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Comparison of slurry effect on machining characteristics of titanium in ultrasonic drilling

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ABSTRACT

This paper initially reviews machining of titanium and its alloys with three different slurries (namely silicon carbide, boron carbide and alumina) and details background work on machinability of the same in ultrasonic drilling. Experimental research has been subsequently presented on the production of 5 mm diameter holes in pure titanium (TITAN15, ASTM Gr2) and titanium alloy (TITAN31, ASTM Gr.5) using ultrasonic drilling. This entailed the use of a 20 kHz piezoelectric transducer with three solid tools of stainless steel, titanium and high-speed steel, operating in silicon carbide, boron carbide and alumina slurry. The data presented includes main effect plots for material removal rate and tool wear rate. The results suggested that boron carbide slurry and stainless steel tool was giving best material removal rate. Also relative hardness of tool–work piece affects the material removal rate in ultrasonic machining.

1. Introduction

Titanium alloys are generally regarded as been amongst the most difficult of work piece materials to machine in spite of their relatively low hardness (e.g. Ti 6/4 annealed ~350 HV). This is due to their low thermal conductivity, which concentrates heat in the cutting zone (Ti 6/4 has a thermal conductivity of 11 W/mK for AISI 405 steel), high chemical reactivity at elevated temperature and a tendency to form localized shear bands. Titanium and its alloys are branded as difficult to machine materials (Verma et al., 2003). Unfortunately, the machining of titanium is in general more difficult and consequently a significant proportion of production costs may relate to machining, even though only small volumes of material may be removed. Titanium and its alloys are very popular and are very widely used in aerospace, marine gas turbine engines and surgical applications. Poor thermal conductivity of titanium alloys retard the dissipation of heat generated, creating, instead a very high temperature at the tool–work piece interface and adversely affecting the tool life (Dornfeld et al., 1999). Titanium is chemically reactive at elevated temperature and therefore the tool material either rapidly dissolves or chemically reacts during the machining process resulting in chipping and premature tool failure (Verma et al., 2003). Compounding of these characteristics is the low elastic modulus of titanium, which permits greater

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deflection of the work piece and once again adds to the complexity of machining these alloys (SME, 1985). The conventional machining processes thus are unable to provide good machining characteristics on titanium alloys. Commercially these alloys are machined by electric discharge machining, which is giving good material removal rate however accuracy and surface finish are some problematic area. Another non-conventional machining process that is ultrasonic drilling is widely used nowadays for both conductive and non-metallic materials; preferably those with low ductility (Koval Chenko et al., 1986; Kremer et al., 1988; Moreland, 1988) and hardness above 40 HRC (Verma et al., 2003; Dornfeld et al., 1999; Ezugwa and Wang, 1997; Gilmore, 1990), e.g. inorganic glasses, silicon nitride, etc. (Thoe et al., 1998; IMS, 2002; Khamba and Singh Rupinder, 2003; Benedict Gary, 1987; Haslehurst, 1981; Pentland and Ektermanis, 1965). In this process tool is made of tough material, oscillated at frequencies of the order of 20–30 Kc/s with amplitude of about 0.02 mm. An abrasive filled fluid flushed through the gap between master and work piece. The material removal mechanism involves both erosion and grinding (Benedict Gary, 1987). The principle of stationary ultrasonic drilling has been shown in Fig. 1.The tiny abrasive chip off microscopic flakes and grinds a counterpart of face. The work material is not stressed, distorted or heated because the grinding force is seldom over 2 lb (IMS, 2002). There is never any tool to work contact, and presence of cool slurry makes this a cold cutting-process.

The tool used for machining has been prepared by silver brazing process (Singh, 2002). The amplitude of vibrations given to the tool also influences the cutting rate (Khamba and Singh Rupinder, 2003). It has been found that the material removal rate is affected by amplitude of oscillations, size of abrasive (Singh, 2002; Singh and Khamba, 2007a). There are number of applications of ultrasonic drilling, ranging from the fabrication of small holes in alumina substrates, to engraving glassware, to drilling large holes through laser blocks (IMS, 2002). Fig. 2 shows the three-dimensional view of ultrasonic drilling using either a magnetostrictive or piezoelectric transducer with brazed and screwed tooling. It has been observed in experimentation using alumina as slurry and TITAN15 as work material, material removal rate first decreases with in increase in power rating (from 150 W to 300 W) and than increases from 300 W to 450 W of ultrasonic drilling machine (USM) (Khamba and Singh Rupinder, 2003).

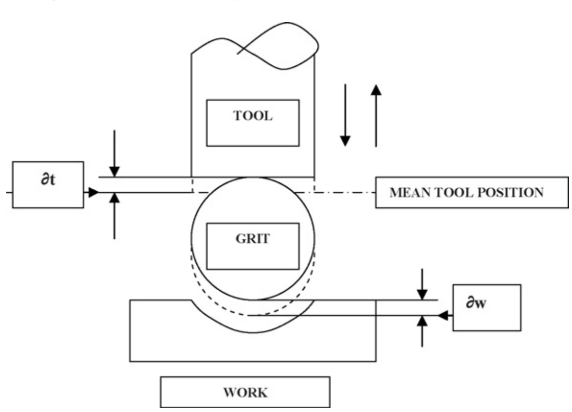

Fig. 1 – Schematic diagram of ultrasonic drilling, ∂t = penetration in to tool, ∂w = penetration in to work piece.

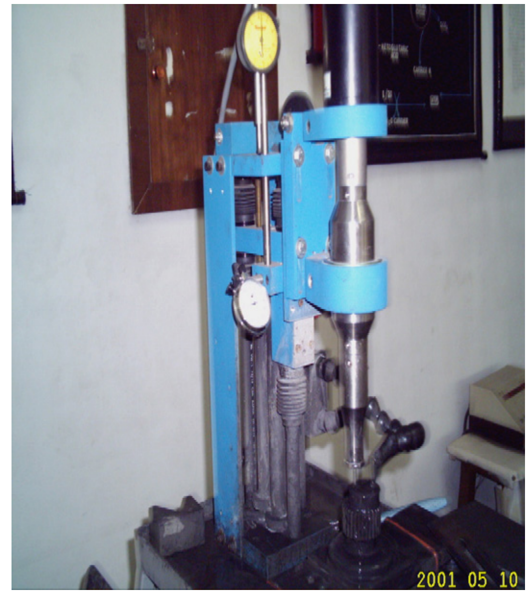

Fig. 2 – Three-dimensional pictorial view of USM.

In the present experimental set-up the typical value of amplitude and frequency of vibration used were 0.0253–0.0258 mm and 20 kHz ± 200 Hz. This experimental study has been conducted with the objective to understand material removal rate and tool wear rate comparison of TITAN15 and TITAN31 (having different composition, different toughness) when drilled ultrasonically; with three different types of slurries, namely silicon carbide (SiC), boron carbide (B_4C), and alumina (Al_2O_3) (each of 320 grit size). The pure titanium TITAN15, has ultimate tensile strength of 491 MPa (chemical analysis: C, 0.006%; H, 0.0007%; N, 0.014%; O, 0.140%; Fe, 0.05%; Ti, balance) and titanium alloy TITAN31, has ultimate tensile strength of 994 MPa (chemical analysis: C, 0.019%; H, 0.0011%; N, 0.007%; O, 0.138%; Al, 6.27%; V, 4.04%; Fe, 0.05%; Ti, balance).

The machining was performed on 500 W Sonic-Mill, ultrasonic drilling machine at three different power ratings (i.e. at 150 W, 300 W and 450 W), based upon pilot experimentation. Three conventional tool materials namely stainless steel (SS), titanium (Ti) and high-speed steel (HSS) have been used as tool combinations with titanium as work material to find out material removal rate (MRRs) and tool wear rate (TWR) at fix slurry concentration and temperature. The slurry concentration was fixed at 15 vol.% and slurry temperature at 25.7 °C (room temperature). An experimental set-up having a provision for variation in the process parameters was designed and fabricated. Fig. 3 shows work piece dimensions. The dimensions of the tool were decided keeping in view the limitations of the 'horn shape' to economize the machining operation (Fig. 4).

2. Experimentation

The experiments have been conducted in six set-ups. In the first set-up, experiment was performed to determine the effect

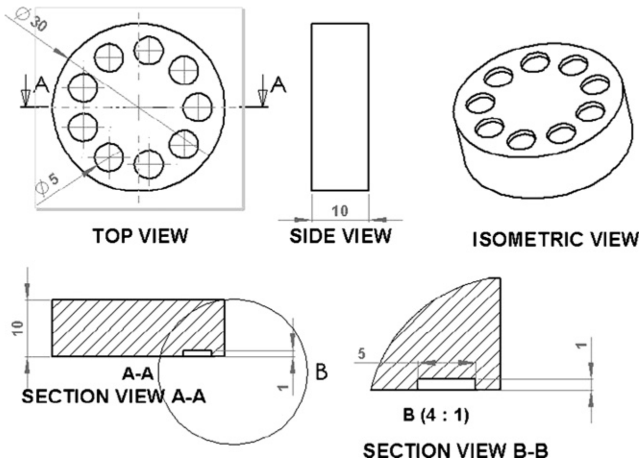

Fig. 3 – Detailed drawing of the work piece.

on 'TITAN15 of SS tool' using alumina slurry of 320 grit size; at 15% concentration in distilled water as suspension media. The experiment started by setting power rating of the machine at (30% of 500 W) 150 W of ultrasonic drilling machine. The initial weight of titanium work piece 'that is of TITAN15' and tool 'that is of SS' was measured. Then machine was allowed to drill for fixed depth of 1 mm with constant slurry flow rate and slurry temperature. The depth was closely watched using dial gauge. Correspondingly, time taken by USM for drilling was measured using stopwatch. After machining was completed, work piece and tool weight was measured for finding difference in weight loss.

Corresponding material removal rate and tool wear rate were calculated at 150 W, 300 W, and 450 W (30%, 60% and 90% of 500 W). In the first set-up two more experiments were set using 'TITAN15 work piece SS tool' with B_4C slurry and SiC slurry, respectively. Fig. 5 shows the trend of MRR and TWR of TITAN15 work material with SS tool at different power rating of machine used.

The second set-up involved machining of 'TITAN31 work piece by SS tool' at three settings of ultrasonic power rating

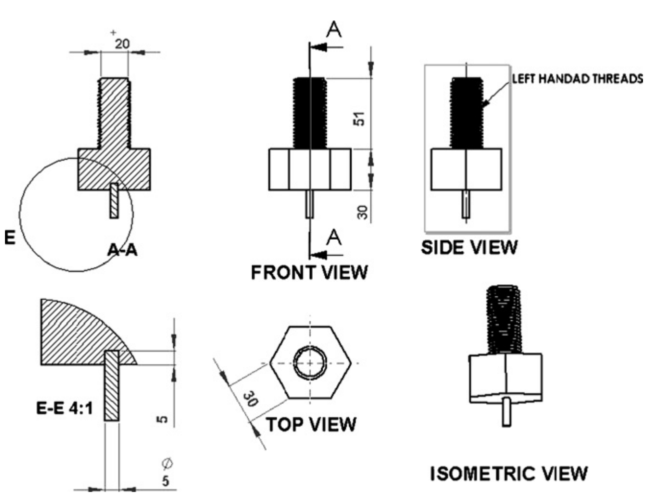

Fig. 4 – Detailed drawing of the tool geometry (Singh and Khamba, 2007a,b).

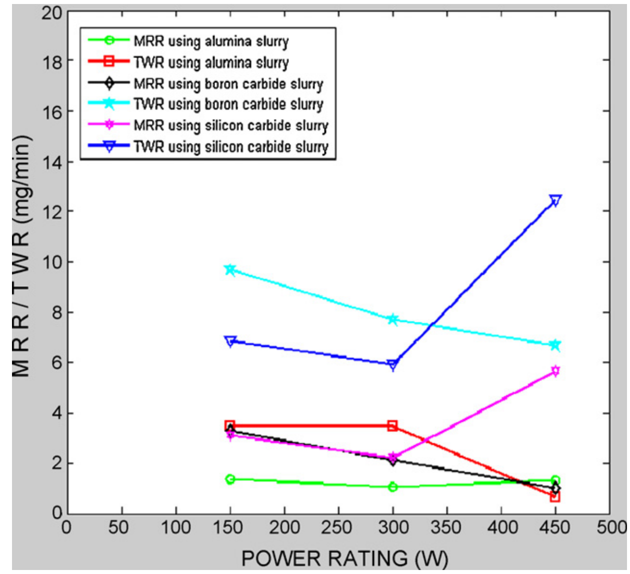

Fig. 5 – MRR and TWR vs. power rating using (W/P TITAN15 and tool SS).

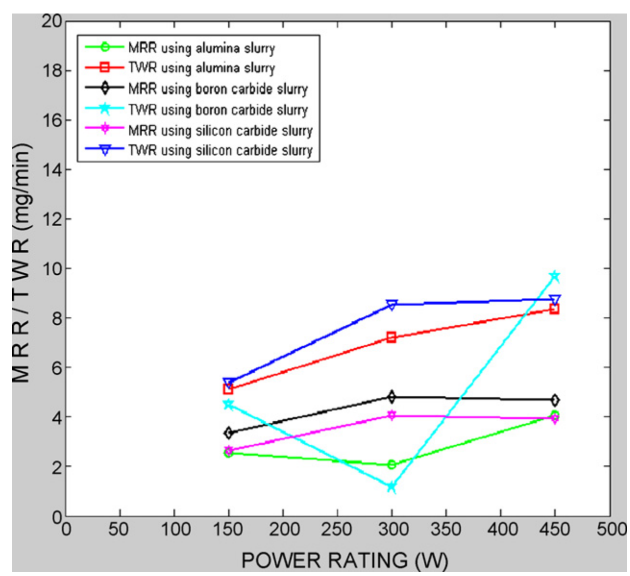

Fig. 6 – MRR and TWR vs. power rating using (W/P TITAN31 and tool SS).

with Al_2O_3, B_4C and SiC slurry. Corresponding MRR and TWR were plotted (refer Fig. 6). The third and fourth set-up covered machining of 'TITAN15 and TITAN31 work piece by Ti tool' at three settings of ultrasonic power rating with Al_2O_3, B_4C and SiC slurry. Corresponding MRR and TWR were plotted (refer Figs. 7 and 8).

In the fifth and sixth set-up machining of 'TITAN15 and TITAN31 work piece by HSS tool' at three settings of ultrasonic power rating with Al_2O_3, B_4C and SiC slurry has been performed. Corresponding MRR and TWR were plotted (refer Figs. 9 and 10).

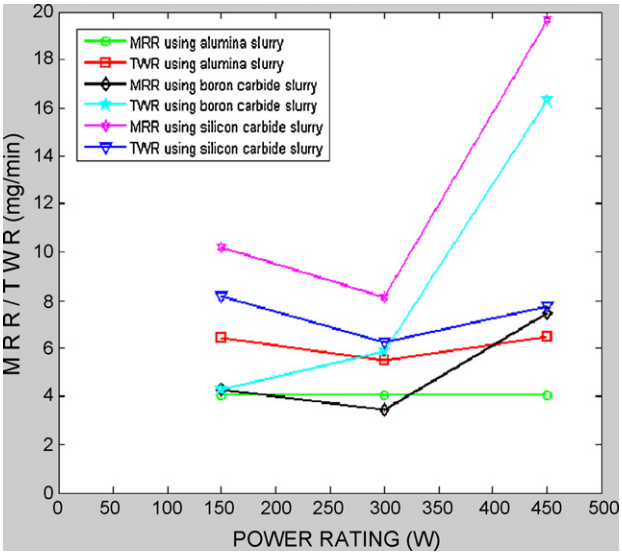

Fig. 7 – MRR and TWR vs. power rating using (W/P TITAN15 and tool Ti).

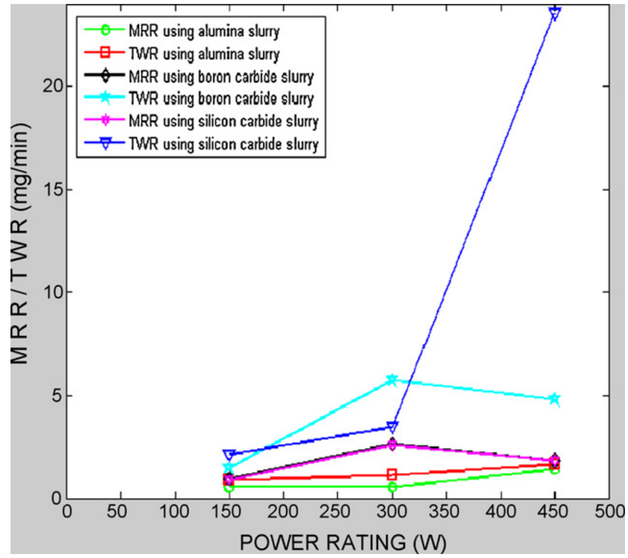

Fig. 9 – MRR and TWR vs. power rating using (W/P TITAN15 and tool HSS).

3. Results and discussion

From repetitive number of experiments conducted under six different set-ups, the comparative results have been plotted. From Fig. 5, it has been observed that MRR of TITAN15 is overall lower than TWR while using SS tool with Al_2O_3 slurry. However trend for MRR in all three experiments of first set-up were similar. The increase of MRR with increase in power rating of machine is quite obvious because of higher value of power rating abrasive particles strikes with more momentum and kinetic energy with work piece. Hence more erosion of work piece but in certain cases, with increase in power rating, MRR decreases which may be because of strain hardening of work piece. The increase of tool wear rate with increase in MRR and power rating is quite obvious but sometimes TWR decreases with power rating increase/increase in MRR; the reason for this is again strain hardening of tool surface. The selection of slurry type for MRR of 'TITAN15' in this case comes out as unimportant factor. However better tool properties were obtained with Al_2O_3 slurry.

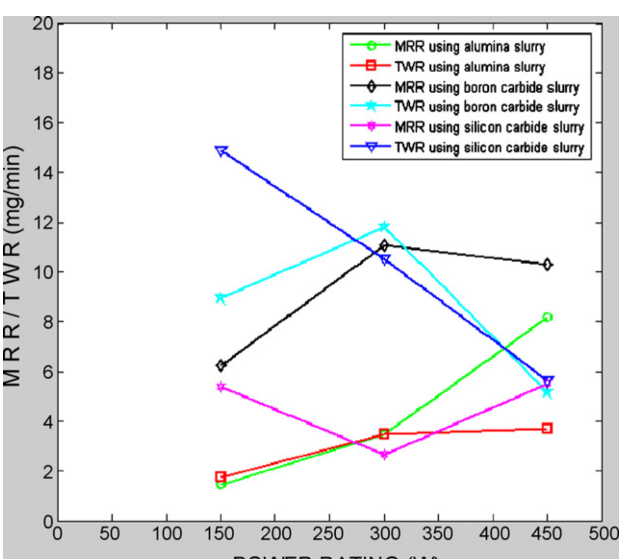

Fig. 8 – MRR and TWR vs. power rating using (W/P TITAN31 and tool Ti).

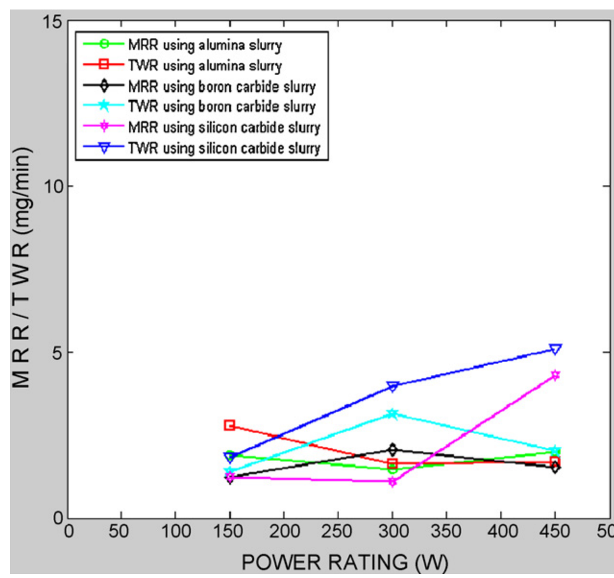

Fig. 10 – MRR and TWR vs. power rating using (W/P TITAN31 and tool HSS).

As regards to machining of 'TITAN31 with SS tool' the trend for MRR and TWR were different from previous case of 'TITAN15 with SS tool' (refer Fig. 6). The main reason for this variation may be strain hardening of work piece/tool material at specific ultrasonic power rating based upon its material/chemical composition characteristics. The best parameter setting for machining of 'TITAN31 with SS tool' has been observed at 300 W with B_4C slurry.

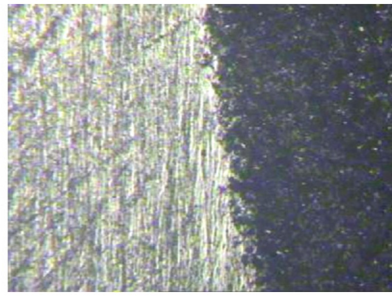

Fig. 11 – Photomicrograph of the machined surface showing comparison of the conventional machining and ultrasonic machining; magnification: 100×. Ultrasonic machined surface (Ra 0.46), conventionally machined surface (Ra 0.8).

In the next set-up while using titanium tool it has been found that for 'TITAN15'; MRR showed insignificant effect of slurry type, where as for 'TITAN31' choice of slurry has come out as important factor. The best settings have been attained with B_4C slurry at 300 W for 'TITAN31'.

The fifth and sixth set-up highlighted machining with 'HSS tool' for 'TITAN15 and ITAN31' work piece. The trend obtained for MRR and TWR in fifth and sixth set-ups is almost similar for Al_2O_3 and B_4C slurry, but for SiC some variation has been observed. Overall B_4C slurry comes out as better option. This may be because of better work piece and tool combinations based on relative hardness of tool and work piece for specific machining conditions.

Fig. 11 shows the surface of an ultrasonically machined titanium sample exhibits a non-directional surface texture when compared with a conventionally machined (ground) surface. These refined grain structure, resulting from ultrasonic machining, can give better strength and mechanical properties. The results agree with experimental observations made otherwise (Singh and Khamba, 2006, 2007b; Jadoun et al., 2006).

4. Conclusions

From the experiment following conclusions can be drawn:

1. Titanium is well machinable using ultrasonic drilling machine. It is not always necessary that if work piece with higher toughness value is machined, it will have less MRR rather it is combination effect of material composition (hardness of work piece) relative of tool and work piece. Less TWR and better MRR can be attained by using specific tool, work piece combination at specific power rating values and controlled experimental conditions like slurry type.
2. Best results have been obtained with SS tool and boron carbide slurry. These results show close relationship between the experimental observations made otherwise (Singh and Khamba, 2007b).
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).

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