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Exploring grindability of Ti-6Al-4V using an indigenously developed environment friendly micro pump based cooling system

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Titanium alloys are ideally suited for different manufacturing applications because of their unique combination of high specific strength over a wide range of temperature, in addition to excellent corrosion resistance properties. However, grinding of titanium alloys is quite difficult due to their high hardness at elevated temperature, low thermal conductivity and elastic modulus. Application of cutting fluid helps to improve grindability, but with the increasing level of environmental consciousness, new technologies have been required to address the problem. This investigation deals with application of alkaline soap water through an indigenously developed micro pump based cooling system during grinding of Ti-6Al-4V. Comparison has been made with dry grinding with respect to some response parameters such as grinding forces, specific energy, surface roughness, grinding chips and ground surface morphology. Results have indicated that grinding forces, specific energy requirement and surface roughness decrease with the application of the micro pump based system. Observation of grinding ratio, chip form and ground surface has shown favourable results. Therefore, this newly developed micro pump system may be recommended to supply soap water for grinding titanium alloys.

Keywords: Grinding, Ti-6Al-4V alloy, Grinding force, Grinding ratio, Surface roughness, Micro pump

1 Introduction

Grinding is a finishing, or semi-finishing, process generally used to shape and finish components made of metals and other materials. Precision and surface finish obtained through grinding can be up to ten times better than that of other conventional machining processes like turning or milling[1,2]. Grinding employs an abrasive tool, usually in the form of a rotating wheel brought into controlled contact with the work surface[3,4].

Rapid advancement of science and technology has called for a great variety of materials with diversified properties, and various new materials such as hardened steel, titanium alloys, nickel based alloys, *etc.* have been developed and applied continuously. Among these materials, Titanium and its alloys are widely employed in manufacturing industry. Titanium alloy is of high strength-to-weight ratio with superior fatigue strength. These alloys have recently received considerable amount of attention due to their wide range of applications in the automotive, aerospace, medical and chemical industries. Titanium alloy, Ti6Al4V, accounts for more than 50% of the titanium alloy production[5,6]. These materials are generally difficult to machine, and machining of these materials is always a big challenge to a machinist[7]. Machining and grinding of titanium and its alloys are difficult due to their chemical reactivity beyond 350 °C, low thermal conductivity and high hot strength[8]. Some special techniques like multi-nozzle cooling, application of pneumatic barriers, using painted wheels, or rexine-pasted, wheel can help facilitate grinding of titanium alloys[9-13].

Grinding requires high energy per unit volume of material removed. Virtually most of this energy is spent as heat[14]. A large amount of heat generated while machining titanium alloy Ti-6Al-4V is conducted to the tool since it cannot be removed with the fast flowing chip or to the workpiece due to low thermal conductivity of titanium alloys, which is about 1/6th that of steels[15]. Mukhopadhyay *et al.*[16] observed that with an increase of in feed during grinding of titanium alloys, problems associated with high temperature increases significantly. In metal cutting processes, use of cutting fluid is a most common strategy to improve tool life, surface finish and dimensional accuracy. However, introduction cutting fluid often produces airborne diseases through the formation of mist, smoke, and other particulates in the shop floor. Therefore, these are associated with

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environmental, health, and safety concerns. Disposal of these cutting fluids also needs appropriate treatments[17-21]. Cost associated with application of cutting fluid is also high. Weinert *et al.*[22] referred the cost related to the use of cutting fluid to be from 7-17% of total cost of the manufactured workpiece. In order to address these problems, MQL (minimum quantity lubrication), or SQL (small quantity lubrication), might be a good solution. MQL, or SQL, reduces the use of cutting fluid to a level up to which the cutting fluid serves its function. Wojcik[23] proved that alkaline based cutting fluid was better suited for grinding of Ti-6Al-4V than any other conventional cutting fluids. The cutting fluid used was proved to be beneficial in past research works[24].

This experimental work concentrates on investigating grindability of Ti-6Al-4V with the implementation of an indigenously developed environment-friendly micro pump based cooling system used to pump environment friendly alkaline soap water as cutting fluid to reduce the use of cutting fluid to a great extent. This cooling technique has proved to be significant in order to improve grindability of titanium alloy compared to flood cooling condition as demonstrated and reported by Mukhopadhyay and Kundu[25]. Teicher *et al.*[24] and Mukhopadhyay *et al.*[26] also suggested that non-conventional metalworking fluids like soap water, vegetable oil, *etc.* are more favourable than convention synthetic coolants for grinding Ti-6Al-4V that justifies the use of alkaline soap water for the experimental setup.

2 Experimental setup and Measurement

Experiments are carried out on a surface grinding machine of HMT Praga division. Force readings are taken for 20 up-grinding passes for two sets of experiments under identical conditions at 10 μm grinding in feed (depth of cut). A strain gauge type dynamometer (Make: Sushma Industries, Bangalore) is used to measure grinding force. Grinding chip and ground surface morphology are observed under stereo microscope. Surface roughness values are measured with the help of a portable surface roughness tester (Mitutoyo, Japan make). Details of experimental condition and equipment used are provided in Table 1. To avoid the non-homogeneity in the workpieces that might have crept in due to its manufacturing process, test samples were cut out from a single parent base plate.

Table 1 — Experimental conditions and equipment used.

Surface Grinding Machine	Make : HMT Praga Division, India; Model : 452 P Infeed Resolution :1 μm; Main Motor Power : 1.5 kW Maximum Spindle Speed : 2800 rpm
Grinding Wheel	Make :Carborundum Universal limited, India Type : Disc Type; Specification : CGC 60 K 5 V Size :Φ200 OD× Φ31.75 Bore× 20Thk
Workpiece	Material : Ti-6Al-4V; Hardness : 33 HRC; Dimension : 120 mm × 60 mm × 6 mm; Composition (by weight): Ti– 88.77%; Al– 6.19%;V– 4.25%; Fe– 0.34%
Environment	• Dry • Wet (using coolant delivered by a micro pump Type : Jet using micro pump Pump : Make– Sobo, India; Power : 10 W Nozzle diameter : 1.21 mm; Coolant : Soap Water Mixture : Clinic plus shampoo and water Mixing ratio : 1:20; Flow rate : 210 ml/min
Force dynamometer	Make : Sushma Grinding Dynamometer, Bengaluru, India Model : SA 116 Range : 0.1 – 100 kg; Resolution : 0.1 kg
Wheel Dresser	Make : Solar, India Specification : 0.5 carat Single Point Diamond Tip Dressing Infeed/depth : 20 μm Dressing Speed: 0.03 m/s
Surface Roughness Tester	Make : Mitutoyo, Japan; Model : Surftest 301 Range : 0.05 – 40 μm; Resolution : 0.05 μm
Stereo Microscope	Make : Gippon, Japan Magnification : 20x to 40x

Figure 1 shows the micro pump setup used to deliver alkaline soap water in to the grinding zone. The coolant enters the grinding zone in form of a jet (coming out through a nozzle of 1.21 mm internal diameter) penetrating the stiff air layer around the grinding wheel. Fluid pressure exerted by the micro pump is expected to sucessfully overcome the stiff air layer to reach the grinding zone. The used coolant is made to flow into the sump and the fluid is continuously recycled after suitable filtration.

3 Experimental Results and Discussion

The following section deals with the results obtained for different experiments performed under dry and wet conditions.

3.1 Grinding Forces

Grinding force is an important criterion for finding the grindability of a particular material. Grinding force is directly related to all other significant parameters in grinding like specific energy, heat generation, surface roughness, ground surface quality, etc. Tangential (F_t) and normal force (F_n) values were recorded by a strain gauge based dynamometer for each of the 20 passes during different grinding experiment. Figure 2 and Fig. 3 show the plots of grinding forces for the two conditions for two sets of replications. Figure 2 and Fig. 3 show that tangential force (F_t) is lower than normal force (F_n) naturally. This is likely due to high negative rake angles of the randomly oriented grits which result in higher rubbing and ploughing action. It is also observed that grinding forces gradually increase for the initial few passes because full infeed does not come in action due to stiffness present in the system. This effect gets eliminated after initial few passes.

It can easily be seen that with the introduction of micro pump based cooling system, grinding forces are reduced remarkably. This may be due to the fact that

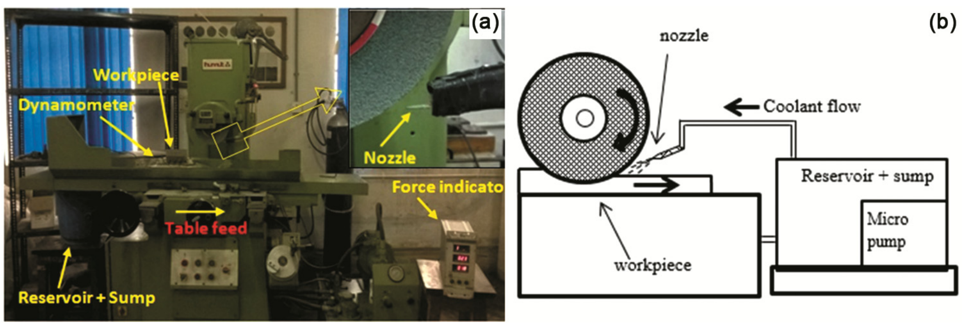

Fig. 1 — Micro pump setup.

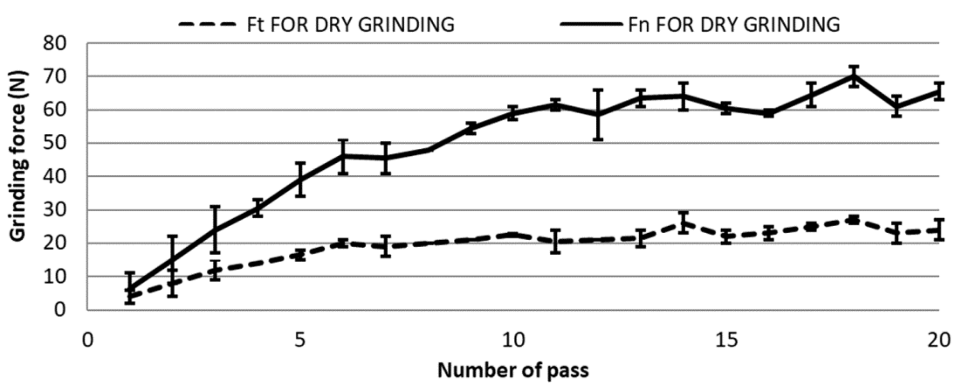

Fig. 2 — Plot of grinding forces of Ti-6Al-4V under dry grinding at 10 micron infeed for replication 1 and 2 of experiments.

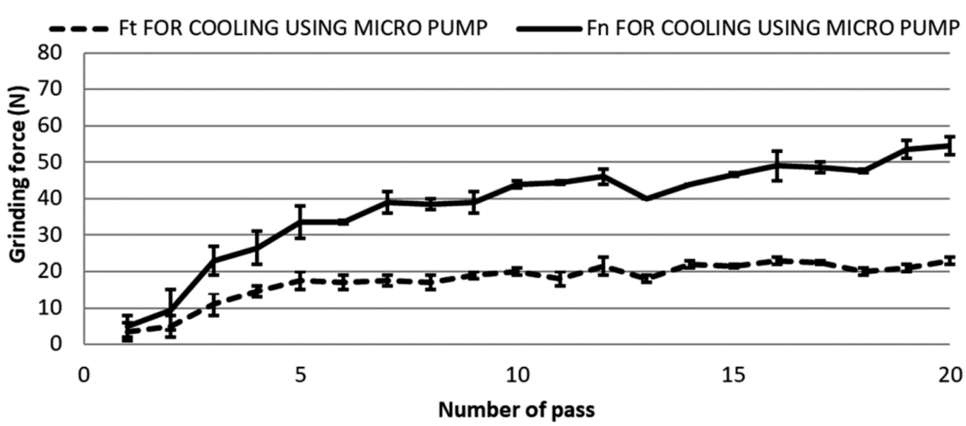

Fig. 3 — Plot of grinding forces of Ti-6Al-4V while grinding with MQL using micro pump at 10 micron infeed for replication 1 and 2 of experiments.

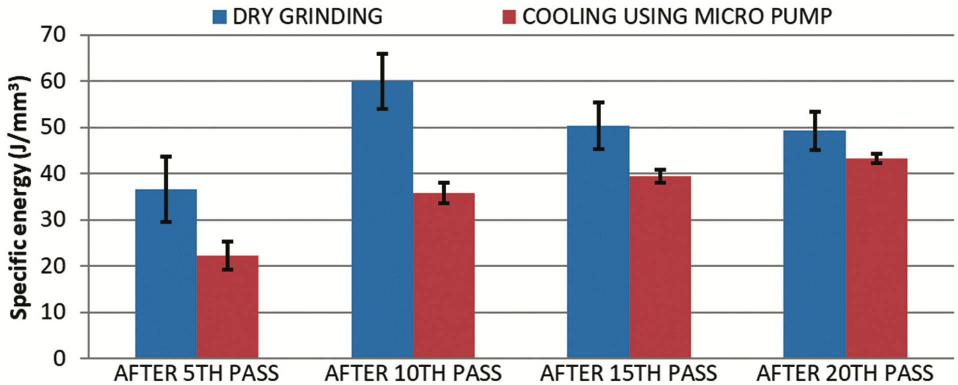

Fig. 4 — Plot of specific energy of Ti-6Al-4V for different cooling conditions at 10 micron infeed for replication 1 and 2 of experiments.

with the application of cutting fluid delivered by the micro pump in the form of a jet, it is able to penetrate the stiff air layer around the grinding wheel and effectively reaches deep inside the grinding zone. It provides considerable amount of cooling and lubrication to the grinding zone, thus effectively reducing grinding forces.

3.2 Specific Energy

Specific energy requirement is comparatively higher in grinding than other machining operations. This may be due to large number of randomly distributed grits having high negative rake angles taking part in grinding operation. This results in more rubbing and ploughing action rather than shearing. Figure 4 shows the plot of specific energy requirement after every 5 passes for all the experiments considered here. Specific energy in J/m^3 is calculated using the following relationship:

$$\text{Specific grinding energy} = \frac{F_t \times V_{wh}}{b \times d \times V_w} \quad \ldots(1)$$

where, F_t= Tangential force (N)
V_{wh}= Velocity of grinding wheel (m/s)
b = Width of workpiece (mm)
d = Actual depth of material removal (micron)
V_w = Table feed (m/s)

From figure 4, it can be clearly seen that specific energy requirement in grinding using micro pump based cooling system is always lesser than that in dry grinding. This is due to the fact that with proper cooling and lubrication provided by the coolant pumped through micro pump based cooling system results in reduction of frictional force. Efficient cooling and chip flushing provided by the coolant jet also restricts wheel loading, retains grit sharpness and thereby improving shearing action during grinding.

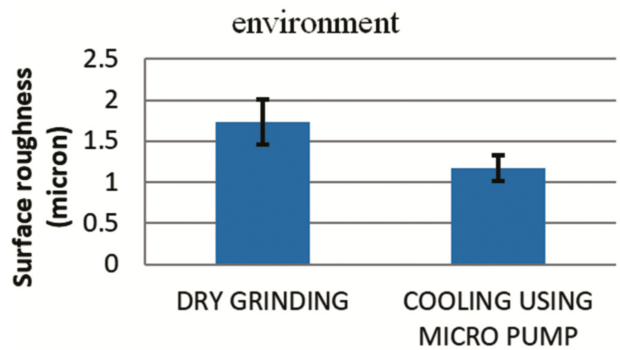

Fig. 5 — Plot of average surface roughness of Ti-6Al-4V for different environmental conditions at 10 micron infeed for replication 1 and 2 of experiments after 20 passes.

3.3 Surface Roughness

Grinding is a finishing, or semi finishing, operation, and surface roughness is an important parameter for assessing grindability. In this experimental investigation, average surface roughness (Ra) value is measured after 20 grinding passes for each experiment. Figure 5 shows surface roughness values for each set of experiments measured with the help of a portable surface roughness tester. Surface roughness value shown here is an average of five different values taken on the ground surface, perpendicular to grinding lay marks. From Figure 5, it can be clearly seen that introduction of micro pump-based cooling system improves surface quality to a good extent. Suppression of chip redeposition due to decrease in friction force by applying cutting fluid through micro pump system may be the possible reason behind.

3.4 Grinding Ratio

Grinding ratio, or simply G-ratio, is defined as the ratio of volume of work material removal to volume of wheel material removal. Figure 6 indicates grinding ratio for Ti-6Al-4V at both environmental conditions. Grinding ratio achieved is much higher in case of grinding using micro pump-based cooling system compared to dry grinding. This is again due to better penetration of the cutting fluid into the grinding zone because of high velocity of the jet providing much better cooling and lubrication effect which reduces friction and wheel loading preventing grit dislodgement from the wheel.

3.5 Chip Study and Surface Morphology

Ground surface morphology and chip forms are other important factors for assessing the grindability of a particular work material. Figure 7 and Fig. 8 show the chip morphology and ground surface form observed under different conditions respectively.

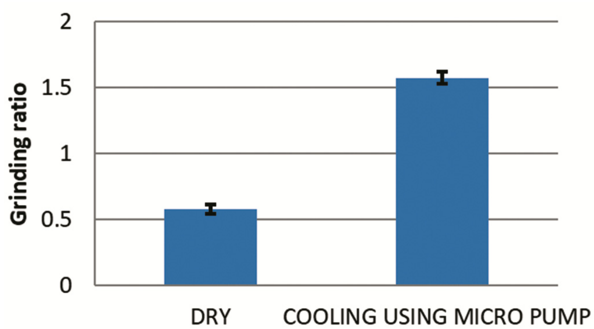

Fig. 6 — Plot of grinding ratio of Ti-6Al-4V for different environmental condition at 10 micron infeed for replication 1 and 2 of experiments after 20 passes.

From both Figure 7 and Figure 8, positive effects of micro pump-based cooling system can be amply observed. Considering chip forms, it can be seen that during dry grinding large blocky chips are obtained which shows higher wheel loading, but application of micro pump-based cooling system has resulted in formation of favourable thin leafy and curled chips suggesting predominant shearing action. During dry grinding, due to excessive heat generation, abrasive grits undergo high rate of wearing and lose its sharp cutting edges. This effect along with wheel loading results in generation of blocky chips[3,14]. However, with effective and efficient application of coolant through micro pump setup, temperature rise is significantly controlled. This leads to make brittle fracture to be the main reason of wheel material removal forming sharp cutting edged abrasive grits which promotes shearing[3,14].

Surface form observed also gives the impression that micro pump based delivery system proves to be much better than dry grinding. During dry grinding, chip re-deposition and crater are observed on the surface suggesting poor surface finish, but with the introduction of coolant through micro pump, smooth

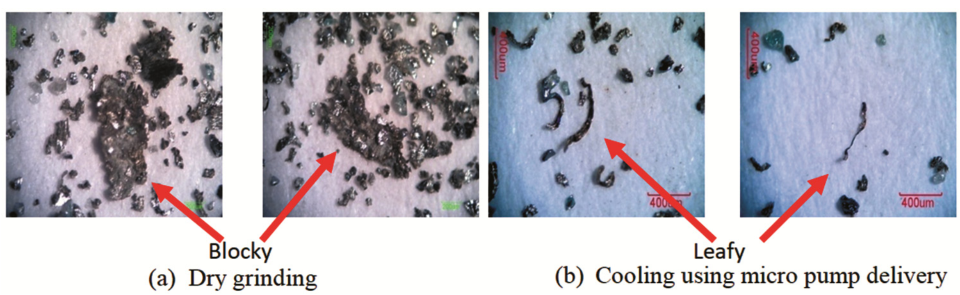

Fig. 7 — Chip form observed during grinding of Ti-6Al-4V for different environmental condition at 10 micron infeed for replication 1 and 2 of experiments for 18th to 20th passes.

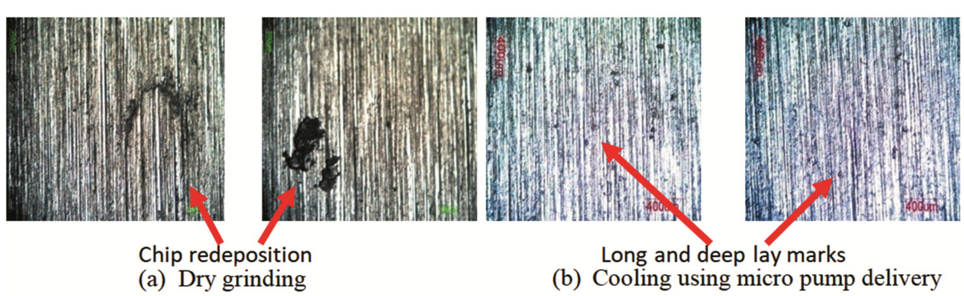

Fig. 8 — Ground surface form observed during grinding of Ti-6Al-4V for different environmental condition at 10 micron infeed for replication 1 and 2 of experiments for 18th to 20th passes.

surface having long and deep lay marks, free from any visual defects, is observed.

4 Conclusions

In the present experimental work, effect of application of cutting fluid through indigenously developed micro pump based delivery system is observed during grinding of Ti-6Al-4V using a silicon carbide wheel.

(i) The results obtained suggests that the new scoolant delivery technique introduced efficiently controls grinding forces, reduces specific energy consumption, improves surface finish and grinding ratio and gives better finish of ground surface.

(ii) The system not only proved its effectiveness in improving grindability but is also economic and environment-friendly.

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