Grindability Improving of Titanium alloy by Using Minimum Quantity Lubrication with Pneumatic Nozzle

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Abstract. Major problem associated while grinding titanium alloy are high specific energy and high grinding zone temperature. To reduce temperature, grinding fluid was used but majority of them was wasted due to formation of stiff air layer around porous grinding wheel rotating at high speed which deflects grinding fluid away from grinding wheel. This paper presents an innovative improvement of MQL process by adding pneumatic nozzle. High compressed air jet from pneumatic nozzle is impinged on grinding wheel surface at an angle of 45° which suppress stiff air layer and clean machined chip, clogged wheel pores from grinding wheel surface. In this work, titanium grade I with alumina grinding wheel is ground at an infeed of 30 µm under flood cooling, MQL and MQL with pneumatic nozzle conditions. Experimental result shows grindability of titanium grade I alloy under MQL with pneumatic nozzle proves to be an extremely efficient in order to lower grinding force, force ratio, wheel wear, wheel loading and surface roughness.

1. Introduction

Titanium and its alloy based super material are widely used in aerospace, defence, and many other industrial applications due to its unique characteristics such as high mechanical strength, light in weight, excellent corrosion resistance and high melting point. Unfortunately, due to its poor thermal conductivity and low specific heat makes the alloy difficult to machined and grind. Sato [1] reported that about 84% of heat goes into workpiece during grinding process which is responsible for thermal damage and surface burn. Mandal et al. [2] expressed that thermal effect occurs due to the resistance offered by the work material against the shearing and also due to the friction resistance between grinding wheel and work piece. Extensive researches were conducted on grinding of super alloys and titanium alloys over past 3 decades to control thermal related problems. These include application of conventional flood cooling, mist cooling, cryo cooling, Z-Z method of cooling solid lubrication, etc. But application of conventional fluids creates several techno-environmental problems such as increase environmental pollution due to chemical dissociation of cutting fluid at high temperature, Soil and water pollution during disposal and it require extra floor space and additional systems for pumping, storage, filtration and recycling.

In grinding, surface speed of the porous wheel is very high, causing formation of a stiff layer around the wheel periphery. The depth of air barrier depends on the grit size and porosity of the wheel. This
stiff air layer formed around the wheel boundary restricts grinding fluid from penetrating into the grinding zone, and reduces the effectiveness of grinding fluid which results in increase of temperature of grinding surface, loss of surface integrities and surface crack [3]. To suppress bad effect of stiff air layer many method have been tried Mandal et al. [4] used a pneumatic barrier for breaking stiff air layer which resulted in maximum fluid penetration and provided better cooling action in grinding zone. Ebberell et al. [5] developed a computational fluid dynamics (CFD) model of air boundary layer around grinding wheel. From the model, it was seen that direction of air layer was along with the wheel rotation direction, and after striking with the work piece at wheel workpiece contact surface, the direction of air flow was reversed. Two different directions of air layer were observed, and for effective fluid delivery, the nozzle was required to be kept above the reverse flow area. Webster [6] suggested that fluid flow is not sufficient to overcome the centrifugal force or to penetrate the air barrier around rotating grinding wheel. This air barrier may be overcome when the jet outlet velocity is equal to grinding wheel periphery velocity.

An attractive alternative for conventional flood cooling and to suppress bad effect of stiff air layers up to certain extent is by using minimum quantity lubrication (MQL) grinding process. This process uses a minimum quantity of lubrication and is referred to as near dry grinding. MQL is a technique that uses spray of small oil droplets in a compressed air jet. The benefit of using MQL is to reduce operational health and safety (OHS) risks, reduces machining costs and environmental impact associated with disposal of the cutting fluids. It is known that the costs related to the use of cutting fluids range from 7-17% of the total costs of the manufactured workpiece [7]. Sadeghi et al. [8] suggested that quantity of lubrication 60 ml/h and delivery pressure 4 bars were the most appropriate value in MQL grinding of titanium alloy Ti-6Al-4V that minimized grinding forces. Shen et al. [9] investigated the wheel wear and tribological characteristics in wet, dry, and MQL grinding of Ti-6Al-4V. He reported that MQL has been used as an alternative solution for flood cooling as well as dry machining. MQL grinding results showed the benefits of reducing grinding forces, improving surface roughness, and preventing work piece burning. Silva et al. [10] studied MQL grinding of Ti-6Al-4V they found that there is less wheel loading and better ground surface as compared with wet and dry condition. Guo et al [11] investigated the use MQL conditions for grinding of Ti-6Al-4V alloy using SiC grinding wheel. The MQL grinding provided better results with less surface damage in comparison with dry and fluid grinding.

Sadeghi et al. [12] investigate that, when abrasive tools are used, a reduction in the use of cutting fluid decrease the cleaning of the wheel pores. According to Di Ilio and Paoletti [13], wheel loading increases grinding forces, wheel wear, and causes high surface roughness on ground parts. However, the efficient removal of the machined chips from the cutting zone is not achieved when MQL is used. To overcome MQL problem a new techniques by adding pneumatic nozzle was used which shows an improvement to clean wheel surface and decrease the formation of stiff air layer. In this work grindability of titanium grade I alloy is compared under flood cooling, MQL and MQL with pneumatic nozzle set up with an in feed of 30µm. For each in feed, various quantitative response parameters such as tangential and normal force, force ratio, surface roughness values, etc. are measured as well as some qualitative response parameters like chip form, surface burn, wheel loading are assessed.

2. Experimental Set-up

Experiments were performed on a surface grinding machine with aluminum oxide (Al₂O₃) grinding wheel. The grinding wheel velocity of 30 m/s is used throughout the experiment with maximum table speed of 0.2 m/s. Detail grinding conditions are shown in table 1.
Table 1 Grinding Conditions

| Description                        | Details                                                                 |
|------------------------------------|-------------------------------------------------------------------------|
| Grinding Machine                   | Manekal & Sons, 600 X200 PARROT                                         |
| Grinding Mode                      | Surface Grinding, Up cut                                                 |
| Grinding Wheel                     | Disc Type Alumina Wheel, Φ 200 mm x 13 mm x Φ31.75 mm                   |
| Grinding wheel specification       | AA 46/54 K5 V8                                                           |
| Work piece                         | Titanium Alloy (Grade – I), 120 mm x 55 mm x 6 mm                       |
| Work piece Composition             | Ti–99.85%, O2-0.02%, N2-0.01%, Fe-0.12%.                                 |
| Depth of cut                       | 30µm per pass                                                           |
| Grinding Fluid                     | Blasscut water soluble oil, Blaser, Switzerland                         |
| MQL Oil                            | Synthetic Oil                                                           |
| Wheel Dresser                      | Single Point 0.5 Carat Diamond Dresser                                  |
| Dressing Depth                     | 20 µm                                                                   |
| Tool Maker Microscope              | Mitutoyo, Japan, Model No. TM-510                                       |
| Surface Roughness Tester           | Surftest 301 (Range: 0.05 – 40 µm)                                     |
| Air Compressor                     | Make: Elgee, Quantity – 2 nos                                           |
| Experimental Environment           | Flood, MQL, MQL with Pneumatic Nozzle                                  |

The work piece (Titanium grade I alloy) was held using a vice mounted on top of grinding dynamometer. Grinding force i.e. tangential force (Ft) and normal force (Fn) have been noted from the display unit of grinding dynamometer. Ten numbers of grinding passes with an in feed of 30 µm are considered in all conditions. Grinding wheel was dressed by using diamond dresser before conducting an experiment. For flood cooling conditions grinding fluid at a flow rate of 2 lit/min is maintain for each passes with an internal nozzle diameter of 6mm.

MQL equipment consists of compressor, pressure regulator, pressure measurement gauge and mixing nozzle. Synthetic oil was used as MQL coolant. Synthetic oil container which was kept above mixing nozzle and was gravity fed. Coolant flow at a rate of 80 ml/h which is mixed with compressed air with an air pressure of 4 bar in MQL mixing nozzle (air atomizer). High pressure atomized spray from MQL nozzle is impinged on grinding zone which was kept at a distance of 12 cm away from the grinding wheel and10 mm above work piece as shown in figure 1(a). In MQL with pneumatic nozzle
setup both nozzle are made to work at same time. Internal diameter of pneumatic nozzle is 4 mm and placed 10 mm away from grinding wheel at an angle of 30° with radial line OA as shown in figure 1(b). From the nozzle compressed gas at a pressure of 4 bar is supplied to block stiff air layer and to remove loose machined chip which stick at the surface of grinding wheel. After final passes ground surface roughness Ra, Rz and Rf value are measured and wheel loading was observed.

3. Experimental result and Discussion

3.1 Observation of grinding forces

During grinding process due to contact of wheel with work piece surface and material removal action of abrasive grains, two grinding forces called tangential and normal force are generated. The tangential force is generated along the reciprocating movement of work table whereas the normal force is exerted to the work surface. With increase in friction, the tangential force increases while normal forces are mostly affected by the work piece hardness [14].

It was observed that normal force (Fn) is much higher than tangential force (Ft) this is due to high hardness (202 HV) of titanium Grade I alloy and highly negative rake angle of wheel grit. Grinding has been performed with cutting velocity of \( V_c = 30 \text{ m/s} \), feed rate \( V_w = 7 \text{ m/min} \), and depth of cut \( h = 30 \mu \text{m} \) with flood cooling, MQL and MQL with pneumatic nozzle conditions. From experimental observation both forces tend to increase at initial phase this is mainly due to rubbing and wheel loading. Figure 3(a) indicates that in flood cooling both forces are slightly high as compared with other two conditions. This may be improper fluid penetration due to presence of stiff air layer. The lower
Grinding force in MQL process is due to better lubrication effect and performance. In MQL grinding the amount of lubrication oil used at contact surface is much lower than flood cooling hence it shows greater efficiency of fluid penetration at initial passes. Grinding force increases with increase in number of passed which show low grind ability in MQL as compared with flood cooling. This may be due to clogging of wheel pores from machined chip. MQL with pneumatic nozzle set up shows overall reduction in grinding forces which indicates good grindability. Compressed air from Pneumatic nozzle penetrates deep into the pores of grinding wheel by breaking still air layer which decrease centrifugal action which are responsible for formation of air layer around grinding wheel and also clean the wheel by removing chip and loose grit from wheel surface result in low grinding force.

Grinding force ratio, which is the ratio of tangential force (Ft) and normal force (Fn) lies within 0.24 to 0.34 at 30µm infeed as shown in figure 2 (b). This range indicates titanium grade I alloy can be ground with alumina wheel. Force ratio is high in MQL with pneumatic nozzle set up which indicates good grinding performance. After initial passes force ratio in conventional MQL process increase gradually but after seventh passed it tends to decrease this may be due to excessive wheel loading and rubbing phenomenon.

3.2 Observation of grinding chip

Chip was collected and observed under tool maker’s microscope with zooming capacity of 20X. In flood cooling mainly shear and segmented chip are observed with little burnt chip indicates cooling and lubrication up to certain extent. In MQL condition slightly less leafy chips are found but more grits are observed after sixth and seventh passed indicates high wheel loading and self dressing. However, better result have been obtained under MQL with pneumatic setup. Mainly shearing chip are found with less number of wheel grit indicating better lubrication effect and decrease rubbing phenomenon in wheel workpiece contact surface

3.3 Observation of wheel loading and wheel wear

Wheel loading was observed after final passes for each grinding conditions. Nagaraj and Chattopadhyay [15] defined wheel loading as the stage of grinding wheel when the particle of the workpiece material either adhere to the grits or became embedded in the voids on the wheel surface under this situation force and temperature rise to a level leading to deterioration in the surface integrity. Turley [16] observed that while grinding titanium alloy, aluminium oxide wheel show more material pick up this is mainly due to high rate of chemical attack by titanium on aluminium grits. Extensive wheel loading was seen in flood cooling and MQL as compared with MQL with pneumatic nozzle conditions. Wheel material removal increases with increase in passes. High wheel material
removal was observed in flood as well as conventional MQL process this is due to high wheel loading and high friction in between work piece-wheel contact surface. With the use of pneumatic nozzle high compress air jet acts as wheel cleaner by removing loaded chip and loose grit particles. Small chip redeposit and few dig out are determined with less burn indicate better cooling effect in MQL with pneumatic nozzle result in low wheel wear.

![Image](image1.png)

(a)  (b)  (c)

**Figure 4:** Pictorial View of Grinding Wheel at an infeed of 30µm under of (a) flood cooling, (b) MQL and (c) MQL with pneumatic nozzle Condition

### 3.4. Specific energy requirement

It is one of the most important parameter to assist grindability. Grinding process attribute to high specific energy due to negative angle of abrasive grit which are responsible for excess rubbing and ploughing. Specific energy also depends on chip formation due to shearing or ploughing and friction between loaded chip and work piece. In this experimental work specific energy is calculated for each number of passes at 30µm in feed as shown in figure 5. MQL with pneumatic barrier shows overall decrease in specific energy due to reduction in friction and rubbing at contact zone. At initial phase conventional MQL process show less specific energy consumption as compared with flood cooling condition but this get reversed with increase in passes. It is calculated by using the following relation

\[
Specific\ Energy = \frac{Ft \times V_c}{b \times h \times V_w}
\]

\[
\text{Where:} \quad Ft = \text{Tangential force (N)}
\]

\[
V_c = \text{Velocity of grinding wheel (30 m/s)}
\]

\[
V_w = \text{Table feed (7 m/min)}
\]

\[
b = \text{Width of work piece (6 mm)}
\]

\[
h = \text{Actual depth of material removal (mm)}.
\]

![Image](image2.png)

**Figure 5:** Specific energy required in grinding titanium grade I alloy at an infeed of 30µm
3.5 Surface quality

Ground surface was observed under tool maker’s microscope. In flood cooling some chips are redeposited on ground surface and heavy deep lay marks with some dig out are seen indicates rubbing and ploughing phenomenon. These heavy lay marks are also seen in conventional MQL process. Good surface quality was observed under MQL with pneumatic nozzle setup. Chip redeposition problem has been reduced to a large extent and very few surface burns are observed with less lay mark.

Surface roughness parameter (Ra, Rz, and Rt) of ground surface are lower in case of MQL with pneumatic nozzle. High surface roughness was obtained in flood cooling condition this may be due to rubbing and ploughing phenomenon from redeposited chip by grinding wheel at contact surface.

Figure 6: Microscope View (20 X) of Ground Surface of Titanium Grade I Alloy at 30 µm Infeed under (a) flood cooling (b) MQL (c) MQL with pneumatic barrier

Surface roughness value at 30 µm Infeed under different cooling conditions

4. Conclusion

Grindibility of titanium grade I alloy with alumina wheel was experimentally investigated under different cooling conditions and concluded as below.

- Minimum quantity lubrication (MQL) can be an alternative of flood cooling under low infeed as MQL is an eco-friendly and high productivity technique.
- Reduction in cutting fluid under high feed decrease heat transfer and increase grinding force and wheel loading
- Efficiency of MQL under high infeed can be increases with the application of Pneumatic nozzle.
- MQL cooling combined with compressed air jet shows better result in lowering grinding force, wheel loading and specific energy requirement as compared with conventional MQL process.
MQL with pneumatic nozzle associated with better result in surface roughness and decrease wheel wear, hence reduces health hazard.

Under all cooling condition MQL with pneumatic nozzle proves to be an alternative solution, contributing to a clean, faster and more cost effective manufacturing.

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