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An experimental study on an indigenously developed ultrasonic vibration assisted minimum quantity lubrication during grinding of Ti-6Al-4V alloy

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Abstract

Minimum quantity lubrication (MQL) is an efficient cooling and lubrication technique widely used in machining and grinding owing to its advantages in terms of better cooling, lubrication, and lower coolant consumption. In MQL grinding, a small quantity of cutting fluid is air-atomized to generate fine liquid droplets, and they are injected into the grinding zone. The effectiveness of MQL system depends on the quality of these droplets. Ultrasonic vibrations can be used to effectively atomize the cutting fluid into fine and uniform sized droplets. In this study, an ultrasonic MQL set up is indigenously developed to generate fine droplets of the cutting fluid using the ultrasonic vibration of a suitably designed horn. A set of experiments have been conducted on Ti-6Al-4V alloy during surface grinding operation with the developed setup, and the results have been compared with dry, flood and air-assisted conventional MQL grinding process. The fine droplets produced by ultrasonic vibration penetrate effectively into the grinding zone and cover the larger surface area at the wheel-workpiece interface. This phenomenon enhances the cooling-lubrication characteristic in the grinding zone and results in retention of abrasive grit sharpness for a longer duration. The results obtained during ultrasonic MQL grinding experiments show that the grinding forces have reduced significantly and the surface roughness has improved compared to dry, flood and conventional MQL grinding.

Keywords: Ultrasonic atomization, minimum quantity lubrication, grinding force, surface finish.

1. INTRODUCTION

Ti-6Al-4V is an important and widely used titanium-based alloy in many engineering applications. It is used for `making important components in aerospace, chemical, power and medical industries due to its higher strength-to-weight ratio, relatively lower density, and excellent corrosion resistance**.** However, Ti-6Al-4V is classified as “difficult-to-machine material” because of its unique characteristics such as low modulus of elasticity as well as thermal conductivity and high chemical reactivity [1]. The lower thermal conductivity and chemical affinity of this alloy adversely affect the quality of products during the grinding process. Grinding is a high-energy consumption process that generates a substantial amount of heat in the grinding zone. This huge amount of heat can cause thermal damage to the ground surface. In grinding of Ti-6Al-4V, the problems of surface burning, generation of thermal stress, thermal wear of grinding wheel, redeposition of grinding chips and chip adhesion on the wheel are commonly observed [2]. Up to a certain extent, these problems can be controlled with the use of cutting/grinding fluids. These grinding fluids have been used in flood or wet cooling mode in which a large amount of the fluid is injected into the grinding zone. However, in wet cooling, only a fraction of the grinding fluid is useful. Hence, wet cooling is a costly, ineffective and non-environment friendly means of grinding. This has led to an emergence of the relatively new concept of coolant application known as Minimum quantity lubrication (MQL). This technique has been suggested by several researchers for improved cooling and lubricating effect during grinding of various engineering materials [3-5]. In this technique, a very limited quantity of cutting fluid mixed with compressed air is injected into the machining zone. MQL appears to be a very popular and useful technique in the machining of engineering materials Tawakoli et al. [5] investigated MQL grinding of 100Cr6 hardened steel and 42CrMo4 soft steel using an air-oil mixture fed into the wheel-work mating zone. They measured the grinding performances in terms of grinding forces and surface quality properties. They concluded that the MQL grinding substantially enhances cutting performance in terms of increasing wheel life and improves the quality of the ground part as compared to dry grinding. The performance of MQL mainly depends upon the level of atomization of the cutting fluid into fine and small droplets. Park et al. [6] and Chetan et al. [7] have conducted an extensive study to investigate the droplet size and their distribution during MQL using air pressure nozzle to atomize the cutting fluid. They reported that the conventional MQL system produces a nonuniform droplet size and distribution of the cutting fluid. The variation in droplet size and distribution mainly depends upon the air pressure, nozzle distance and flow rate of cutting fluid. The atomization of grinding fluid into fine droplets and their uniform distribution results in covering a larger surface area which significantly improves the cooling and lubrication phenomena in grinding. Ultrasonic atomization of the cutting fluid is a relatively newer concept in which a cutting fluid gets atomized into ultra-fine liquid droplets using the ultrasonic vibrations. Ultrasonic atomization produces liquid droplets finer than those produced by a spray nozzle and can diffuse the droplets into the gas phase without significant thermal change compared with other atomization techniques [8]. Using this technique, the diameter of the mist can also be controlled by changing the frequency of the ultrasonic transducer. The sizes of these liquid particles are much smaller and uniform than those produced in conventional MQL condition. Jun et al. [9] developed a cutting fluid application system using ultrasonic vibration as the atomization mechanism in the micro-end milling of aluminium 7075. They compared the performance of the developed system for machinability enhancement of the material with dry and flood cooling conditions. They concluded that the ultrasonic atomized cutting fluids are effective in increasing tool life in micro-milling operations. Ishimatsu et al. [10] studied the effect of fluid excited by ultrasonic vibration in grinding of aluminium and alloy tool steel. They set the ultrasonic exciter which applies vibration energy on grinding fluid between the fluid supplying nozzle and grinding wheel. It was experimentally demonstrated

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that the excited grinding fluid prevented wheel loading and improved the surface finish. In another study by them, the grinding force and grinding temperature were investigated, and the reduction of both grinding force and thermal escalation was confirmed [11]. It was also found that the burn marks on the ground surface of titanium were prevented. Recently, Huang et al. [12] investigated the lubrication in grinding using multi-walled carbon nanotube (MWCNTs) nanofluids with ultrasonic-assisted dispersion during grinding of NAK80 mold steel. They compared the grinding performance of MQL and ultrasonic MQL grinding. They observed that the nanoparticle agglomeration prevented the entry of nanoparticles into the grinding zone during conventional MQL. However, in Ultrasonic MQL the nanofluid got uniformly dispersed. This has efficiently improved the lubrication resulting in lower grinding forces and better surface quality in case of ultrasonic MQL as compared to conventional MQL grinding process. The above literature discussions clearly point towards the improvement in grinding aspects of materials using Ultrasonic MQL.

Based on the above discussion, the present study aims to investigate the grinding performance through application of indigenously developed ultrasonic vibration assisted minimum quantity lubrication (UMQL) in surface grinding of Ti-6Al-4V. In this work, soluble oil cutting fluid is effectively impinged into the grinding zone by indigenously designed and developed UMQL setup. The grinding performance has been evaluated in terms of measured grinding forces, mean surface roughness, and some microscopic analysis of the ground surfaces.

2. EXPERIMENTAL SETUP

The UMQL system consists of many components, such as an ultrasonic generator, ultrasonic horn, air compressor, air pressure regulator, fluid reservoir and flow regulator. An aluminium horn having a natural frequency around 20 kHz is specially designed and fabricated to vibrate at an ultrasonic frequency of 20 KHz. Special attentions are required in the design and manufacturing of horn which is coupled to the ultrasonic generator. If a horn is manufactured incorrectly, it may hamper the UMQL performance and may even lead to considerable damage to the transducer and generator system [13]. The ANSYS software is used to perform modal and harmonic analyses for designing of the suitable horn. A pictorial view of the developed horn is as shown in Fig. 1. The cutting fluid is supplied from the reservoir by gravity at a constant flow rate of 250 ml/hr to the vibratory horn through the passage made in the horn. As the cutting fluid comes out of the horn, it gets atomized into very fine droplets because of the vibrations of the horn. These atomized droplets are focused and injected into the grinding zone with the help of compressed air at a pressure of 4 bar. The experiments were carried out on a CNC surface grinding machine (*SMARTH1224*, *Chevalier*) using silicon carbide grinding wheel of specification C60K5V. KISTLER 9257B dynamometer has been used for measuring the grinding forces. The surface roughness of the ground surfaces has been measured using a surface profilometer (Talysurf, Taylor Hobson, UK). The photographic view of the experimental setup is given in Fig.2.

3. EXPERIMENTAL RESULTS

While grinding Ti-6Al-4V alloy, wheel speed, table speed and depth of cut have been taken as the process parameters (factors), each factor consisting of three levels as shown in Table 1.

Fig. 1. Photograph of the horn

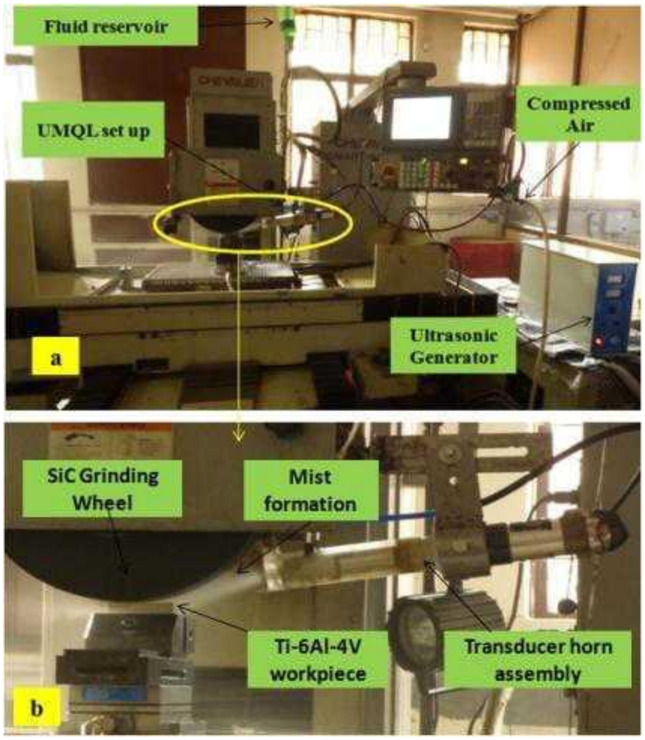

Fig. 2. A Photograph of experimental set up: (a) Grinding Machine, (b) UMQL setup

Table 1: Details of experimental process parameters

Factors	Symbol	Unit	Levels		
			-1	0	1
Wheel Speed	V_S	m/sec	10	15	20
Table feed	V_W	m/min	3	6	9
Depth of cut	a_e	μm	5	10	15

Grinding experiments have been performed at the above-mentioned process parameters with MQL and UMQL grinding mode and the results were compared.

3.1 Tangential force variation

Tangential force is an extremely important parameter in the grinding process. Tangential force is directly related to material removal and involves with sliding and ploughing of grains on the work surface. It plays a major role in deciding the energy requirements in grinding process and to decide the grinding difficulties of different materials. It is expected to be more dependent on the lubrication condition. The average value of tangential force during grinding with different process parameters in different environments- Flood cooling techniques (FCT), MQL and UMQL are shown in Fig. 3. It is observed that the MQL and UMQL produced lower grinding forces than FCT grinding. Moreover, the UMQL grinding has generated the lowest tangential forces. The reason may be that the mist generated from UMQL produce fine droplets of uniform shape and size which can be dispersed uniformly in the grinding zone and forms a uniform protective layer of cutting fluid. This makes the penetration and sliding of abrasive grains easier and provides significant lubrication to reduce the friction between grinding wheel and workpiece, resulting in lower tangential forces.

3.2 Normal Force variation

Normal grinding force is the required force for penetration of abrasive grains to the workpiece. Normal force represents the ease of penetration of abrasive grits on the workpiece surface. As shown in Fig. 3, the normal forces obtained during UMQL are lower than FCT and MQL grinding. In case of MQL and UMQL grinding, efficient penetration of cutting fluid to the grinding zones results in proper lubrication. So, penetration of grain is easier resulting in lower normal grinding forces. Further in UMQL, because of the fine cutting fluid droplets, the cutting fluid can reach the microfracture of abrasive grains keep them sharp to further reduce the normal forces.

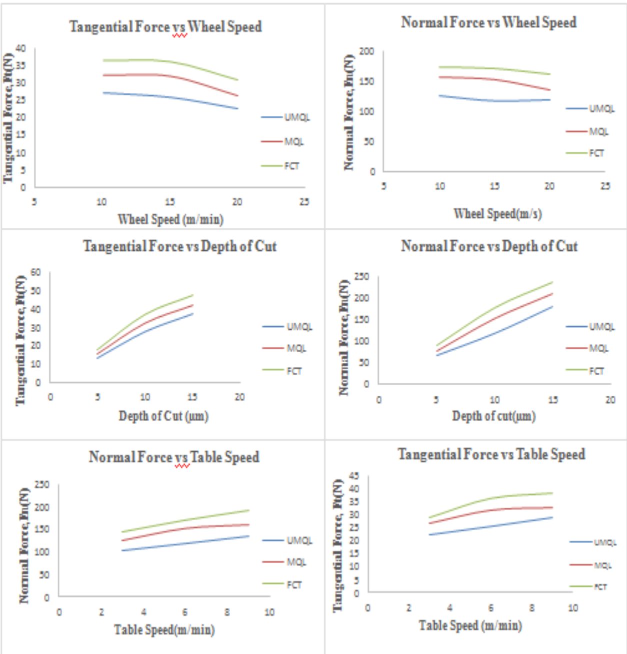

Fig. 3. Variation in grinding forces with different process parameters under different grinding environments.

3. 4. Surface roughness

Fig. 5 shows the variations in surface roughness during grinding with different process parameters under MQL and UMQL grinding environments. It has been found that the UMQL grinding results in lower average surface roughness while grinding with all the process parameters. These results mean that UMQL grinding can yield better workpiece surface quality than MQL grinding which clearly indicates the formation of an effective lubricating layer by cutting fluid droplets between the contacting surfaces. Fig. 6 show the micrographs of ground surfaces taken in a stereo-zoom microscope under dry and UMQL grinding. It can be clearly shown that the rubbing and ploughing marks are obtained during dry grinding while a smooth and defect-free surface is obtained during UMQL grinding.

3.3 Cutting fluid droplets distribution

As shown in fig. 4, the cutting fluid droplets are smaller in size and more uniformly distributed in case of UMQL as compared to the conventional MQL. The smaller droplet size leads to the easier entry of cutting fluid droplets into the grinding. There are two theories regarding the mechanism of droplet formation in ultrasonic atomization: cavitation theory and capillary wave theory. [8]. As per cavitation hypothesis, due to the high-intensity ultrasonic vibrations, cavitation bubbles are formed. When these bubbles strike the surface of the liquid, they form further bubbles thus initiating a chain reaction. The other is the capillary wave hypothesis in which due to ultrasonic vibrations, high amplitude capillary waves are formed. When these capillary waves become unstable, they tear the crests and troughs apart thus generating very fine droplets. These droplets enter into the cutting zone and form a thin film of lubricant over the surface of the workpiece during grinding. It also results in the reduction of relative distances between the droplets leading to an increased number of droplets entering into the grinding zone.

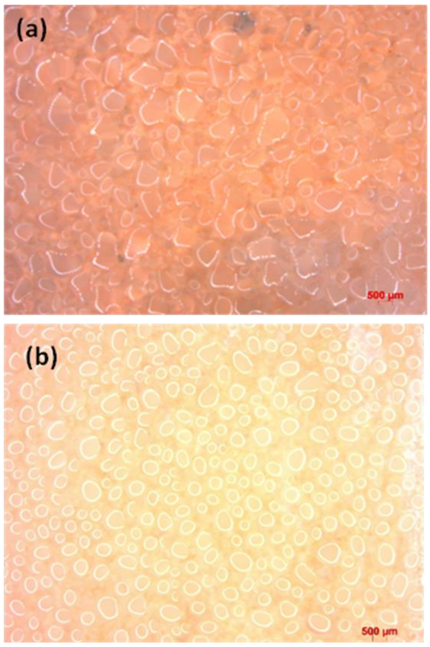

Fig. 4. Droplet obtained (a) With traditional MQL setup (b) UMQL setup at 7.5X magnification

4. CONCLUSION

In the present study, the effect of an ultrasonic vibration assisted minimum quantity lubrication (UMQL) on grinding of Ti6Al4V alloy has been studied using indigenously designed and developed UMQL setup. Experiments were carried out using flood cooling technique, MQL technique, and UMQL technique.

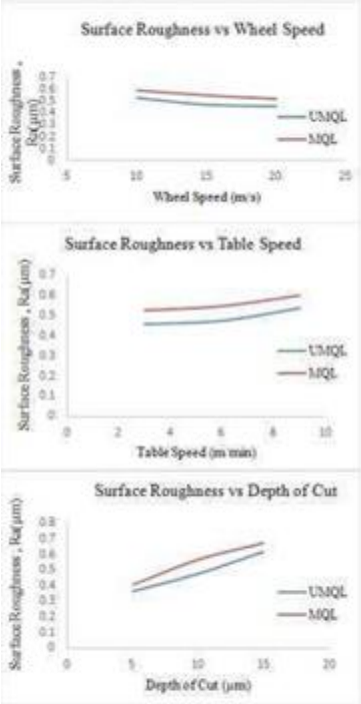

Fig. 5. Variation in surface roughness with different process parameters under MQL and UMQL grinding.

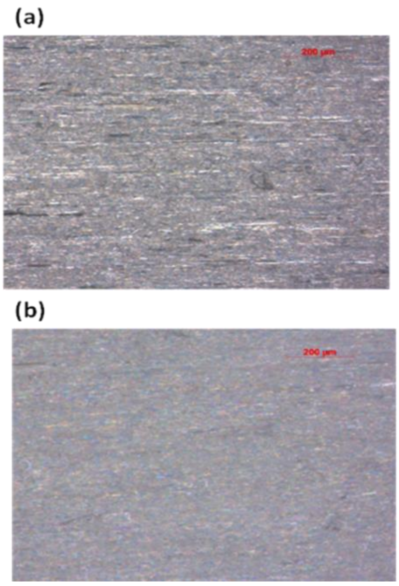

Fig. 6. Surface micrographs after (a) dry grinding condition and (b) UMQL condition at 100X magnification

The experimental results have been found to be encouraging as lower tangential force, and normal force was obtained during UMQL grinding. The surface roughness has also been improved using UMQL grinding. The improved grinding performance is due to the very fine and uniformly distributed cutting fluid droplets obtained during UMQL. Smaller droplet size leads to easier entry into the grinding zone and uniform distribution of cutting fluid droplets leads to better lubrication. Lower grinding forces lead to lower heat generation and reduced power consumption during grinding. Hence, UMQL has a huge potential for improving the grinding performance of difficult to machine materials like Ti-6Al-4V titanium alloy.

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