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Ultrasonic-Assisted Grinding of Ti6Al4V Alloy

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Abstract

In conventional grinding of hard to cut materials such as Ti6Al4V alloys, surface burning, redeposition and adhesion of chips to the grinding wheel and workpiece occur visibly unless it is carried out at low speeds and with high volume of cutting fluid. Ultrasonic assisted grinding is an efficient machining process which improves the machinability of hard-to-cut materials by changing the kinematics of the process. In this research, the effect of imposition of ultrasonic vibration on the grinding of Ti6Al4V alloy is studied. Longitudinal vibration at ultrasonic frequency range (20 kHz) is applied on the workpiece and machining forces and surface roughness are compared between conventional grinding (CG) and ultrasonic assisted grinding (UAG) processes. An ultrasonic setup is designed, optimized and fabricated based on combination of mathematical modeling, FEM analysis and genetic algorithm. Comparison between CG and UAG at several cutting and feed speeds and cutting depths are carried out, and the effect of ultrasonic vibration in dry condition is also studied. The results show reduction of grinding forces and improvement of surface roughness when ultrasonic vibration is applied on the workpiece.

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1. Introduction

The use of titanium alloy especially Ti6Al4V for industrial applications is rapidly increasing due to its high strength-to-weight ratio, biocompatibility and robust mechanical property at high temperatures. Aerospace and marine industries, gas turbines and biomedical implants are some of the areas of application of this alloy. However, poor machinability caused by poor thermal properties and high reactivity at high temperatures hinder the manufacturing of Ti6Al4V parts.

In conventional grinding (CG) of titanium alloys, surface burning, redeposition, high tool wear, chip adhesion on wheel and thermal stress are reported [1]. Some efforts have been reported to improve machining conditions of Ti alloys and eliminate usual problems [2]. Various cutting fluids such as different oils, water, alkaline fluid, liquid nitrogen, air flow and cryogenic system have been investigated, with some degrees of success, but usually surface burning and

redeposition were visible. Various non-traditional processes such as Electro Discharge Machining (EDM), Ultrasonic Machining (USM), Ultrasonic-Assisted Machining (UAM) and Laser-Assisted Machining (LAM) are employed to eliminate problems with conventional machining [3-4]. Among these methods, UAM offers a good choice due to its simple setup, reducing the heat affected zone, and being less hazardous by decreasing coolant consumption. Reduction in machining forces, burr size, coolant consumption and tool wear as well as improved surface integrity and material removal rate are reported for UAM in comparison to conventional methods [3-7].

The effects of wheel speed, grit size, wheel type, depth of cut and cutting fluid on the surface quality of Ti6Al4V workpiece, under CG conditions was studied experimentally by Turlity [1]. Experimental results indicated that redeposition due to Ti high reactivity is the main factor for low surface quality. Sadeghi et al. [2] compared different cutting fluids and cooling methods for CG of Ti6Al4V. Conventional lubrication,

Minimal Quantity Lubrication (MQL) and dry grinding are considered as the cooling methods.

Pujana et al. [6] showed that lower feed forces and higher process temperatures resulted when ultrasonic vibration was superimposed on drilling of Ti6Al4V samples. Rotary ultrasonic machining of brittle materials and titanium was studied experimentally and theoretically by Qin et al. [7]. Ghahramani et al. [8] investigated the effects of ultrasonic oscillation in grinding of Ti6Al4V workpieces and reported reduced tangential and normal forces and improved surface finish. UAG was also used by Akbari et al. [9] for ceramic material (Al_2O_3). They reported a 22% reduction in grinding forces and an 8% improvement in surface finish.

In this study, the effects of ultrasonic oscillation on conventional grinding of Ti6Al4V6 are experimentally studied. Also, grinding of Ti alloy at dry conditions compared to wet conditions. For this purpose, an ultrasonic setup is designed; optimized and fabricated that applies longitudinal vibration at ultrasonic frequency range on the workpiece. A combination of genetic algorithm as optimization instrument, mathematical modelling based on full factorial design and FEM modal analysis is used to obtain optimum ultrasonic setup. Experiments at various cutting speeds, feed speeds, coolant volume and depths of cut are performed with and without ultrasonic vibration. Grinding forces and surface roughness are recorded and compared to evaluate the effect of ultrasonic vibration.

2. Setup

In UAM, low amplitude motion in ultrasonic frequency range (over 17500 kHz) is super-imposed on the tool or workpiece. Most ultrasonic actuators need especial equipment to transmit and amplify the motion to create the desired shape. To have valuable and reliable experimental data, it is imperative to design and build an efficient setup. A combination of mathematical modelling and optimization method are implemented to achieve an efficient system. Results of finite element analysis are least-square fitted to obtain the objective function for optimization of the design such that the system works at a longitudinal resonance frequency of 22 kHz at an amplitude enhancement factor of 7 (amplitude value of workpiece with respect to the actuator generated amplitude). Finally, genetic algorithm is implemented to optimize the design parameters.

2.1. Initial design

The proposed setup is composed of a piezoelectric transducer, a horn, a booster and a flexible structure as shown in Fig. 1. The horn is connected to the transducer

to enhance the amplitude. The booster is used for transmission and further amplitude enhancement. The flexible structure contains the plane on which the workpiece is attached.

Initial design for horn and booster are achieved by means of wave equation in cylindrical bar with some simplification. Due to the complexity of the flexible structure geometry, FEM analysis is used to obtain initial parameters predictions and setup evaluation.

2.2. Mathematical modeling

It was first determined that the best conditions for ultrasonic vibration occurs when longitudinal vibration at 22 kHz frequency and amplitude enhancement factor of 7 is applied. Therefore an objective function was defined to minimize the error with respect to these conditions. The objective function is composed of two functions which are derived through mathematical modelling, one for frequency (f_f) and the other for the enhancement factor (f_a), A in this equation is a constant.

$$F = |22000 - f_f| + A \times |7 - f_a| \quad (1)$$

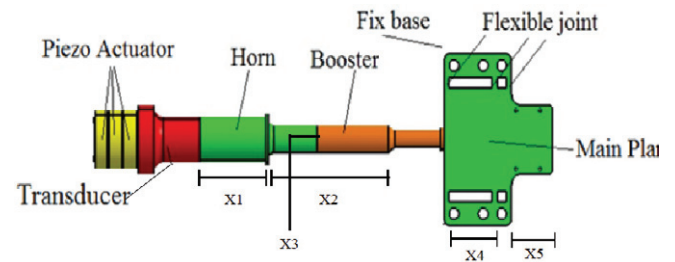


Fig.1. Ultrasonic setup components

In order to optimize the parameters, it is necessary to express f_f and f_a in terms of design parameters. The selected design parameters and their ranges of variation are reported in table 1. The parameters are the length of the first part of the horn-booster (X_1), the middle length of the horn-booster (X_2), the diameter of the middle part of the horn-booster (X_3), the distance between the first and the second flexible joints (X_4) and the length of the last part of the main plane (X_5) (Fig. 1).

Table 1: Design parameters

Design parameter	Variation interval (mm)
X_1	[50,70]
X_2	[110,130]
X_3	[20,30]
X_4	[30,50]
X_5	[35,50]

In this work, the mathematical model is defined using a combination of a two level full factorial design and finite element modal analysis. In the full the factorial design for two level, each parameter accepts two states in the variation interval. The two-level full factorial design with P parameter yield 2^P different systems. To obtain required information for each system, finite element modal analysis is used. By combining, the two-level full factorial design and finite element modal analysis data, two linear polynomials are derived to model mathematically longitudinal natural frequency and amplitude enhancement (Equation 2 and Equation 3). Each equation has 32 constants. The constants of these equations (a_{ijkmn}, b_{ijkmn}) are obtained by substituting modal analysis data in the derived equations, using the least square technique.

$$f_f = \sum_{i=0}^1 \sum_{j=0}^1 \sum_{k=0}^1 \sum_{m=0}^1 \sum_{n=0}^1 (a_{ijkmn} X1^i X2^j X3^k X4^m X5^n) \quad (2)$$

$$f_a = \sum_{i=0}^1 \sum_{j=0}^1 \sum_{k=0}^1 \sum_{m=0}^1 \sum_{n=0}^1 (b_{ijkmn} X1^i X2^j X3^k X4^m X5^n) \quad (3)$$

2.3. Optimization

In this work, genetic algorithm (GA) is used to optimize the design parameters. Table 2 displays the optimum values obtained from GA. The optimization yields a longitudinal frequency of 22001.21 Hz and an enhancement factor of 7.311. The optimum setup parameters are then used in an FEM modal analysis for verification. The resonant frequency from FEM modal analysis is 22068 Hz which shows an error of just about 0.03 percent. Finally, the setup was built according to final optimization results. After building the setup, its longitudinal resonance frequency was obtained by means of the generator software which sweeps the frequency range at low sampling rate. The actual resonant frequency of the setup was around 20.5 kHz, which shows around 6% error with respect to the FEM results. The error is within a reasonable range, and the setup can be effectively used for UAG.

Table 2: Optimization results

Parameter	Optimum value	f_f mathematic model	f_f FEM	Error
X1	65			
X2	125.46			
X3	22.61	22001.21 Hz	22068	0.03 %
X4	48.4		Hz	
X5	44.735			

3. Experiments

Fig. 2 shows the UAG setup consisting of transducer, horn, booster and flexible structure. Using this setup, plunge grinding of Ti6Al4V was carried out on a flat surface grinding machine. Table 3 shows the mechanical properties of workpiece. Comparison between UAG and CG is carried out at various depths of cut, cutting speeds and feed speeds. The difference between UAG in dry and wet grinding is tested too. Table 4 presents the machining conditions used in the test. A 3-axis table top dynamometer (KISTLER, type B9257) is used to measure tangential and normal forces. The workpiece is attached to the flexible plate, which is itself attached on the dynamometer. Surface roughness has been measured by a TR200 portable roughness tester. Ultrasonic vibration has been generated by a piezoelectric transducer and a generator (Master sonic MSG 2000). The vibration is applied on the workpiece in feed direction.

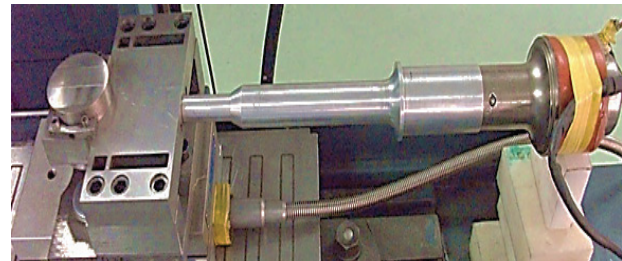


Fig.2. Designed and built Ultrasonic setup

Table 3: Ti6Al4V properties

Density	Hardness	Yield Strength	E, Modulus
4430 (kg/m ³)	36 (HRC)	925 (MPa)	113.8 (GPa)

Table 4: Machining conditions

Wheel speed	15-25 m/s
Depth of cut	5-10-15 μm
Table speed	0.24 & 0.3 m/s
Grinding wheel	Tyrolit - 89A60K5AV217 (175×15×51 mm)
Dressing tool	Single point diamond
Cutting fluid	Alkaline soap & dry
Workpiece	Ti6Al4V (Ø 50 × 14 mm)
Ultrasonic frequency	20400±200 Hz
Ultrasonic direction	feed direction

4. Results and Discussion

In what follows, the effects of superposition of ultrasonic vibration on grinding of Ti6Al4V are studied. Grinding forces and surface roughness at various cutting

conditions for CG and UAG are illustrated in Fig. 3 to Fig. 5.

It is observed that in all cases, normal forces are larger than tangential forces due to the high negative rake angle and occurrence of rubbing action. By increasing the depth of cut, grinding forces in both UAG and CG increase, but in UAG a shift to lower values is visible. Although results do not follow a uniform trend for grinding forces with variation of cutting speed, reduction in grinding forces and surface roughness is observed in all UAG experiments. This non-uniformity can be attributed to the built up edge effect resulting from high reactivity and wheel loading due to adhesion of Ti alloy.

When ultrasonic vibration is applied, the results at wet conditions show an average reduction of 13.5% and 14.2% in normal and tangential forces, respectively. The reduction of grinding forces for dry UAG are nearly twice as much as that in wet condition. Larger force reduction in dry state may be attributed to material softening at higher temperatures due to the absence of coolant. However, surface burning for dry CG is obvious whereas in UAG, the surface quality is better. Fig. 7 compares the surface quality in dry CG and dry UAG. In this figure, the improvement of surface quality in UAG is visible. Surface roughness along feed direction in average shows a 10% improvement when vibration is imposed.

The imposed ultrasonic vibration influences the grinding process kinematics. When vibration is present, variation in the undeformed chip thickness happens which influences the grinding forces. In the presence of oscillation, impact loads are generated between the grits and workpiece surface. The impact loads provide a self-sharpening action for abrasive grains and thus keep them sharp. For sharper grains, penetration in the material will be easier and consequently, reduction in grinding forces will be resulted. Besides, impact loads enhance the brittle fracture mechanism and increase the micro crack length on the surface, which results in more convenient penetration and reduction of grinding forces. In ultrasonic mode, depending on cutting depth and vibration amplitude, the contact area between grits and workpiece can vary, leading to a decline in forces.

In grinding process, the normal force has the largest effect on the surface roughness and surface plastic deformation, whereas the tangential force influences the heat generation. Since in UAG grinding, the forces are decreased, improvement in surface quality and surface roughness are expected. When oscillation is superimposed, adhesion of Ti chips to abrasive grits is decreased; therefore, redeposition is reduced, leading to a better surface quality. Furthermore, in the presence of ultrasonic vibration, the penetration of cutting fluid to

the cutting zone becomes easier, which may result in improved surface integrity.

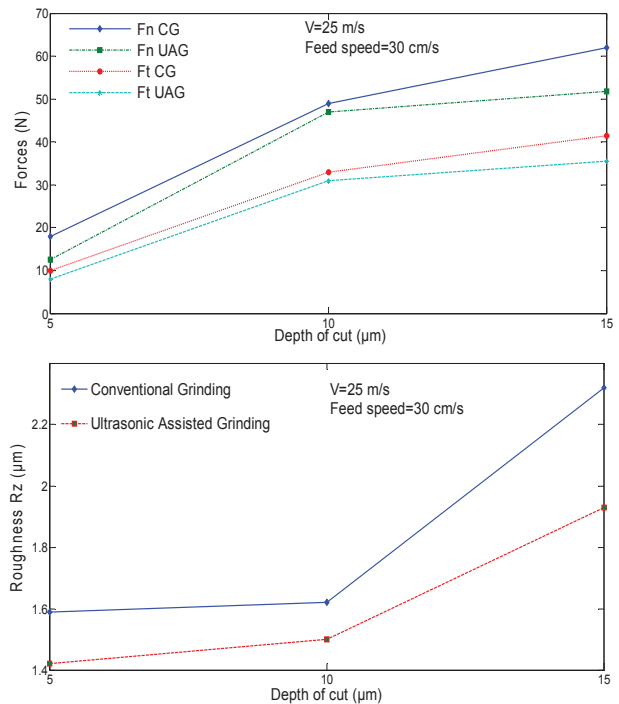


Fig. 3. Grinding forces and Surface roughness versus depth of cut for UAG and CG, V=25 m/s, Feed speed=0.3 m/s, coolant rate=2 lit/min

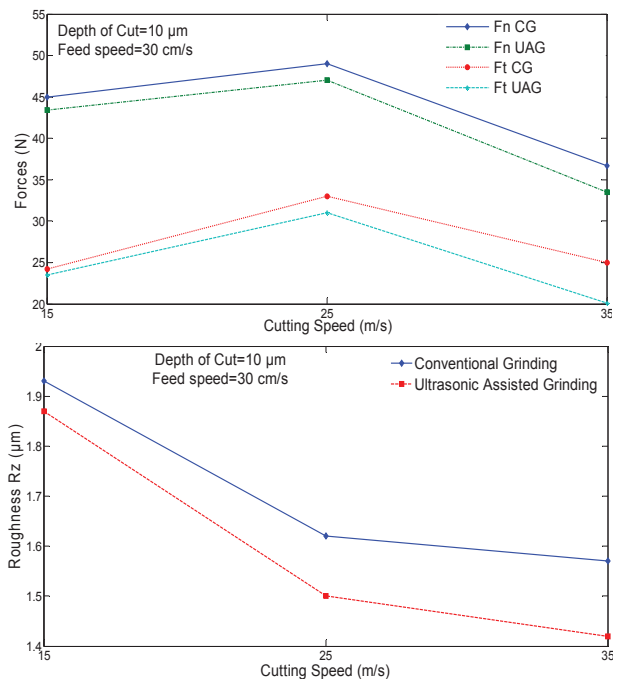


Fig. 4. Grinding forces and Surface roughness versus cutting speed for UAG and CG, depth of cut=10 μm, Feed speed=0.3 m/s, coolant rate=2 lit/min

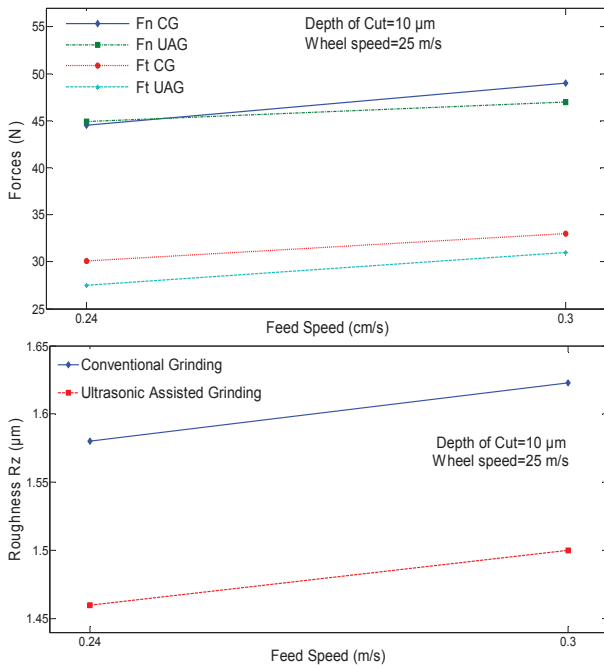


Fig. 5. Grinding forces and surface roughness versus feed speed for UAG and CG, depth of cut=10 μm, cutting speed=25 m/s, coolant=2 lit/min

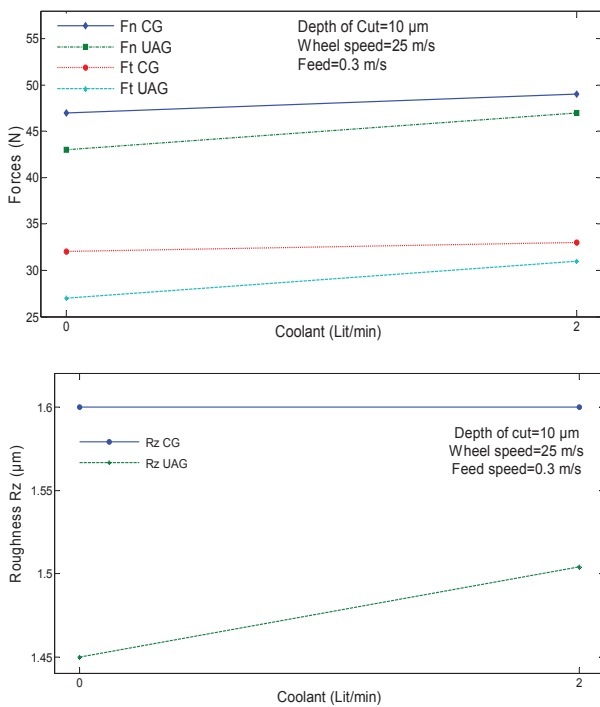
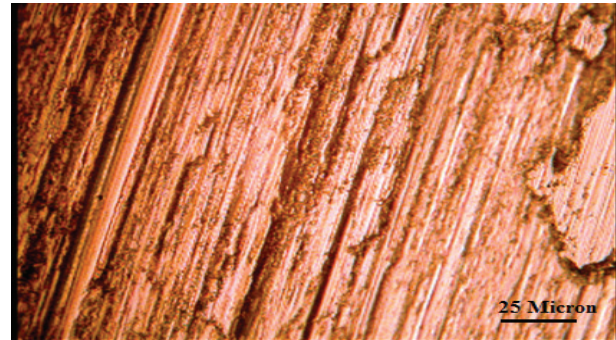
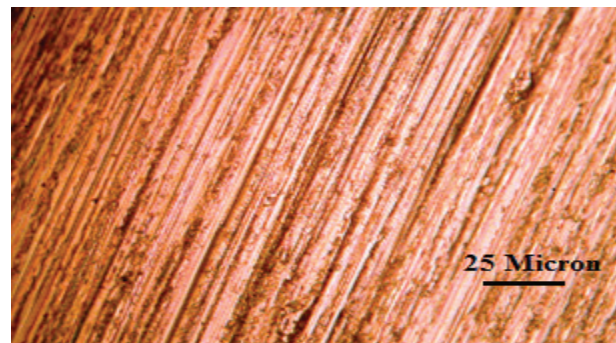


Fig. 6. Grinding forces and surface roughness versus coolant volume (dry and wet) for UAG and CG, depth of cut=10 μm, cutting speed=25 m/s, Feed speed=0.3 m/s



(a) Dry conventional grinding



(b) Dry ultrasonic assisted grinding

Fig.7. surface quality for dry conventional grinding and dry ultrasonic assisted grinding

5. Conclusions

In this investigation, the cutting forces and surface finish are compared between CG and UAG procedures. For this purpose a system is designed, optimized and fabricated to impose linear vibration at ultrasonic frequency range on Ti6Al4V work piece at feed direction.

Improvements in forces and surface quality may be attributed to the variation in the dynamics of the grinding process when vibrations are applied. Ultrasonic vibration generate impact loads, lower contact surface, variation in cutting depth, self-sharpening and improvement in lubricant penetration that leads to change in grinding forces and surface quality.

The obtained results show that:

1. Grinding forces have been reduced at all UAG experiments.
2. Normal and tangential forces in UAG have an average reduction of 13.5% and 14.2%, respectively.
3. Surface roughness shows an average 10% improvement when ultrasonic vibration is imposed.
4. The decline of forces is more for dry UAG in comparison to wet UAG.
5. In UAG, higher depth of cut and feed can be selected in comparison to CG with still better surfaces than CG.

6. Due to the reduction of grinding forces and improvement of surface roughness in UAG, grinding at higher cutting depth and cutting speed with lower coolant consumption are possible which lead to higher production rate and lower manufacturing cost. Furthermore, the decrease in coolant consumption is desirable for environmentally conscious manufacturing.

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