100 and 150 m/min, the feed rate (0.04 mm/tooth), depth of cut (2 mm) as kept constant and flood coolant was used during machining. Effect of cutting speed on the surface integrity and fatigue property of both alloys at a stress level of 600 MPa was investigated and no clear relationship was found between cutting speed and surface roughness and also there was no measurable influence on the fatigue life of either alloy. The BA condition appeared to be more susceptible to surface damage associated with machining and had higher surface roughness than MA condition. The MA heat treatment had significantly longer fatigue life than the BA heat treatment attributed to general microstructural effects including grain size-fatigue property relationship rather than surface roughness.

V. CONCLUSIONS AND SCOPES

An extensive study was carried out for turning and milling of Titanium alloys considering machining parameters such has tool materials, coolants, cutting speed, depth of cut, feed etc. and different combinations of these parameters.

HSM of Ti-alloys could be done by using advanced cutting tools inserts like BCBN, PCBN, PCD and Cemented Carbide tools. More efforts should be kept in improving conventional machining because non-conventional machining is not suitable for mass production. Though much work was already carried out regarding the machining of Ti-alloys, still more attention is to be given to other machining parameters for cost efficient machining of Ti-alloys considering optimization techniques, statistical methods and simulations. In order to have advancement in this process, innovation and development of tool materials and tool geometry should be considered by industries and researchers as the machining of Ti-alloys is mainly dependent on the tribological aspects like wear and the coolant. The tool wear determines the tool life which is essential for mass production, cost reduction and without uninterrupted cutting. New spindle designs and milling cutters should accomplish tool inserts having shapes like round, pentagonal, hexagonal, hectagonal and octagonal cornered. Coolants play the important role for improving the tool conditions as the heat dissipation while machining Ti-alloys is less because of low thermal conductivity.

Different heat treatment techniques on the work piece, non-reacting, cost effective lubricants and coolants may derive the attention of the researchers in this field.

Latest measuring equipment's are required to measure and analyse the machining parameters under different working conditions for improving the machining process like Temperature measurement by Thermal imaging camera and Infrared pyrometer, Cutting forces with Piezoelectric-Dynamometer and analyzer. Microstructures, Tool wear measurement with Advanced Wave length dispersive X-ray analysis and Scanning Electron Microscope. Piezoelectric–Transducers for Acoustic Emissions and Surface Roughness by Contact type Profilometer.

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