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Investigation of grinding performance in ultrasonic vibration assisted grinding of Ti-6Al-4V alloy using minimum quantity lubrication

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Abstract—**Minimum quantity lubrication (MQL) is an efficient cooling and lubrication technique usually used these days in grinding operation. It is found to be advantageous for improving the grinding performance in terms of reduced grinding forces, surface integrity and production cost since it offers better cooling, lubrication, and lower coolant consumption. Ultrasonic vibration assisted grinding (UAG) has also shown the improvement in the grinding performance owing to the change in the nature of cutting process in UAG. In this study, the grinding performance of UAG combined with MQL using soluble oil on Ti-6Al-4V alloy is studied through surface grinding experiments. The results show significant improvement in surface finish and reduction in grinding forces are achieved in UAG with MQL grinding process as compared with conventional dry and ultrasonic vibration assisted dry grinding.**

Keywords**- UAG, MQL, grinding force, surface finish, Ti-6Al-4V.**

I. INTRODUCTION

Titanium and its alloys are appealing materials because of their high strength-to-weight ratios that can be maintained at high temperatures, great corrosion resistance, and excellent biocompatibility [1]. While titanium alloys are most commonly used in the aerospace industry, they are also finding uses in biomedical, sporting goods, automotive, and general engineering. Hence, it is very important for researchers to identify the efficient machining processes for manufacturing of the engineering components made of Ti-alloys.

Grinding is the greatest and possibly the most promising machining solution for hard-to-cut materials including ceramics and super alloys. Grinding specific energy is commonly known to be substantially higher than that of other cutting techniques. This is due to the fundamental mechanism of material removal during grinding, which entails ploughing of the abrasive grains and their excessive sliding and rubbing across the workpiece surface. Grinding with a high specific energy, which can raise the workpiece temperature to melting temperatures in some situations, needs the use of a substantial volume of coolant during the process. Some new techniques, such as minimum quantity lubrication (MQL), near dry grinding and ultrasonic assisted grinding (UAG) have been developed to solve the environmental problems and health hazards associated with the usage of such coolant.

Several studies have advocated the notion of MQL to solve the environmental, health, and economic difficulties associated with traditional bulk cooling procedures, and this technique significantly improves the cooling and lubrication during machining/grinding [2-7]. A very small amount of cutting fluid is atomized into fine droplets using the MQL process. The grinding/machining zone can then be fed with these fine cutting fluid droplets. The schematic representation of the MQL system, which is commonly used for grinding is shown in figure 1. Fluid containers, air compressors, pipelines, control valves, nozzles, etc. are some of the basic components of the MQL system. Using a dial flow regulator, the cutting fluid from the reservoir is delivered to the nozzle at a predetermined flow rate. The spray nozzle's other open end delivers high-pressure compressed air to atomize the cutting fluid. The atomized cutting fluid is subsequently sprayed in the form of fine droplets onto the grinding zone. MQL grinding technology was researched by Tawakoli et al. [6]. In MQL, an aerosol, a mixture of air and oil, was fed into the wheel-work zone. They discovered that MQL grinding significantly improves cutting performance as compared to dry grinding in terms of augmented wheel life and improved ground part quality. MQL technique has gotten a lot of interest in grinding processes since it decreases the environmental impacts caused by usage of traditional cutting fluids. It is also operative in reducing the grinding force, in attaining of better surface finish, and being less damaging to the surface integrity. The MQL has long been recognized as a viable approach for sustainable grinding of diverse engineering materials. Nonetheless, some research suggests that the cooling effects of MQL are inconclusive [8, 9].

On the other hand, UAG has been recognized as a promising grinding technique by some researchers [10-16]. The imposed ultrasonic vibration is supposed to influence the process kinematics during machining or grinding. The use of ultrasonic vibration during grinding causes variations in the undeformed chip thickness, which effects the grinding forces. Impact loads are formed between the grits and the workpiece surface when oscillation is present. The impact loads operate as a self-sharpening mechanism for abrasive grains, allowing them to remain sharp for longer periods of time. Sharper grains penetrate the work material more easily, resulting in reduced grinding forces. Further, the impact load increases the brittle fracture mechanism and prolong surface micro fractures, allowing for effective grit penetration.

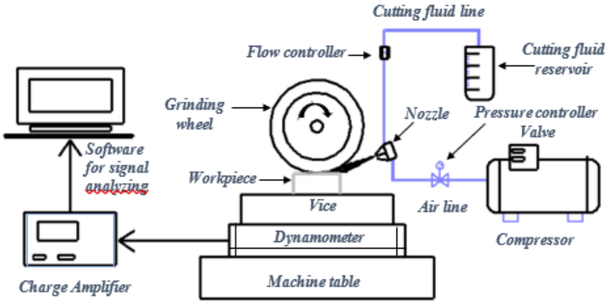

Figure 1. Schematic representation of the MQL system.

During ultrasonic mode, the contact area between grits and workpiece changes according to cutting depth and vibration amplitude, resulting in a decrease in forces. Figure 2 depicts a typical UAG experimental setup [10]. The ultrasonic power supply converts 50 Hz electrical signals into high-frequency electrical impulses, which are then converted into mechanical vibrations with a frequency of around 20 kHz by the piezoelectric transducer. The vibration amplitude is amplified by the booster and the horn/sonotrode before being communicated to the workpiece. The workpiece is usually vibrated using ultrasonic vibration in the cross feed or longitudinal direction of the grinding wheel [10, 11]. The effect of ultrasonic vibration on mild steel dry grinding was examined by Tawakoli et al. [10]. They reported that ultrasonic vibration reduced friction by applying additional stress to the grit-workpiece rapid welds. Ultrasonic vibration also helps to reduce the time it takes for two asperities on opposite surfaces of grit and workpiece to make short contact. As a result, the asperities do not form a stronger bond, and the surface roughness improves. Chen et al. [11] used ultrasonic vibration in a cross-feed direction to grind a C45 carbon steel workpiece, comparing the surface roughness to traditional grinding. They also looked at how vibration amplitude affected surface roughness. They discovered that as vibration amplitude increased, the values of the surface roughness parameters Ra and Rt dropped. Azarhoushang et al. [12] investigated the UAG of ceramic matrix composites (CMCs). According to their research, the reduction in grinding forces achieved at higher vibration amplitudes. Further, the ultrasonic-assisted creep feed grinding of nickel-based superalloy was researched by Bhaduri et al. [13]. They developed a block sonotrode that actuates the workpiece with a predictable frequency (about 20kHz). The normal and tangential grinding forces were shown to be reduced by up to 23% and 43%, respectively. They also discovered that using UAG the 3D surface roughness (Sa) of the ground part reduced by up to 45%. Spur and Holl [14] investigated sintered silicon nitride and alumina creep feed grinding with ultrasonic assistance. Ultrasonic vibrations were applied to the workpiece at high frequencies of roughly 22 kHz and low amplitudes of 4 to 15 microns. They examined the grinding forces, surface roughness, and radial wheel wear to learn more about the process. They reported that the workpiece motion became sinusoidal as a result of the ultrasonic vibration, and the grits did not contact the workpiece constantly, leading in a decrease in real contact time. The wheel's thermal burden decreased as a result of this. In addition, the whole process made it easier for coolant to reach the grinding zone. Furthermore, due of the smaller impact on the grinding wheel and shorter contact length, the frictional effect was minimized, lowering the grinding forces. They also found that grit splintering increased during ultrasonic grinding, whereas grit flattening reduced. As a result of the low friction and thermal loading, more cutting edges became active, and grit pull-out was minimized. Abdullah et al. [15] studied the impact of longitudinal ultrasonic vibration applied to the Inconel738LC superalloy workpiece during dry creep feed up grinding. They also opined that the cutting path of the abrasive grit changes to a sinusoidal curve due to ultrasonic vibration, whereas it stays a continuous arc during traditional grinding. As a result, grit enters the workpiece quickly and escapes it sharply. Hence, the problem of extended grit rubbing and ploughing, which is common during conventional grinding, is reduced, and the chip forms immediately after the grit contacts the workpiece surface. Tawakoli et al. [16] compared the results of ultrasonic-assisted dry grinding of 42CrMo4 using a vitrified bonded cBN grinding wheel to conventional dry grinding. They were able to minimize the grinding forces, surface roughness, and heat damage to the ground product by using ultrasonic vibration.

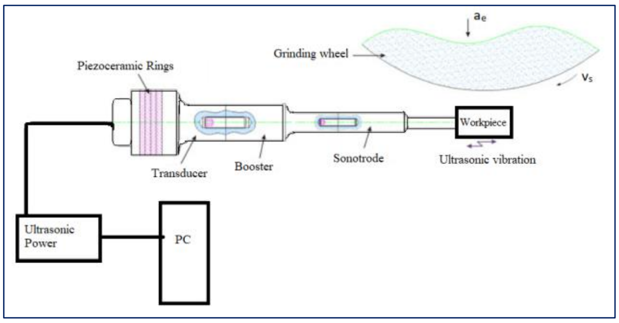

Figure 2. Scheme of a typical UAG experimental setup [10].

According to the above-mentioned literature studies, UAG and MQL are promising grinding techniques that have attracted a lot of attention because of their superior features such as lower grinding force, higher material removal rate, better surface quality, longer grinding wheel life, and lower grinding heat generation when compared to conventional grinding (CG). Moreover, if these techniques are combined, they may have a significant impact on the grinding characteristics of important engineering materials. Hence, the current research proposes to analyze the performance improvement of Ti-6Al-4V alloy grinding using MQL with UAG. The grinding performance was assessed by investigating the grinding forces, surface roughness characteristics, and ground surface quality.

II. EXPERIMENTAL PROCEDURE

Surface grinding experiments were carried out on a 3-axis CNC surface cum profile grinder in down cut plunge mode under CG dry, UAG, and UAG with MQL conditions. The conventional SiC grinding wheel (GC-60-K-5-V; dimension: 200 × 13 × 1.75 mm) and Ti–6Al–4V workpiece (dimension: 32 × 40 × 12 mm) were used in the experiments. For MQL experiments, soluble oil which is a mixture of water-soluble cutting oil in 1:30 ratio (CoolEdge SL, Castor oil) has been used. To maintain uniform wheel topography, dressing of grinding wheel has been carried out before each experiment with a single point diamond dresser. A 3D piezoelectric dynamometer was used to monitor normal and tangential grinding forces in real time (KISTLER, 9257B). The surface roughness of the ground surface was measured using a portable surface profilometer (HANDYSURF E-35A/B). An experimental setup is indigenously designed and developed to apply high frequency vibration to the Ti-6Al-4V workpiece at low amplitude. The photographic view of the experimental setup is shown in figure 3. The grinding parameters and the experimental setup data are given in Table I.

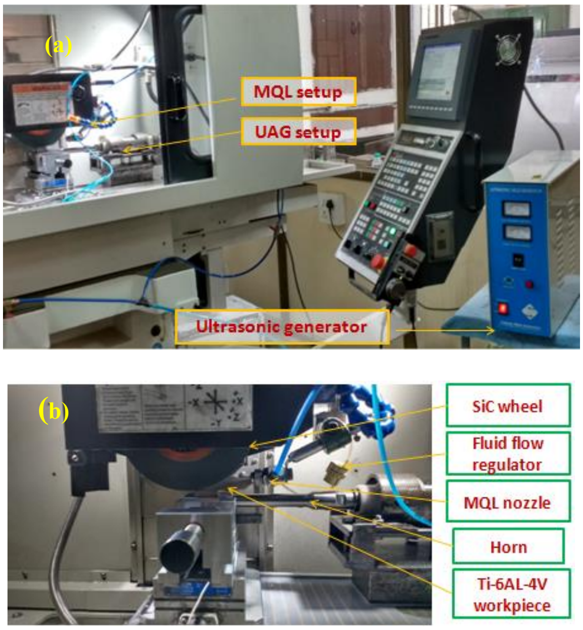

Figure 3. Experimental set-ups: (a) Grinding Machine, (b) UAG and MQL set-up.

A commercially available generator and a transducer were used to produce ultrasonic vibration, applied to the workpiece in the feed direction. The vibration generated by the transducer and generator were enhanced and transmitted by booster and the horn. The design and manufacture of a horn requires extra care. If a horn is made incorrectly, it might affect grinding performance and causes substantial impairment to the transducer and generator system. The complete vibration system consists of a piezoelectric transducer, a booster, a horn, and a distinct fixture. A 50 Hz power source is converted into high-frequency electrical impulses by the ultrasonic power supply. These high-frequency electrical impulses are sent to a piezoelectric transducer and converted into mechanical vibrations due to the piezoelectric effect. The magnitude of the vibration is subsequently amplified by the booster and delivered to the workpiece attached to the horn. To maintain the uniformity during the experimentation, all the grinding experiments were done using the same experimental settings with the ultrasonic generator's power ON during UAG and OFF during CG.

III. RESULTS AND DISCUSSIONS

A. Friction Coefficient (Ft/Fn)

The result of apparent coefficient of friction (Ft/Fn) obtained during different grinding environment is shown in the figure 4. It has been observed that the UAG technique reduces friction coefficient as compared to conventional dry grinding. Moreover, UAG with MQL shows a further reduction in friction coefficient. It is most likely owing to increased oil penetration into the grinding zone, which allows for more efficient cooling and lubrication. Further, the UAG interrupts the grinding action, allowing cutting fluids to flow into the contact zone and improving lubrication. This effective lubrication improves grain slipping between the wheel and the workpiece, lowering friction between the two. Moreover, the generated heat has time to diffuse and disperse during the moment the workpiece is no longer in contact with the grinding wheel. Also, because of the high frequency vibration, the two asperities on the opposite surfaces get less time to remain in momentary contact and form the stronger bond. Hence, it can be said that the periodic grain/workpiece separation together with pressurized coolant mist helps in achieving better cooling and lubrication effect in case of UAG with MQL, and hence reducing the coefficient of friction as compared to UAG and conventional dry grinding.

B. Tangential grinding force

It is crucial in calculating the amount of energy required to grind various engineering materials. It is greatly affected by the lubrication state during grinding, as well as the sliding and ploughing action of the abrasive grains. Figure 5a shows the variations in tangential grinding forces under different grinding environments. The tangential forces are highest during conventional dry grinding due to the deficiency of cooling and lubrication that causes the abrasive grits to get blunt at a faster rate resulting in severe rubbing and ploughing. However, in UAG, periodic cutting mechanism helps to prevent undesirable rubbing and plowing resulting in lower grinding forces. Moreover, when UAG is combined with the MQL, it provides the lowest tangential forces due to the synergistic impact of UAG and MQL. Hence UAG with MQL grinding gives improved grinding performance.

Table I. Experiment parameters for grinding

Parameters	Description
Grinding kinematic parameters	Grinding wheel speed: 30 m/s Table speed: 6 m/min Depth of cut: 4,8,12,16 µm
Grinding environment	Conventional dry grinding (CG Dry) UAG UAG + MQL
MQL parameters	Intermediate nozzle position Air pressure-5 bar Flow rate–250 ml/h
Dressing parameters	Wheel speed: 1000 rpm Dressing depth: total of 40 µm in 4 passes Dressing lead: 200 mm/min
UAG parameters	Vibration frequency - 20 kHz Vibration amplitude - 10 µm

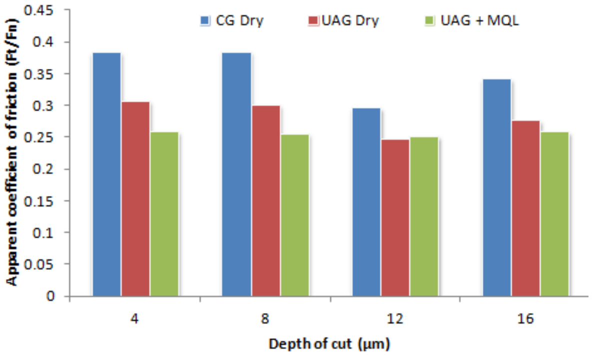

Figure 4. Variation in coefficient of friction with depth of cut under different grinding environments.

C. *Normal grinding force*

It is the force required for abrasive grains to penetrate the workpiece. The ease with which abrasive grits penetrate the workpiece surface can be assessed using the normal force. Figure 5b depicts the differences in normal grinding forces in various grinding settings. Due to the lack of a heat dissipation medium, conventional dry grinding promotes rapid dulling of grains and cutting edges, as well as increased ploughing and rubbing actions, hence, it produces a higher normal grinding forces. Whereas, sharper cutting edges during UAG aids in the effective penetration of abrasive grit into the workpiece surface and reduces ploughing and rubbing by reducing the uncut chip thickness, and hence lower down the normal grinding forces. Furthermore, in UAG with MQL grinding, effective cutting fluid penetration into the grinding zones contributes to proper lubrication. As a result, grain penetration is easier, resulting in lowest normal grinding forces.

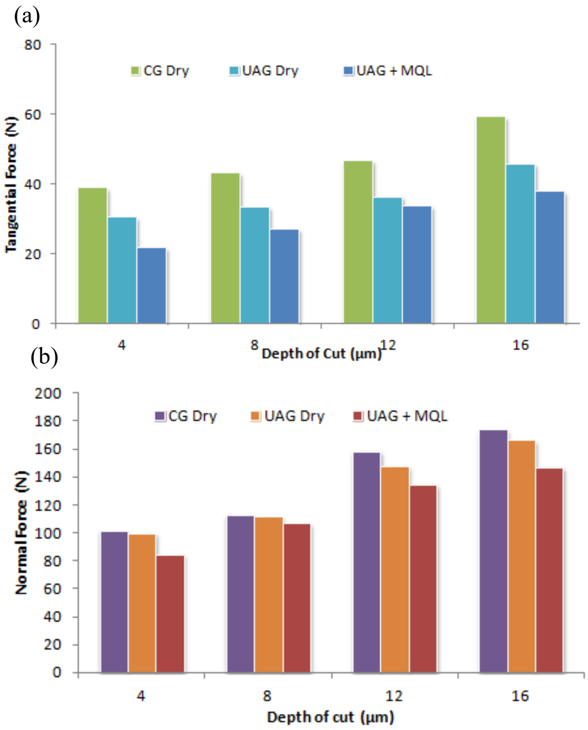

Figure 5. Variation in grinding forces with depth of cut under different grinding environments.

D. *Surface roughness*

Figure 6 depicts surface roughness fluctuations during grinding in various grinding situations. While grinding with all process parameters, it was discovered that using UAG with MQL grinding results in lowest average surface roughness, as compare to the other grinding environments.

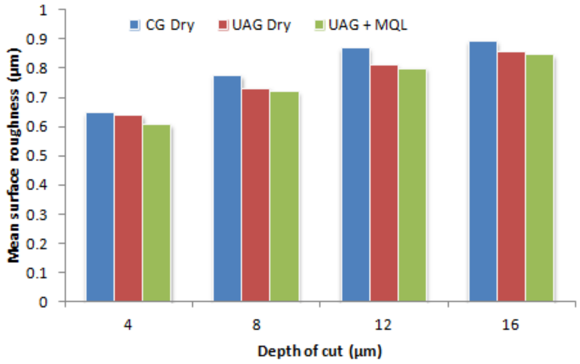

Figure 6. Variation in surface roughness with depth of cut under different grinding environments.

Figures 7(a-c) show the micrographs of ground surfaces taken in a stereo-zoom microscope under conventional dry grinding, UAG and UAG with MQL grinding. It can be clearly seen that the rubbing and plowing marks are obtained during conventional dry grinding while a smooth and defect free surface is obtained during UAG with MQL grinding. The rubbing and plowing in absence of proper cooling during conventional dry grinding make the abrasive particles dull at faster rate, increase the grinding temperature and the inherent thermal properties of the alloy leads to redeposition of workpiece material which results in increased forces and the surface roughness. In grinding, the normal force has a stronger effect on surface plastic deformation and surface roughness, whereas the tangential force has a more effect on heat generation. UAG ensures efficient grinding by reduced grinding forces, which results in a better surface quality and the distinct grinding chips (as shown in fig. 7d). Such distinct grinding chips also demonstrate the effectiveness and ease of grinding during UAG. Further, due to the synergistic effect of UAG and MQL, high surface quality of the ground product can be obtained.

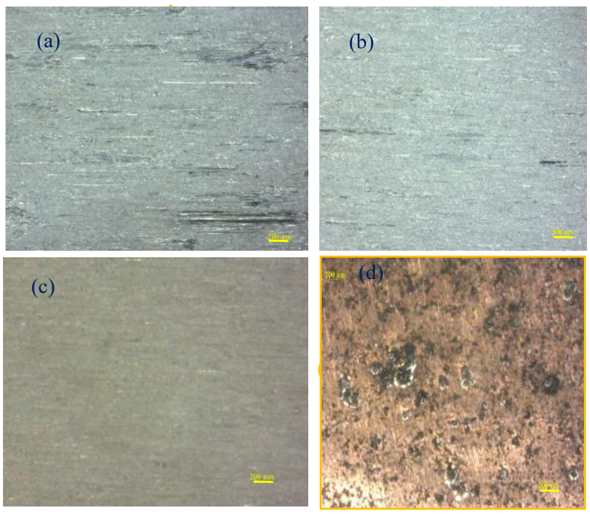

Figure 7. Surface micrographs after (a) Conventional dry grinding, (b) UAG, (c) UAG with MQL grinding, (d) Chips during UAG grinding condition

IV. CONCLUSION

In this work, the effect of UAG combined with MQL on grinding of Ti-6Al-4V alloy was investigated using an indigenously designed and developed setups. Dry conventional grinding, UAG and UAG with MQL techniques are thoroughly studied in the experiments. The results show that lowest tangential force and normal force were obtained during UAG with MQL grinding. The surface roughness has also been improved using UAG with MQL grinding. This improved grinding performance is due to the reciprocating grit motion combined with proper lubrication. Hence, UAG combined with MQL can be recommended as a new way of improving the grinding performance for difficult to machine materials like Ti-6Al-4V titanium alloys.

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