A Review on Ultrasonic Machining of Titanium Alloys

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Abstract: **Due to excellent properties of Titanium and its alloy such as high strength-to-weight ratio, low thermal conductivity, and high corrosion resistance this material is widely used in aerospace, marine gas turbine engines, medical equipment's. Due to high hardness, brittleness, low thermal conductivity of Titanium alloy, cost effective machining is critical parameter. Ultrasonic Machining is a non-traditional process which consists of abrasive in the form of slurry and tool oscillating at high frequency (about 15 to 30 kHz) and at low amplitude (20 to 100 microns). The material removal rate in Ultrasonic machining of Titanium and its alloy is very slow which makes the machining process costly.There has been a critical need for cost-effective machining processes for titanium and its alloys. The material removal rate in Ultrasonic machining is mainly related to striking and hammering of abrasive particle used in slurry form between the workpiece and ultrasonically oscillating tool. The critical parameter responsible for Material removal rate and surface finish and dimensional accuracy are amplitude and vibration of oscillating tool, feed force and pressure, Abrasive material, grain size and shape, contact area of tool, concentration of abrasive in slurry etc. So, in order to increase the MRR reduce the tool wear rate and achieve good surface finish and accuracy USM is integrated with EDM and also the Rotary USM used to make the USM cost effective machining process.**

Keywords: **Ultrasonic Machining, Titanium and its Alloy, Material Removal Rate(MRR), Tool Wear Rate(TWR), Surface Roughness(SR)**

I. INTRODUCTION

Titanium and its alloys has excellent properties such as high strength, stiffness at elevated temperatures, chemical inertness, high specific strength, excellent corrosion resistance, and oxidation resistance due to which these are used for potential engineering applications. Because of difficulty in machining, shaping, finishing and to achieve precise dimensional accuracy makes the Titanium and its alloy components costly and hindered its application due to unavailability of cost effective conventional machining process [3].

- Due to poor thermal conductivity of Titanium and its alloy, heat generated at cutting edge and tool face during machining not dissipated quickly which leads to increase in tool wear rate and exhibits the non-uniform shear strain in chip formation (serrated chips).
- Due to very short length of contact between chip and tool leads to high temperature and stress at the cutting edge.
- The cutting force also fluctuated due to serrated chips formation.
- Due to vibrational force along with high temperature exhibits the micro-fatigue loading on cutting tool results severe flank wear and tear. So, achieving good surface finish by a single machiningprocess is poor.

Therefore, it is important to find a cost-effective machining processes for titanium and its alloys. However, improvements in the cutting tool have been takes place in past some years i.e.- coatedcarbides, ceramics, cubic boron nitride, and polycrystallinediamond. With the application of these tool improved the machining of cast iron, steels, and high temperature alloys such asnickel-based alloys and super alloys. But the progress in the fields of machining oftitanium alloys is not much so far.In order to improve the machining of titanium and its alloys done by cryogenic machining. In cryogenic machining either work piece is freezes or tool is cooled byusing a cryogenic coolant. Mostly the machining work of titaniumis related to drilling, so twist drilling and vibration-assisteddrilling are two conventional machining methods. As we know that Titanium andits alloys are very sensitive to changes in cutting speed of tool.Industry generally operates at low cutting speeds in order to enhance tool life. Due to low modulus of elasticity of titanium bouncy actionis generated, which requires therigidity of a machine tool.

For cost-effective machining of Titanium and its alloy some key points need to be taken care:

- Low cutting speeds. Because tool tip temperature severely affected more by cutting speed of tool than by any other singlevariable. A temperature increases from 427°C to 927°C if speed change from 6 to 46 m per minute withcarbide tools.
- Maintain high feed rates. Feed rate does not increase the temperature so much as by speed. If Feed change from 0.05 to 0.51 mm per revolutionresults in a temperature increase by 149°C.
- Use sufficient amounts of cutting fluid. Because it also facilitates to washes away chips, carries away heat, and reduces cuttingforces.

- Use sharp tools and replace them at the first sign ofwear. Tool wear is not linear while working with titanium, complete tool failure take place quickly after small initial amountof wear.
- Never stop feed when a tool and a work piece are inmoving contact. Because it leads to work hardening and promotes smearing, galling, seizing, results total tool breakdown.

However, by incorporating above things the machining of Titanium and its alloy improves but still major area of concern is **Short tool life**, **Poor surface finish** and **limitation of process**in conventional machining of Titanium [6].

1.1 Metallurgy of Titanium Alloys

When pure titanium heated to the temperature of 882.5 ℃, transformation changing from cph (alpha phase) to bcc(beta phase) allotropically. By the addition of certain elementsin titanium, transformation temperature is very influenced. With the addition **of Al, O_2, N and C ele**ments the transformation temperature increases known as **alpha stabilizers** on the other side ‘**beta stabilizers’ (Mo, V, Nb, Cu and Si**), produces a decrease in transformation temperature. Some elements have negligible influence on the temperatureof transformation, calledas ‘neutral elements’ (Sn and Zr). Titanium alloys may be classified mainly in four groups:

1. *Unalloyed titanium:* Pure titanium have low strength but excellent corrosion resistance properties. Strength of pure titanium can be increased by addition of small amount of O_2 and Fe.
2. *Alpha and near-alpha alloys.* Titanium alloy having alphastabilizers called alpha alloy having excellent creep resistance property. The alloy which contains alpha stabilizers as well as some quantities of beta stabilizers are called near-alpha alloy.
3. *Alpha-beta alloys.*Alpha-beta alloy is a mixture of ‘alpha’ and ‘beta’ phases at normal room temperature and having both alpha and beta stabilizers. Alpha-beta alloy is mostly used in aerospace industry and commonly known as Ti-6A1-4V.
4. *Beta alloys.* Beta alloy having more quantities of beta stabilizers, this alloy is very dense and high hardenability properties.

1.2 Applications of Titanium Alloy

Pure titanium, alpha and near-alpha alloys are widely used in cryogenic applications and high corrosion resistance applications. Alpha-beta alloys are mostlyapplicable forhigh strengthapplications. Beta alloys used in applications requires good hardenability, good forge ability and cold formability.In aerospace industry we mostly use alpha-beta alloy Ti-6A1-4V which accounts 45per cent of the total titanium production. Remaining unalloyed grades comprise about 30 percent and all other titanium alloys comprise the remaining 25 percent. [7]

In order to improve the tool life, surface finish and complex cavity machining of titanium and its alloys,un-conventional machining processes such as EDM, USM, LBM,RUM,USV have been used. But due to somelimitations such asrecast layer formation, heat affected zone, thermal stresses, dimensional inaccuracies and surface finish machined component life is critically affected.Due to loss of surface integrity of titanium alloy reduces the fatigue Strength of component.Fatigue properties of titanium alloys depend on good compressive surface stress induced by tool actionduring machining.

Ultrasonic machining (USM) is one of effective un-conventionalmachining method thatcan beapplied fortitanium and its Alloy. In USM, the abrasive slurry isused to flowin between the work surface and ultrasonically oscillating tool. SO, due to repeatedimpacts of abrasive grains on the work surface lead to enhancement of compressive surface stress therefore improving thefatigue life of titanium components along with the surfaceintegrity.However, in USM process the MRR is very slow and tool life is less. Material removal rate can be increased by integrating of USM with EDM or by Rotary Ultrasonic machining which also improve the tool life and surface finish. The recast layer formation due to EDM can also be eliminated. [9]

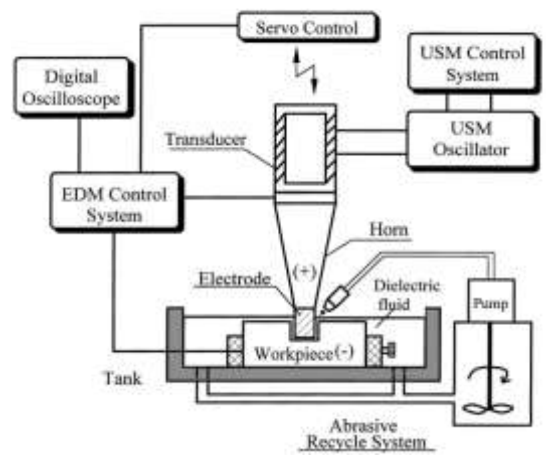

Fig:1 Detailed schematic diagram of integrated USM with EDM [1].

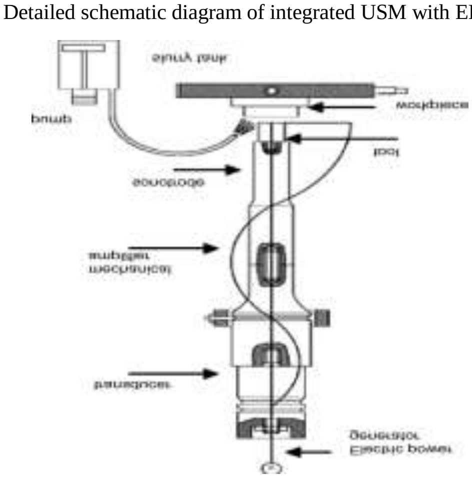

Fig:2 Detailed schematic diagram of USM [2].

Fig. 3. Compact 500W USM machine for small, light-weight work piece [9].

Electro-discharge machining (EDM) is a non-conventional thermoelectric process havingso many benefits over conventional machiningprocess. We can machine any complex shape, regardless of material brittleness, strength or hardness. The material removal rate of EDM is lower than that of conventional process. Moreover, due to formation of recast layer, surface cracks, micro-pits lead to poor surface finish and accuracy, so reduces the lifeof moulds or machinery components.This is a big challenge in EDM to improving the surface quality and increase the material removal rate (MRR). Ultrasonic machining (USM) is suitable for hard and brittle materials due to thinner material zone affected during machining. The main drawback of USM is low MRR, high tool wear rate which affects the low dimensional accuracy in comparison of other non-conventional machining. Mr.Khairydid investigationon the dynamic parameters for the USM process. The USM process is related to hammering and striking of abrasive particles between the oscillating tool and the workpiece. Kremer and his co-workers foundthatthe electrode-assisted ultrasonic vibration (USV) would improve discharge efficiency. Yan and Chen reported that if EDM combines with USV and dielectric fluid would improve the EDM machining performance of titanium alloy. They also found that in order to improve the MRR in ceramics and titanium alloy theintegration of USMand EDM shows positive results.As individually both EDM and USM processes having low MRR and poor surface finish. So, it is important to find a new technique which can reduce the disadvantages of EDM such as recast layer formation and improve the surface finish and increase the MRR. In current research it has been found that by integrating of EDM and USM, we get higher MRR and eliminate the recast layer. The thickness of recast layer due to EDM is reduced by striking force of abrasive grains aroused by electrode USV. During EDM process the debris formed on machined surface would be homogeneously distributed by electrode USV, which reduces the chance of arcing. This paper shows the effect of machining parameter by varying the EDM and USM machining conditions on MRR, electrode wear ratio (EWR), relative electrode wear ratio (REWR), and thickness of recast layer. Finally, it is concluded that integration of USM and EDM expected to enhance MRR, reduction of recast layer so increase the machining efficiency.

II. LITERATURE REVIEW

S. No	Author	Year	Process Review	Output Parameter	Benefit/Conclusion
1	Yan Cherng Lin, Biing Hwa Yan, Yong Song Chang	December 1998	Machining characteristics of titanium alloy (Ti±6Al±4V) using a combination process of EDM with USM	1. Influence of SiC concentration in dielectric fluid on MRR 2. Effect ofdischarge energy on MRR 3. Effect of discharge energy on EWR 4. Effect of discharge energy on Surface Roughness 5. Formation of recast layer	1. abrasive concentration in the dielectric fluid could provide higher MRR. 2. Shorter the ignition delays more energy introduced into the discharge gap, so more melted volume of material and higher MRR 3. More peak current increases the EWR while pulse duration not having much effect on EWR 4. As discharge energy increases produce larger crater. While using EDM &USM combination surface roughness is better with Kerosene as dielectric fluid than that of distilled water 5. Use of distilled water as dielectric fluid shows better heat removal so thinner recast layer formation takes place.
2	Jatinder Kumarand M.K. Muju	December 2010	Effect of tool properties, Power rating and slurry size in USM of Titanium	1. The material removal rate of Titanium (ASTM Grade I) has been found to depend on the tool material, grit size of the slurry used and power rating.	1. Best results for MRR have been obtained with High Carbon Steel, grit size 220 of the alumina slurry and power rating of 400 W. 2. The tool wear rate for Titanium alloy (ASTM Grade V) is very less as compared to High Carbon Steel as tool material. 3. For Grit size factor, level 1 (mesh size 220)

				2. Effect on TWR 3. Effect of Grit Size 4. Effect of power rating	was identified as the most significant for its effect on the variation in MRR, TWR and Surface roughness 4. For power rating factor, level 4 (400 W) has been most significant for MRR and TWR
3	R. Singh , J.S. Khamba	January 2007	Taguchi Technique for modelling material removal rate in ultrasonic machining of titanium	1. Tool Material 2. Slurry concentration 3. Slurry Type 4. Slurry Temperature 5. Power ratings 6. Slurry Grit Size	1. **Tool Material removal rate S/N** (A1) S.S. 17.20 (A2) H.S.S 9.76 (A3) H.C.S 14.48 (A4) Carbide 8.78 (A5) Diamond 9.47 (A6) Titanium 6.46 **2. Slurry concentration** (B1) 15% 11.37 (B2) 20% 10.05 (B3) 25% 11.65 **3. Slurry type** (C1) Boron carbide 13.40 (C2) Silicon carbide12.50 (C3) Alumina 7.17 **4. Slurry temperature** (D1) 10 ◦C 12.33 (D2) 25 ◦C 8.88 (D3) 60 ◦C 11.86 **5. Power rating** (E1) 30% 9.73 (E2) 60% 7.04 (E3) 90% 16.31 6. S**lurry grit size** (F1) 220 10.41 (F2) 320 13.79 (F3) 500 8.88 For MRR, most significant factor has been ultrasonic power rating with contribution of 28%, followed by type of tool with contribution of 24.6%. The third significant factor has been slurry type with contribution of 13.3%.
4	R. Singh , J.S. Khamba	October 2006	Macro-model for ultrasonic machining of titanium and its alloys: designed experiments	1. Effect on Material Removal Rate by Material tool and type of slurry 2. Effect of Tool Wear Rate on Power ratings and Grit size of slurry 3. Effect on surface roughness due to slurry concentration and temperature	1. For the MRR, the power rating and type of tool were important factors, followed by slurry type. The best results were obtained with an SS tool at a 90 per cent power rating with boron carbide slurry. 2. As regards the TWR, the type of tool and the power rating were important factors followed by the grit size of the slurry. The optimized results were obtained with an SS tool at a 90 per cent power rating and a 500-grit size. 3. For the SR, the slurry temperature was most Important, followed by the slurry concentration and the type of tool. The best results were obtained at 25℃ at 25 per cent concentration with an SS tool.
5	R. Singh, J.S. Khamba	June 2007	Comparison of slurry effect on machining characteristics of titanium in ultrasonic drilling	Ultrasonic drilling of 5mm hole in pure (TITAN15, ASTM Gr2) and titanium alloy (TITAN31, ASTM Gr.5) with 6 setups. MRR and TWR and slurry and power rating are the variable used. **First set-up** with TITAN15 of SS Tool using alumina slurry of 320 grit Size and 15 % concentration.**Second set-up** with TITAN31 of SS tool with different slurry material and conc. **Third and fourth** covered TITAN15 and TITAN31 workpiece with Ti Tool. **Fifth & Sixth** covered TITAN15 & TITAN31 with HSS tool with different slurry material	1. Titanium is well machinable using ultrasonic drilling machine. 2. Best results have been obtained with SS tool and boron carbide slurry. 3. No major fatigue problems were encountered with the stainless steel, titanium and high-speed steel tool, any chipping/fracture generally being due to tool/hole misalignment during fabrication 4. The verification experiments revealed that on an average there was 34.46% improvement in MRR, for the selected work piece (TITAN15 and TITAN31).
6.	Jatinder Kumar & J. S.	September 2009	Modelling the material removal	1. Evaluation of S/N Ratio 2. Assessment of main effects	Aim of this research is to find out cost-effective machining of titaniumby USM andoptimising

	Khamba		rate in ultrasonic machining of titanium using dimensional analysis	3. Analysis of variance (ANOVA) 4. Prediction of mean 5. Micro structure analysis 6. Micro-model for prediction of MRR	theprocess parameter for MRR through Taguchi'stechnique for DOE. The following observation have been made from this research: 1. Optimum MRR in USM of titanium can be achieved byusing a tool material of higher hardness (cementedcarbide) along with a higher power rating (400 W),coarse grit size (220), and a hard abrasive (boron carbide) material. 2. With regards to the averageresponse, % contribution on powerrating 42%, abrasive type(21.3%) and slurry grit size (17.2%). Tool materialfactor on MRRwith %contribution of 13.7%. 3. USM is a very random process. Minor fluctuations inthe process variables such as slurry concentration cancause significant alteration in the results. 4. The outcome of the macro-model has been used for further development of a micro-model for predictionof MRR. 5. Ahigh input energy rate promotes the brittlefracture. For extremely small values of energy input, purelyductile failure mode was observed
7	A **R Machado,** BSc, MSc and J Wallbank, BSc, **MSc, PhD** Department of Engineering, University of Warwick, Coventry	February 1990	Machining of titanium and its alloys	Chip formation and effects of cutting, conditions specific machining problems, surface integrity, cutting temperature and stresses, tool wear rate	Titanium's chip is serrated and it is formed by a mechanism called 'catastrophic thermoplastic shear', intense shear occurring in the thin layers between the segments due to the rate of softening (caused by the highly localized temperature) being higher than the rate of work hardening. Dissolution-diffusion, attrition and plastic deformationfrequently predominate at the flank and craterareas of the tool, depending mainly on the cutting conditionsand tool material. Notch wear is mainly caused by a fracture process and/or chemical reaction The cutting temperature and the stresses during machining are high and dwell very near the cutting edge. The high cutting temperature is due to the heat generated during catastrophic thermoplastic shear, the thin chips, a thin secondary zone and a short chip tool contact length. The stresses are high due to the small contact area and the high strength of titanium even at elevated temperature.
8	N.J. Churi* and Z.J. Pei, C. Treadwell	2007	Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables	Spindle rotational speed Feedrate Vibration power supply Vibration frequency Effects on cutting force Grit Size Diamond Concentration Metal bond Type Effect of surface roughness of Hole	The effects of different tool variables (grit size, metal bond type and diamond concentration) on output variables (tool wear, cutting force, surface roughness) have been investigated. The tool with grit size of mesh #60/80 gives higher cutting force and surface roughness but lower tool wear compared to the tool with grit size of mesh #80/100. • The tool with lower diamond concentration (80) gives lower surface roughness and tool wear but higher cutting force compared to the tool with higher diamond concentration (100). • The tool with bond type B gives lower cutting force, surface roughness for rod and tool wear but higher surface roughness for hole compared to the tool withbond type C.
9	Jatinder Kumar J.S. Khamba S.K.Mohapatr a	2008	An investigation into the machining characteristics of titanium using ultrasonic machining	Material removal rate Tool wear rate Surface roughness	ANOVA (Analysis of variance) was performed on the response variables data produced from the experimentation approach was designed by using full factorials approach. Two-way interactions among tool and power rating, tool and grit size and grit size-power rating were also significant for MRR and TWR. The **MRR** titanium (ASTM Grade I) has been found to depend on the toolmaterial, grit size of the slurry used and power rating. Best results for MRRhave been obtained with high carbon steel, grit size 220 of the

					alumina slurryand power rating of 400 W. The **TWR** for titanium alloy (ASTM Grade V) is very less as compared to highcarbon steel as tool material. TWR has found to be maximum at the points of maximum MRR.Optimum results for TWR were obtained with titanium alloy as tool material,grit size 500 and power rating of 200 W. **Surface roughness(SR**) of the machined surface has been found to depend on gritsize of the slurry used. Tool material and power rating have negligible effecton SR. Optimum values for SR were obtainedwith grit size 500 for alumina for both tool materials.

III. CONCLUSIONS

1. Due to non-thermal process in Ultrasonic machining, this is also suitable for non-conductive and brittle and hardness above 40 HRC.
2. In order to drill especially small holes in titanium without damage of surface integrity specifically cracking is possible by using ultrasonic drilling. It is not necessary that machining of high toughness material has low material removal rate. The MRR is depends upon material composition (hardness, toughness, thermal conductivity) relative to the tool and work piece material.
3. Neither any fatigue problems were seen with the HSS tool, nor any chipping/fracture generally being due to tool/hole misalignment during fabrication.No deformation of the work piece material microstructure seen by using Ultrasonic drilling.Better surface finish is acquired when machining is carried out at low temperature (10 ◦C) than that of higher temperature at all Power Rating values.
4. The Horn and Tool design are very important in USM because they provide a resonance state in USM to maximize the material removal rate. Horn material should be corrosion resistant, strong enough to take screw attachment, have high toughness, good brazing characteristics, good acoustic transmission properties and high fatigue resistance at high working amplitude. The tightening of screw attachment with tool horn should be optimum, higher tightening results in to permanent ultrasonic welding of screw with horn. Acoustic washer of proper size and shape which is generally made up of copper or white metal should be used and to be replaced after every dismantling of tool/horn assembly for optimum MRR/TWR.
5. The hardness of abrasive used in slurry should always be greater than that of work piece material, moreover larger grit sizes of abrasive and slurry concentration improves the results in to higher MRR. As slurry concentration and slurry flowrate affects seriously to MRR and tool wear rate as well as tool life, so proper care of splashed slurry from tank due to high vibration of tool to be taken.
6. USM is assumed to be stress and damage free process,Incontour machining of workpiece it is required to automaticallyadjust the output high frequency to match exactresonant frequency of the tool assembly. Automatic adjustment of output frequency also eliminates the small errors in set up and tool wear, minimising acoustic energy loss and very small heat generation.
7. CNC programming is preferred in USM for making complex shape machining in the workpiece rather than die sinking with complex tool.Depending upon specific application of USM machining, tool material should possess properties like high wear resistance,good elastic and fatigue strength properties, and haveoptimum values of toughness and hardness.
8. The insert of the tool tip should be counter sunk in head ofscrew and for joint preparation silver brazing with filler rodwhich contains silver composition above 50% is generally usedfor high joint strength and better tool life. The optimum static load also plays a very important role in order to maximize MRR along with tool configuration (e.g. shape and cross-sectional area), the amplitude of vibration and mean grit size of abrasive.
9. The slurry acts as a coolant for the horn, tool andwork piece,supplies fresh abrasive to the cutting zone and removesdebris from the cutting area. The tool may crack from joint ifinadequate supply of slurry is there. It also provides a goodacoustic bond between the tool, abrasive and work piece,allowing efficient energy transfer.For efficient cooling of workpiece and tool, the transport medium for the abrasive should possess lowviscosity with a density approaching that of the abrasive,good wetting properties and, mostly, high thermal conductivityand specific heat is good for efficient cooling. Water is oneof best option as regard to transport media for slurry.

IV. FUTURE SCOPE

In Ultrasonic machining of Titanium alloy has significant issue in understanding of material removal rate during the machining process. Further study of material removal rate and better surface finish of machining product is still a challenge in the Ultrasonic machining process. Tool holder design, fixing of tool, slurry concentration and slurry type, size and shape also greatly influence the micro machining of Ultrasonic machining process. Environment aspect also greatly influence the material removal rate and accuracy and surface finish of machined component. The scope of Ultrasonic micro machining of micro channels in ceramics, in glass and in the area of fabrication of micro heat exchanger and sensors and in the area of fluidmechanics.

REFERENCES

[1]. Yan Cherng Lin, Biing Hwa Yan, Yong Song Chang Machining characteristics of titanium alloy (Ti±6Al±4V) using a combination process of EDM with USM,Department of Mechanical Engineering, National Central University, Chung-Li 320, Taiwan, Received 18 December 1998.

[2]. Jatinder Kumar and M.K. Muju, An assessment of the effect of tool properties, power rating and slurry size in ultrasonic machining of titanium International Conference on Theoretical, Applied, Computational and Experimental Mechanics, December 27-29, 2010, IIT Kharagpur, India, ICTACEM-2010/ (paper No. 183).

[3]. R. Singh, J.S. Khamba, Taguchi Technique for modelling material removal rate in ultrasonic machining of titanium, Received 1 September 2006; received in revised form 16 January 2007; accepted 25 January 2007, New York, 1987, pp. 67–86 [Chapter 6].

[4]. R Singhand J S Khamba Micromodel for ultrasonic machining of titaniumand its alloys:The manuscript was received on 27 March 2006 and was accepted after revision for publication on 30 October 2006.DOI: 10.1243/09544054JEM593.

[5]. R. Singha, J.S. Khamba Comparison of slurry effect on machining characteristics of titanium in ultrasonic drilling,2007 Elsevier B.V. All rights reserved. doi:10.1016/j.jmatprotec.2007.06.026.

[6]. Jatinder Kumar & J. S. Khamba, Modelling the material removal rate in ultrasonic machining of titanium using dimensional analysis Int J Adv Manuf Technol (2010) 48:103–119 DOI 10.1007/s00170-009-2287-1, Received: 21 June 2008 / Accepted: 27 August 2009 / Published online: 13 September 2009# Springer-Verlag London Limited 2009.

[7]. A R Machado, BSc, MSc and J Wallbank, BSc, MSc, PhD, Department of Engineering, University of Warwick, Coventry Machining of titanium and its alloys-a review Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 1990 204: 53, DOI: 10.1243/PIME_PROC_1990_204_047_02.

[8]. N.J. Churi and Z.J. Pei, Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA, C. Treadwell, President, Sonic-Mill Corporation, 7500 Bluewater Road NW, Albuquerque, NM 87121, USA, Rotary ultrasonic machining of titanium alloy (Ti-6Al-4V): effects of tool variables, Int. J. Precision Technology, Vol. 1, No. 1, 2007.

[9]. Jatinder Kumar, J.S. Khamba, S.K.Mohapatra, An investigation into the machining characteristics of titanium using ultrasonic machining, Int. J. Machining and Machinabiliy of Materials, Vol. 3, Nos. 1/2, 2008.