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Wear Behavior of a Vitrified Bond CBN Wheel by Ultrasonic-Assisted Creep Feed Profile Grinding of Inconel 718

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Abstract. Generally in the grinding of modern aviation materials such as nickel-based superalloys, problems frequently occur in terms of burr formation, profile loss of the wheel, high heat generation in the contact zone, high grinding forces as well as low process reliability. A recent and promising method to overcome these technological constraints is the use of ultrasonic assistance, where high-frequency and low amplitude vibrations are superimposed on the movement of the workpiece. This paper presents the design of an ultrasonically vibrated block sonotrode and the experimental investigation of ultrasonically assisted profile grinding of Inconel 718. The profile wear, radial wear of the wheel, grinding forces and surface roughness by ultrasonic-assisted and conventional profile grinding were measured and compared. The obtained results show that the application of ultrasonic vibration can decrease the radial wear of the wheel, profile wear, grinding forces and surface roughness considerably.

Introduction

Conventional grinding (CG) of modern nickel-based superalloys causes high grinding temperatures and forces and subsequently rapid wear of the wheel and profile due to their high strength and abrasivity even at relatively low cutting speeds. Hence, conventional aluminum oxide wheels are gradually being replaced by cubic boron nitride (CBN) grinding wheels in the aerospace, bearing, automotive and turbine industries. Superior wear resistance and heat conductivity are the main advantages of the CBN wheels over conventional aluminum oxide wheels. These properties result in a lower wear of the wheel and less of a tendency for thermal damages and undesirable residual stresses [1]. However, in the grinding of nickel-based superalloys even with CBN wheels, problems frequently occur in terms of burr formation, profile loss of the wheel, high heat generation in the contact zone and high grinding forces. Compared with resin-bonded, metal-bonded or electroplated CBN wheels, the vitrified CBN wheels are more often preferred for form and profile grinding due to their better dressability. The high profile wear of the CBN vitrified wheel and time consuming and costly dressing process with relatively short intervals when grinding nickel-based superalloys with the CBN vitrified wheel have hindered the wide application of CBN wheels in the industry. Some industries still prefer to utilize aluminum oxide wheels and continuous dressing process when profile grinding of nickel-based superalloys.

A recent and promising technique to overcome these technological constraints is known as ultrasonic-assisted grinding (UAG). The principle of this technique is adding high frequency (16-40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 μm) in the feed or cross feed direction to the wheel or workpiece. Considerably lower grinding forces, higher material removal rates and decreased grinding temperatures have been announced as advantages of ultrasonic-assisted grinding over conventional grinding [2 - 5]. Babitsky et al. have proved that deformation processes for ultrasonic-assisted machining are restricted in the vicinity of the cutting edge along the surface of the workpiece and are not observed underneath the cutter, in contrast to the conventional machining process [6]. They demonstrated that compared to conventional machining, ultrasonic-

assisted machining of high-strength aerospace superalloys (aviation materials), e.g. Inconel, C263 alloy, etc., leads to significantly reduced cutting forces and superior quality of the machined surface, permitting efficient machining of these materials. In this investigation, an ultrasonic unit has been designed and developed to grind nickel-based superalloys ultrasonically. Grinding forces, surface roughness, surface profile, profile wear and radial tool wear are compared for profile grinding of Inconel 718 with and without superimposing of ultrasonic vibrations to the process.

Experimental set-up and procedures

The experimental setup and the Profile of the Test Wheel are illustrated in Fig. 1. The grinding forces are measured by a dynamometer which is mounted beneath the workpiece and on the machine table. In order to obtain the radial wheel wear and profile wear, thin steel sheets were ground after dressing and at prefixed intervals. Hence, the radial and profile wear were calculated by measuring the profile and depth differences of these sheets, utilizing a surface profile measurement device.

The ultrasonic power supply converts 50 Hz electrical supply to high-frequency electrical impulses. These high-frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (20 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the block sonotrode and transmitted to the workpiece fixed on the block sonotrode. The resultant vibration amplitude of the workpiece reaches 8 μm at a frequency of about 20 kHz. Vibration is applied to the workpiece in the feed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The tests were carried out for both ultrasonic-assisted grinding (UAG) and conventional grinding (CG) with the same instrument. However, during the CG the ultrasonic generator was switched off.

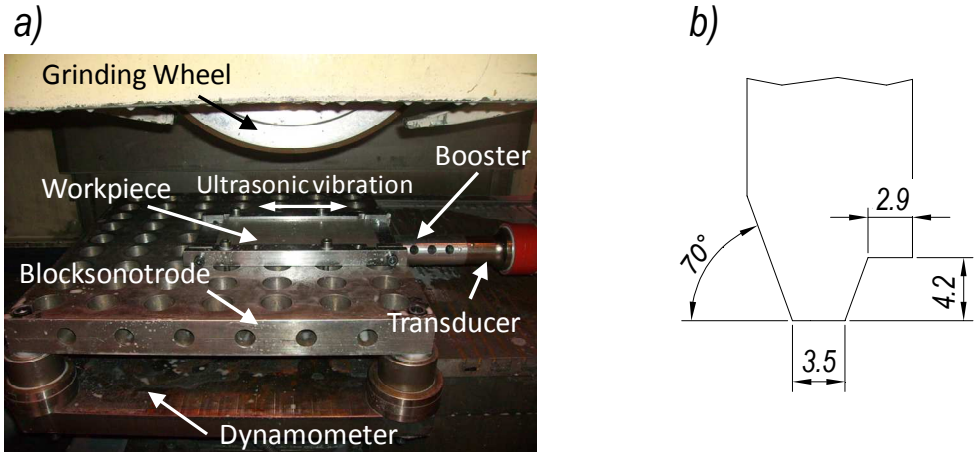

Fig. 1. a) The experimental set-up, b) Test wheel profile

A new AMMM technology is utilized in this investigation. Many vibrating modes can be synchronously excited by the AMMM generator to produce uniform and repeatable multimode vibrations with a high intensity, while avoiding the creation of stationary and standing waves, so that the whole vibrating system is fully agitated. The AMMM generator is also able to produce variable frequency sweeping oscillations around a central operating frequency, and contains an amplitude-modulated output signal (where the frequency of amplitude modulation follows sub-harmonic low frequency vibrating modes of the mechanical system) [7 - 9]. The AMMM generator is capable of measuring the resonance frequency within 10 kHz and 100 kHz with a resolution of 10 Hz. The generator converts phase shifts (from -90° to 90°) to voltage in a range between 0 and 5 V.

The experimental equipment consists of the following:

- *Machine tool:* Elb Micro-Cut AC8 CNC universal surface grinding machine
- *Surface roughness and profile tester:* Hommel-Werke model T-8000
- *Dynamometer:* Kistler piezoelectric dynamometer model 9255B
- *Eddy current displacement measurement system:* Micro epsilon eddyNCDT 3300, to measure the amplitude of vibration; Measuring ranges 0 – 0.5 mm, Linearity 0.2%, Resolution 0.005%, Measuring rate 100 kHz
- *Ultrasonic Vibration Generator*: AMMM-1000 W generator-MP Interconsulting, Frequency ranges of 18.000 to 50 kHz.

The settings of main machining parameters for the present study are summarized in Table 1.

Table 1. Major machining parameters

Grinding wheel	Vitrified bond CBN grinding wheel, B151 C150
Workpiece	Inconel 718 (200 x 100 x 14 mm)
Grinding conditions	Feed speed v_{ft} = 300 mm/min; Cutting speed v_c = 60 m/s Depth of cut a_e = 3 mm (with full contact of the wheel profile)
Coolant	Emulsion (5%), 50 l/min
Grinding process	Creep feed profile grinding
Dresser	Electroplated diamond form roller D427
Dressing conditions	Overlap ratio u_d = 4; Wheel peripheral speed v_{sd} = 60 m/s; Depth of dressing cut a_{ed} = 3 μm, Dressing speed ratio q_d = 0.5
Ultrasonic vibration	Parallel to the feed direction, Frequency f = 22 kHz, Amplitude A = 8 μm

Experimental results and discussion

Investigations were carried out comparing conventional grinding with ultrasonic assisted grinding. Radial tool wear, profile wear, the grinding forces and surface roughness were measured. In all the carried out experiments normal grinding forces were higher than tangential grinding forces and both normal and tangential forces were reduced considerably by the ultrasonic-assisted grinding process.

Figs. 2–4 show the grinding forces (F_t and F_n), surface roughness (R_a and R_z) and radial wear of the grinding wheel (Δr) when UAG and CG, with increasing material removal v'_w. In UAG, grinding forces and temperature, and consequently the wear of the abrasive grains are relatively low. Therefore, the need for dressing is significantly reduced and the grinding wheel life is increased considerably. This leads to a more time and cost efficient process.

However, the situation is completely reversed in CG. During the conventional grinding process an increase in the grinding forces leads to an increase in cutting temperature and wear of the abrasive grains. Hence the abrasive grains will become dull, in turn the grinding forces and temperature will increase and the surface roughness will reduce.

As the profile created by the wheel almost makes the surface roughness measurement normal to the grinding process impossible, the surface roughness presented in Fig. 3 is measured at parallel direction to the grinding process. As shown, there is no significant difference in surface roughness between CG and UAG. This is hard to explain and need further investigations (planned as the next researches) to find out the effects of the ultrasonic vibrations on the phenomena such as wheel clogging [10], self-sharpening and micro-fracture of the grains in grinding of nickel-based superalloys.

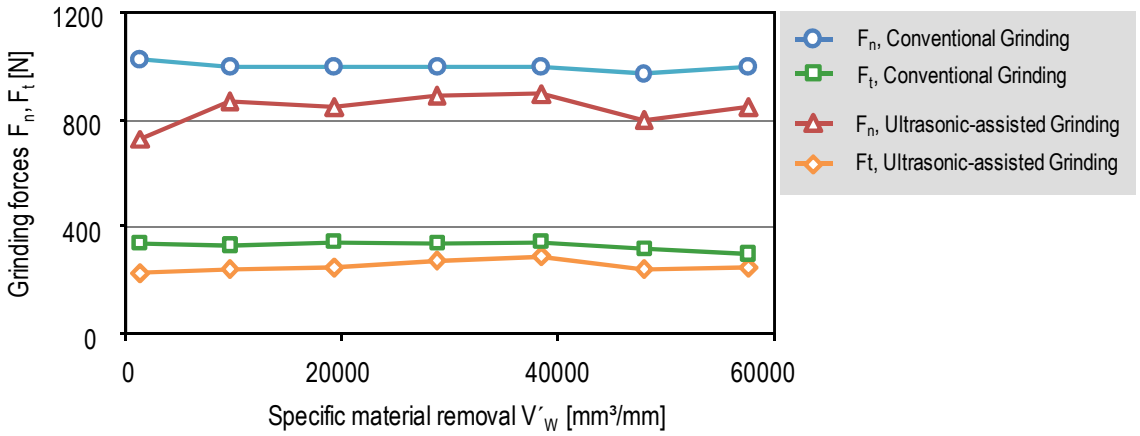

Fig. 2. Effect of specific material removal on grinding forces

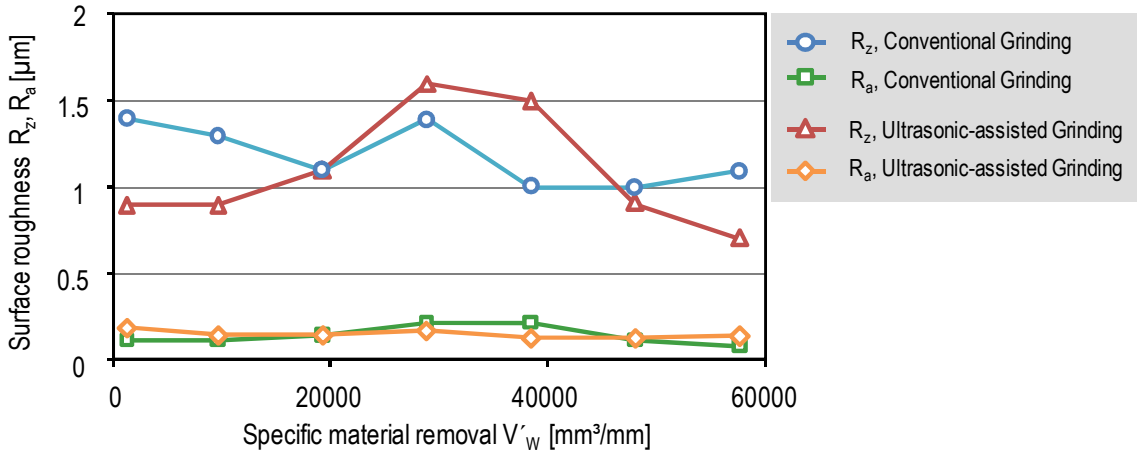

Fig. 3. Effect of specific material removal on surface roughness (R_a and R_z)

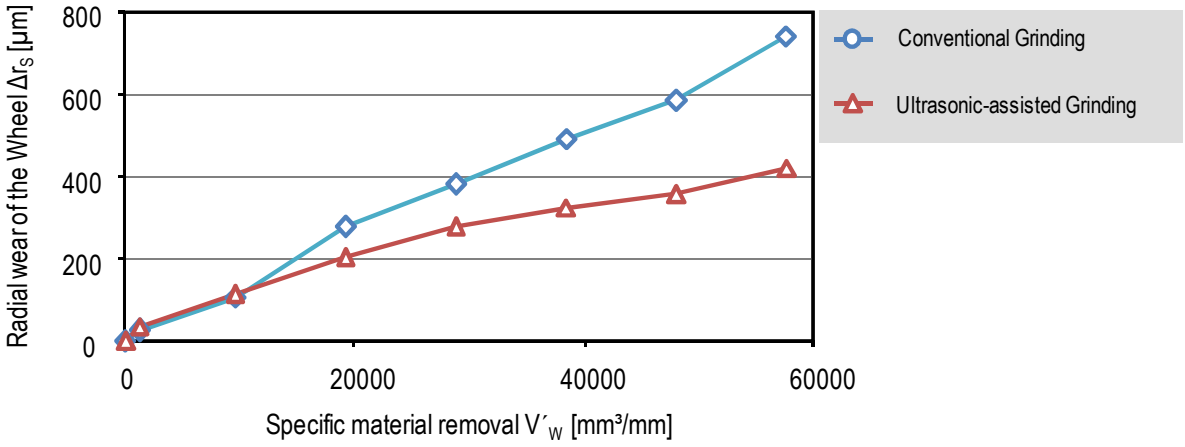

Fig. 4. Effect of specific material removal on radial wear of the grinding wheel

Inconel 718 is a high-grade heat-resistant Ni-based superalloy widely used in the gas turbine blades and aerospace industry. The excellent material toughness results in difficulty in chip breaking during the process. In addition, precipitate hardening of γ´´ secondary phase (Ni_3Nb) together with work-hardening during machining makes the cutting condition even worse [11]. All these difficulties lead to serious tool wear and less material removal rate (MRR). This material is very abrasive and causes cutting edges blunting and high cutting temperatures. As can be seen from Fig. 4, UAG and CG processes demonstrate almost same wear behavior at low specific material

removals (first stages of tool wear). However, the CG results in a rapid increase of radial wear at relatively high specific material removals, i.e. $v'_w > 10000$ mm^3/mm. This can be due to macro fracture, grains pullout and wear of the bond at progressed wear stages, as a consequence of high grinding forces and temperatures. On the other hand, UAG exhibits almost a linear wear behavior along the creep feed profile grinding process.

Due to the high-frequency interaction of active grains on the workpiece, the cutting process in ultrasonic assisted grinding process becomes discontinuous and ultrasonic impact action occurs, causing the material to begin to rollover more easily as well as more micro-cracking propagation in the cutting zone which both make an effective interaction between grits and the workpiece surface [12]. Therefore, the grinding forces and frictional effects are decreased, so that less plastic deformation occurs. In addition, as the sliding speed in the ultrasonic-assisted grinding process due to ultrasonic vibration is higher than the sliding speed in the conventional grinding process, the coefficient of friction reduces [3].

Profile wear of the wheel for both UAG and CG processes are also measured and compared with each other. Fig. 5 shows the measured profile wears at specific material removal equal to 60000 mm^3/mm. Compared to the ultrasonic-assisted grinding process (UAG), conventional grinding process (CG) has induced higher profile wear (almost 45% higher profile wear at the deepest area of the profile). Additionally, in the contrary with CG, the geometry of the profile is almost kept constant by UAG and the various points of profile are worn almost equally.

Fig. 6 shows photographs of the burrs formed at the ground workpiece during the grinding experiments. As can be seen from the figure, the UAG produces almost no grinding burrs. On the other hand, CG produces very long and thick grinding burrs. Hence, another finishing process is required to remove these burrs, which leads to a higher machining time and cost.

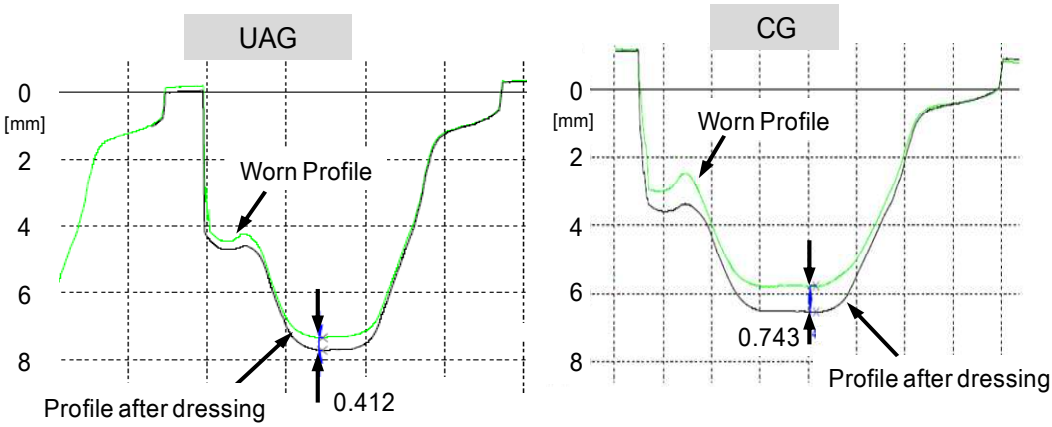

Fig. 5. Profile wear comparison between ultrasonic-assisted grinding (right) and conventional grinding (left) at $v'_w = 60000$ mm^3/mm

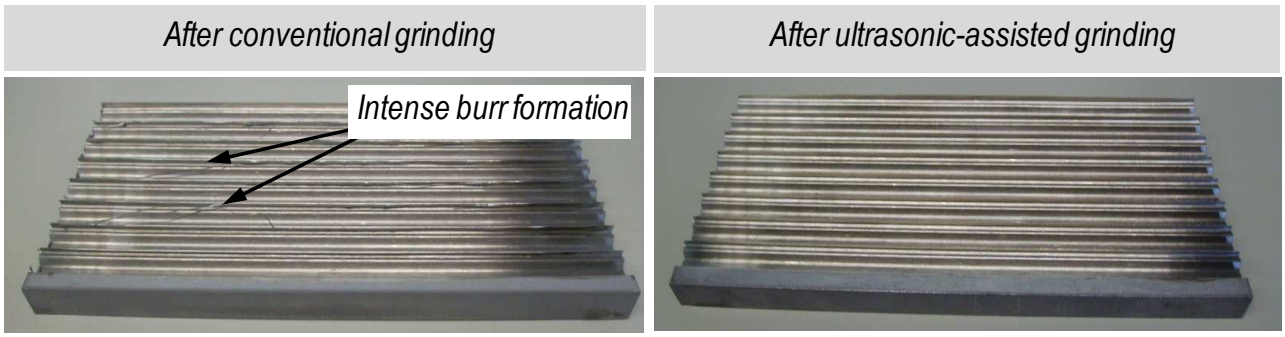

Fig. 6. Burr formation by creep feed profile grinding.

Summary

Comparison of the UAG and CG methods for creep feed profile grinding process demonstrate considerable advantages of the former technology for grinding nickel-based superalloys.

- The grinding forces induced by ultrasonic-assisted grinding (UAG) process are lower than those in conventional grinding process.
- Comparative experiments demonstrated up to significant reduction in radial wear and profile wear of the grinding wheel for the workpieces machined with superimposed ultrasonic vibration.
- The burr formation is much lower in UAG in comparison with those in CG.

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