Enhancing grindability of Ti–6Al–4V applying ecological fluids under SQL using SiC wheel

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Abstract

Improving grindability of a given material with the application of cutting fluid is a well-established strategy. However, demands from sustainable manufacturing strive for reduction in cutting fluid consumption as well as introduction of unconventional coolants of non-toxic origin to be employed during the operation without sacrificing its performance. Present experimental investigation deals with the analyses of the performances of some unconventional cutting fluids viz. soap water, sodium nitrite and propylene glycol under small quantity lubrication while grinding Ti–6Al–4V using silicon carbide wheel. Relevant parameters to estimate grindability, like grinding force and specific energy requirements, surface roughness, grinding ratio (G ratio), SEM micrographs of ground surface and images of grinding chips are critically analysed and compared with the results obtained using conventional synthetic fluid and dry grinding. Results have revealed that the unconventional grinding fluids perform more satisfactorily. Among all the fluids applied, propylene glycol has provided with much superior grinding results. It has significantly reduced grinding forces, specific energy, surface roughness and improved G ratio while providing superior surface quality.

Keywords Grinding · Titanium · Green manufacturing · Drop-by-drop · Economic delivery system · SQL/MQL

1 Introduction

Grinding is being widely used during finishing operations in the manufacturing industries. However, it is one of the most complex material removal processes in existence due to higher specific energy requirement owing to large number of abrasive grits of negative rake angle taking part in cutting action [1, 2]. The complexities aggregate while processing of difficult-to-machine (DTM) material Ti–6Al–4V because of the properties like high chemical activeness at elevated temperature, low thermal conductivity and susceptibility to form build-up edge on cutting tool surfaces. Nevertheless, Ti–6Al–4V possesses some unique properties like high specific strength, high corrosion and creep resistance, biocompatibility, and high strength at an elevated temperature for which it is being extensively used in several cutting-edge fields like automobile, shipping,

aerospace, etc. [3–5]. This requires Ti–6Al–4V to be processed into parts having high form of accuracy with specified dimensions and tolerance [3–6].

Grindability, defined as ease of grinding, of Ti–6Al–4V can effectively be improved by the selection of proper work-tool combination, process parameters, dressing conditions, suitable cutting fluid, delivery systems, etc. [7–9]. Among all the alternatives to improve grindability, application of cutting fluid is the most noteworthy. Suitable fluid, when applied through effective delivery system can result in better lubrication and cooling effects at the grinding zone that subsequently, lead into effective removal of swarfs [10]. Conventional synthetic cutting fluids often has a very negative impact on operator's and environmental health. Moreover, they contribute generously towards the economic exploitation of the grinding. In this context, minimum quantity lubrication (MQL)

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method has become popular, where the amount of cutting fluid is restricted without compromising with the performances. Moreover, MQL, which is sometimes referred as SQL or restricted quantity lubrication (RQL) has been found to be much better than flood cooling in obtaining grindability for a given material [11–13]. Numerous studies have been devoted towards establishing the positive effects of MQL over conventional flood cooling condition [12–15]. Guo et al. [14] employed MQL system for grinding Ti–6Al–4V under mist cooling and found it to be superior than conventional flood cooling. In similar works, Sadeghi and his co-workers [15] observed that vegetable oils, when applied in mist cooling form exhibit favourable grinding quality than flood cooling and dry grinding. Although, found suitable than flood cooling, MQL in mist cooling system may sometimes possess greater threat to operators' healths as the fluid in atomized form easily interferes with their respiratory systems. Mukhopadhyay and Kundu [13] used a miniature pump-based SQL technique and reported to achieve enhanced grindability compared to flood cooling. Mukhopadhyay et al. [16] also reported that alkaline coolant such as soap water performs more satisfactorily compared to convention coolants while using miniature pump-based SQL mode of coolant delivery.

From the literature survey it is evident that the prime focus lies on the employment of economic delivery setup to minimize the potential detrimental effects of grinding process on environment and operator's health without compromising with the quality of the process. However, the detrimental effects of using grinding fluids can further be reduced by employing environment friendly grinding fluids in addition. Present experimental study deals with applications of different unconventional and environment safe grinding fluids namely soap water, sodium nitrite and propylene glycol, which are considered to be non-toxic to humans, through an SQL based drop-by-drop (DBD) delivery technique for grinding of Ti–6Al–4V using SiC wheel. The developed delivery setup is novel, simple and economic and is expected to minimize the associated

setup and operational costs to a large extent as it does not demand external power while operating. Also, the cutting fluids selected to be used following the principle of sustainability in manufacturing that leads the process to be relatively economic. For estimating the grindability, relevant parameters like grinding force and specific energy requirements, surface roughness, G ratio, SEM micrographs of ground surface and images of grinding chips are critically analysed and compared with the results obtained using conventional synthetic fluid and dry grinding.

2 Materials and methods

Experiments have been performed on a horizontal surface grinder of HMT Praga made, in up-grinding mode in both dry and wet environments using identical SiC wheels. The use of SiC wheel for grinding titanium alloys is supported by many researchers [17–19], due to the superior friability of silicon carbide abrasive grits that enables to retain their sharpness for longer period of time. Also SiC grits have a tendency to withstand higher temperature without being glazed out as compared to alumina grits [1]. To eliminate the experimental uncertainties related to the manufacturing of the base material, identical Ti–6Al–4V workpiece samples of 60 mm × 60 mm × 6 mm dimensions have been prepared from a single source. Three unconventional grinding fluids namely soap water, sodium nitrite and propylene glycol, which are considered to be environmentally safe and non-toxic to humans have been delivered through an in-house made simple and economic SQL based DBD setup. This DBD system works under gravity where an infusion tube carries the coolant to the nozzle from reservoir and the cutting fluid is allowed to fall on the to-be ground surface in drop by drop manner at a rate of 0.26 ml/s as depicted in Fig. 1. The flow rate is controlled by a regulator attached to the infusion tube. To compare the effectiveness of these fluids, conventional grinding fluid (Blasocut) has also been delivered using the identical setup while grinding Ti–6Al–4V

Fig. 1 SQL based drop-by-drop fluid delivery setup, **a** Schematic showing the penetration through stiff air layer, **b** Pictorial view at the nozzle end

using SiC wheel. Identical experiments have also been performed in dry environment for analysing the results. First, the SiC wheel is dressed using a conventional and economic mechanical dressing process [20, 21] employing a single point 0.75 carat diamond dresser in 20 µm infeed, which is the optimum infeed for dressing conventional wheels while grinding Ti–6Al–4V [22, 23]. Followed by spark out process, twenty grinding passes have been conducted for each set of condition. Grinding force requirements have been measured and recorded using a high precision strain gauge type dynamometer (resolution: 0.98 N) for each grinding pass. The details of the experiments and instruments/tools are depicted in Table 1.

2.1 Specific energy

Requirement of specific energy has been evaluated during each set of experimentation considering twenty grinding passes using the following expression.

$$\text{Specific energy (J/mm}^3\text{)} = \frac{F_t \times V_{wh}}{b \times d \times V_w} \quad (1)$$

where F_t is the tangential force component in N, V_{wh} is the velocity of grinding wheel in m/s, b is the width of the workpiece in mm, d is the depth of material removal in µm and V_w is table feed in m/s.

2.2 Force modelling

A semi-empirical model for force prediction has been developed to delve in depth as detailed below.

Refer to Fig. 1a, normal component of grinding force is written as,

$$F'_n = F'_{nc} + F'_{ns} \quad (2)$$

where F'_{nc} and F'_{ns} are normal chip formation and sliding forces respectively [18].

These forces can be expressed as follows [24]

$$F'_{nc} = \frac{\pi}{4} \frac{V_w}{V_s} ab \sin \theta \quad (3)$$

$$F'_{ns} = 4C\delta p_0 b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \quad (4)$$

where a is grinding infeed in µm, b is width of the workpiece in mm, θ is cone tip angle/2 in rad., δ is tip area of the worn grit in mm², p_0 is a constant, V_w is workpiece velocity (0.23 m/s), V_s is wheel velocity (30.17 m/s) and d_e is diameter of the wheel (200 mm).

Therefore, from Eqs. 2–4,

$$F'_n = \frac{\pi}{4} \frac{V_w}{V_s} ab \sin \theta + 4C\delta p_0 b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \quad (5)$$

or,

Table 1 Experimental details

Surface grinding machine	Make: HMT, Praga division; Model: 452P; spindle speed: 2880 rpm
Grinding wheel	Make: carborundum universal limited Specification: CGC 60 K 5 V8
Grinding environment	Dry SQL using drop by drop method Nozzle diameter: 2.1 mm; Flow rate: 0.26 ml/s
Grinding infeed	5 µm, 10 µm and 15 µm
Grinding fluid	Blasocut 2000 universal Alkaline Soap water Sodium nitrite solution (40% H ₂ O) Propylene glycol
Force dynamometer	Make: Sushma grinding Dynamometer, Bengaluru; Model: SA 116 Range: 0.98–980 N; Resolution: 0.98 N
Stereo microscope	Make: Gippon, Japan; magnification: 20× to 40×
Wheel dresser	Make: Norton Abrasives, India Specification: 0.75 carat single point diamond Dressing Infeed: 20 µm
Surface roughness tester	Make: Mitutoyo, Japan; Model: Surf test 301 Range: 0.05–40 µm; resolution: 0.05 µm
Scanning electron microscope	Make: Zeiss, USA; Serial: EVO-18

$$F'_n = K_1 \frac{V_w}{V_s} ab + K_2 b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \quad (6)$$

where $K_1 \left(= \frac{\pi}{4} \sin \theta \right)$ and $K_2 (= 4C\delta p_0)$ are determined empirically. Table 2 contains the values of K_1 and K_2 for the different environments considered herein.

Replacing the values of K_1 and K_2 from Table 2 in Eq. 6, the following expressions (Eqs. 7–11) are formed to evaluate theoretical normal force components for different environments.

$$(F'_n)_{dry} = \left\{ -310200 \frac{V_w}{V_s} ab + 1523900b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \right\} \quad (7)$$

$$(F'_n)_{blaso} = \left\{ -369700 \frac{V_w}{V_s} ab + 1547700b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \right\} \quad (8)$$

$$(F'_n)_{soap\ water} = \left\{ -345200 \frac{V_w}{V_s} ab + 1477200b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \right\} \quad (9)$$

$$(F'_n)_{sodium\ nitrite} = \left\{ -624900 \frac{V_w}{V_s} ab + 1707500b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \right\} \quad (10)$$

$$(F'_n)_{prop\ glycol} = \left\{ -330700 \frac{V_w}{V_s} ab + 1358900b \frac{V_w}{V_s} \left(\frac{a}{d_e} \right)^{1/2} \right\} \quad (11)$$

3 Results and discussion

Grindability is evaluated based on several parameters like force requirements, surface roughness, surface integrity, G ratio, chip-forms, etc. Force requirement for material removal is an important consideration during grinding, as large number of cutting edges with negative rake angle are engaged during the operation. Figure 2a represents the variation of grinding force requirements during twenty passes at 10 μ m infeed. The trend remains same for each set of experimentations performed at 5 and 15 μ m infeed.

From Fig. 2a, it can be seen that normal force (F_n) is always greater than tangential counterpart (F_t) due to the presence of abrasives grits, predominantly having negative rake angle.

Fig. 2 **a** variation of grinding force for different grinding condition with 10 μ m grinding infeed, **b** average grinding force for different grinding condition

These negative raked grits exert a greater thrust force onto the work-tool interaction zone [16]. It can also be noted from Fig. 2a that both the force components have relatively lower values till 7th pass as the system tries to overcome the associated relative stiffness. Hence, the average of both the force components during different grinding environments under three infeed values viz. 5, 10 and 15 μ m are calculated considering 8th to 20th passes as depicted in Fig. 2b. The trend observed in Fig. 2b, suggests that force requirement in dry grinding is the highest, which is quite understandable as it lacks in presence of any form of lubrication and cooling. Due to this the work-tool interaction zone is subjected to greater

Table 2 Values of empirical constants K_1 and K_2 for different environments

Environ-ments	Dry	Blasocut	Soap water	Sodium nitrite	Propylene glycol
K_1	− 310,200	− 369,700	− 345,200	− 624,900	− 330,700
K_2	1,523,900	1,547,700	1,477,200	1,707,500	1,358,900

amount of friction force. The requirement of higher cutting forces gives rise to higher cutting energy associated with the process [25]. With the introduction of fluids through DBD technique, the force requirement has decreased considerably. The trend is found to be blasocut, sodium nitrate, soap water and propylene glycol in an order of decreasing force requirement. The reason behind this may be attributed to the viscosity of the different coolants. As from Table 3 it can be seen that the viscosity of propylene glycol is the highest which enables the fluid to form an effective layer on the grinding surface. This has led to better penetration of the coolant through the stiff air layer into the grinding zone. Similarly, with decrease in viscosity of the fluids, their respective performance also decreases. For a deeper understanding of the obtained force data, a semi-empirical model has been developed as detailed in the *force modelling* subsection. Variation of average normal force has been calculated using the Eqs. 7–11 and are compared with the experimental data as depicted in Fig. 3a. Figure 3a clearly suggests a close proximity in the theoretical and experimental values verifying the exactness of the developed model.

Specific energy requirements are calculated using Eq. 1 for each grinding environment and plotted in Fig. 3b. Dry grinding has resulted in highest consumption of energy for material removal due to absence of cooling and lubrication. With the application of cutting fluid, the trend shows similar behaviour as in case of force requirement. Grinding using propylene glycol as fluid, exhibits a reduction of specific energy requirement by about 22–28% compared to dry grinding under varying grinding infeed values. This is due to the superior penetration of the grinding fluid into the grinding zone owing to its higher viscosity. This is supported by the lower surface roughness parameters experienced during grinding using propylene glycol as can be seen from Fig. 4. From Fig. 4 it can also be noticed that dry grinding has generated roughest surface due to the absence of cooling and lubrication whereas, grinding using soap water closely follows the performance of propylene glycol. Dry grinding also promotes wheel loading to a great extent and this clogging may give rise to increase in the height of surface irregularities as pointed out by Kaplonek et al. [26]. Sodium nitrite has not been found as effective as propylene glycol and soap water; however, performed better than the conventional Blasocut fluid. Propylene glycol has managed to reduce

Table 3 Values of dynamic viscosity of the different grinding fluids considered here

Environments	Blasocut	Soap water	Sodium nitrite	Propylene glycol
Viscosity (cP)	0.13	2.79	1.9	42

Fig. 3 a Theoretical and experimental normal grinding force components for 10 μm infeed under different environments, b Specific energy requirements at different grinding infeed, based on 20 passes

surface roughness by 1.5–2 times over dry grinding. As the coolant has been able to provide enhanced lubrication into the grinding zone, the effects of rubbing and ploughing are reduced and shearing effect is improved. This also has resulted into superior retention of cutting edges and lesser grit dislodgement resulting in improved grinding wheel life. These two effects have improved the G ratio under propylene glycol as can be observed in Fig. 5.

G ratio during dry grinding is the lowest pointing to the escalated grit dislodgement that may have occurred. Higher grit dislodgement and grain flattening [27] has also been resulted due to greater force during dry grinding. In some cases, the obtained value of G-ratio is less than 1.

Fig. 4 Average surface roughness for different grinding environments

Fig. 5 G ratio obtained during different grinding environments

This implies that more wheel material is being removed compared to work material. This can be attributed to the fact that as silicon carbide wheel has considerably higher friability index and Ti-6Al-4V retains its hardness at elevated temperature, enhances the generation/requirement of high cutting forces coercing the wheel to undergo auto-sharpening more frequently. This results in high material removal from the wheel. The parameter suggests the importance of application of cutting fluid during grinding of Ti-6Al-4V. Grinding using conventional fluid and

sodium nitrite has not resulted satisfactory G ratio, indicating comparatively lesser cooling and lubrication than soap water and propylene glycol as grinding fluids. Propylene glycol has performed best considering G ratio where it has managed to improve the ratio by 4–4.5 times compared to dry grinding.

Surface quality obtained during the process is an important parameter to evaluate grindability. Surface morphology observed under scanning electron microscope is depicted in Fig. 6. Poor surface quality can be noticed during dry grinding with the presence of scars, holes and material pullout. This can be attributed to the absence of lubrication in the zone. Conventional fluid and sodium nitrite also have failed to generate a superior surface whereas, grinding using soap water has generated much improved surface with uniform grinding marks suggesting enhanced shearing. Surface generated using propylene glycol is found to be in proper agreement with the previous observed trends and exhibits much superior surface with uniform and long grinding marks, implying enhanced shearing action. This can be reconfirmed with the type of grinding chips obtained, as chip-forms obtained during the process can be a prime factor to evaluate grindability. The SEM micrographs of chips, collected during 20th pass are shown in Fig. 7. Figure 7e exhibits leafy and curled type chips, indicating improved shearing action while using propylene glycol as grinding fluid, whereas dry grinding (Fig. 7a) has produced chunky and blocky type of chips

Fig. 6 SEM micrographs of the ground surface obtained during different grinding environments, **a** dry, **b** blasocut, **c** soap water, **d** sodium nitrite, **e** propylene glycol

Fig. 7 Chip-forms observed during different grinding environments, **a** dry, **b** blasocut, **c** soap water, **d** sodium nitrite, **e** propylene glycol

pointing to higher wheel loading, which has contributed to higher force and specific energy requirements, and has reduced surface smoothness and G ratio. Grinding using conventional coolant has also resulted in formation of blocky chip showing the inferior grindability. When compared to the chips obtained during grinding with propylene glycol, reduction in chip sizes can be clearly seen. In a recent study Mukhopadhyay and Kundu [28] have obtained similar trends while using alumina wheel for grinding Ti-6Al-4V under a different fluid delivery setup.

4 Conclusions

In the present experimental investigation of grinding of Ti-6Al-4V with SiC wheel, suitability of three unconventional and environment friendly grinding fluid has been evaluated under a novel SQL based DBD setup. Grindability at different environments has been critically analyzed with the help of the relevant parameters like grinding force and specific energy requirements, G ratio, surface roughness parameters, surface morphology and chip-forms under three different grinding infeed values viz. 5, 10 and 15 µm. The major findings from the current study are as follows.

- Application of cutting fluid enhances grindability of the material compared to dry grinding.

- Conventional synthetic oil-based fluid (blasocut) is not suitable for grinding Ti-6Al-4V.
- Among the different unconventional fluids, propylene glycol has served to be the most superior in order to improve grindability of Ti-6Al-4V. It has decreased force requirement by 15–28% and specific energy requirement by 22–28% under varying grinding infeed while compared with dry grinding. It has also improved surface smoothness by 1.5–2 times and G ratio by 4–4.5 times compared to dry grinding.
- Micrographs of the ground surface under SEM also suggest that propylene glycol generated a much-improved ground surface with uniform and long grinding marks, implying enhanced shearing action.
- The micrographs of the chips also indicate improved shearing action while using propylene glycol as grinding fluid.
- The developed method of cutting fluid delivery system poses itself as having significant potential to be used during machining of different materials as the system is economic, ecological and effective.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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