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Grinding titanium Ti-6Al-4V alloy with electroplated cubic boron nitride wheel under cryogenic cooling †

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Abstract

A grinding experiment was conducted with Ti-6Al-4V alloy in a wet and cryogenic coolant environment. An electroplated cubic boron nitride grinding wheel was used for this experiment. The input process parameters that were considered were depth of cut and nozzle inclination angle. The output response parameters that were considered were tangential forces, normal forces, grinding zone temperature, specific energy, and surface roughness (R_a). Experimental results indicate an 8% to 27% reduction in tangential force and 3% to 12% reduction in normal force when liquid nitrogen was used as coolant. R_a is reduced by a maximum of 38% over wet grinding, and grinding zone temperature is reduced by up to 55%. Surface modification and chip morphology were analyzed. Experimental results indicated that the nozzle angle at 45^o has a significant effect on the grinding process.

Keywords: Ti-6Al-4V; CBN; Cryogenic coolant

1. Introduction

Grinding is a finishing process that is essential for many manufacturing processes. A material is removed by the influence of abrasive grit on the work material at high cutting speed [1]. The heat generated at the time of the grinding process plays an important role in determining quality. The high friction between the abrasive grit and work material is converted into heat energy to elevate thermal damage and stress. The high temperature at the grinding zone leads to the sticking of abrasive grit particles on the work material [2].

Heat dissipation from the grinding zone is a major impediment because of the large contact area between the work piece and the wheel. Coolant lubrication is necessary to reduce the friction between the wheel and the work material, and to prevent thermal damage of the work material. Hence, cooling atmosphere plays an important role in the grinding process [3, 4]. The formation of a stiff boundary layer on the grinding wheel prevents the cutting fluid from reaching the grinding zone. The application of an oil-based coolant leads to biological air pollution, water pollution, and soil contamination during disposal. The cost of storage and recycling of the oil-based coolant is high [5].

Cryogenic coolant is an alternative cutting fluid. Liquid nitrogen (LN_2) is environmentally safe, is used as a coolant in many machining processes, and requires no disposal facilities. Dhananchezian et al. [6] reported that the application of LN_2 in the turning process produced improved defect-free surfaces and offered low cutting forces because of the effective control of the temperature in the grinding zone. N. B. Fredj et al. [7] investigated the effect of cryogenic cooling on AISI 304 stainless steel and found that LN_2 reduces grinding zone temperature to more than 500°C compared with oil-based grinding fluids. Moreover, surface roughness (R_a) is reduced by up to 40% compared with oil-based grinding fluid.

Manimaran et al. [8] reported that applying LN_2 reduces grinding forces by up to 32%, improves R_a by 30% to 49%, and reduces grinding zone temperature within the range of 45% to 49%. Moreover, Ravi et al. [9] reported that LN_2 in the milling process significantly improves R_a to control temperature and cutting force. Dae-Hooko et al. [10] found that cryogenic heat treatment is an effective method to reduce residual stress. Paul et al. [11] reported that cryogenic coolant reduces tensile residual stress for all materials under different feed levels. Moreover, cryogenic coolant has better chip formation, lesser grinding force, and lower grinding zone temperature compared with an oil-based coolant. Hence, the application of LN_2 is effective in controlling grinding force, R_a, and grinding zone temperature. The focus of the present study is the grinding of Ti-6Al-4V with an electroplated Cubic boron nitride (CBN) grinding wheel under cryogenic cooling and conven-

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tional oil-based coolant. Ti-6Al-4V is a hardened material and is difficult to machine. Ti-6Al-4V has low thermal conductivity, low modulus of elasticity, and high chemical reactivity at an elevated temperature [12].

Guo et al. [13] reported that grinding Ti-6Al-4V at a high feed rate in a dry condition creates micro grooves, cutting marks, and oxidation of the ground surface. Turley et al. [14] stated that grit particles from the grinding wheel in conventional grinding of Ti-6Al-4V are deposited on the ground surface. This deposition results in poor surface finish and increased grinding force. The grinding of Ti-6Al-4V with an aluminum oxide wheel results in increased deposition of grit particles on the ground surface compared with that of a silicon carbide wheel. Ji et al. [15] reported that surface finish can be achieved by mechanical grinding hybrid machining. Ding et al. [16] reported reduced residual stress and depth of the affected zone when brazed CBN abrasive in creep feed grinding is used. Taghitawakoli et al. [17] indicated that using a structured CBN wheel in cylindrical plunge dry grinding shows low grinding force and thermal damage under conventional cooling.

Teicher et al. [18] conducted experiments in plunge mode that reciprocates surface grinding under different environmental conditions (i.e., dry, LN_2, oil-based, and alkaline soaps). CBN and a diamond wheel were used for grinding titanium Ti-6Al-4V. Teicher et al. found that LN_2 did not reduce the grinding force to the expected amount. Literature indicated that the CBN wheel is better when machining a hardened material and becomes ineffective under dry conditions. No attempt has been made to find the effect of varying nozzle angles. Thus, the present study aims to investigate the effect of varying the nozzle angle and the Depth of cut (DOC) of the Ti-6Al-4V material in cryogenic and conventional environments.

2. Experimental details

2.1 Experimental setup

The schematic experimental setup is shown in Fig. 1. The grinding operation was performed on Ti-6Al-4V under cryogenic and wet cooling conditions. CBN wheels of 250 mm x 76 mm x 25 mm were used to conduct the experiment. A Ti-6Al-4V work piece material of 164 mm x 100 mm x 10 mm was clamped on the top surface of a KISTLER 9257B dynamometer. A cryogenic cooling system was developed to supply LN_2 to the grinding zone. The delivery pressure of LN_2 was 4 bar, and standoff distance of 40 mm was constant for all the experiments. High pressure was generated by supplying compressed air into the LN_2 container, and a separate change-over attachment for varying the nozzle angle was employed. Conventional cooling consisted of 20% coolant oil in water, which was supplied to the machining area.

The details of the grinding condition are given in Table 1. The grinding forces were measured using a piezoelectric transducer-based dynamometer (Kistler 9257B). The dynamometer consists of three-component force sensors fitted under high preload between a base and a top plate. Moreover, a four-component measurement needs a multi-core high-insulation that connects the cable and the four-charge amplifier channel system [i.e., multichannel charge amplifier (type 5070A)], which converts charge signals from the dynamometer into output voltages.

Table 1. Details of the grinding condition.

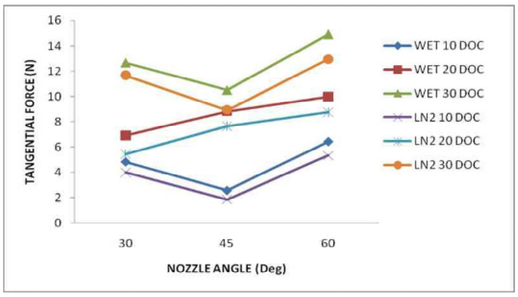
Machine	2.25 kw hydraulic surface grinder
Grinding wheel	Electroplated CBN
Work piece	Ti-6Al-4V
Depth of cut (DOC)	10, 20 and 30 μm
Wheel speed	31.4 m/s
Table speed (Work speed)	0.15 m/s
Cross feed	10 μm
Nozzle angle	30°, 45° and 60°
Cooling environments	Wet and liquid nitrogen
LN_2 pressure	4 bar
Dressing	Single-point diamond dresser
Dressing depth	10 μm
Dressing environment	Dry

Fig. 1. Photograph of the experimental setup.

The noncontact-type infrared pyrometer measured grinding zone temperature. R_a value was measured using a Taylsurf 3+ surftronic profilometer with a transverse length of 4 mm and cut off length of 0.8 mm. The non-contact 3D R_a was measured by Tally-Surf CCI profilometry equipment. Scanning electron microscopy was used to examine surface modification and chip morphology.

3. Results and discussion

An experimental study was conducted under conventional and LN_2 environments involving the grinding of Ti-6Al-4V with an electroplated CBN wheel. The experimental results of LN_2 cooling in terms of tangential forces, normal forces, specific energy, grinding zone temperature, R_a, surface modification, and chip morphology were compared with those of wet



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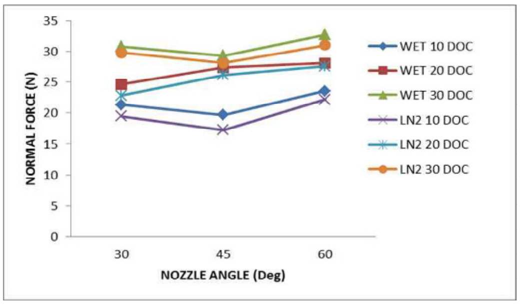


(b)

Fig. 2. Variation in the (a) tangential; (b) normal force (i.e., different levels of DOC with various angles of inclination under wet and cryogenic coolants).

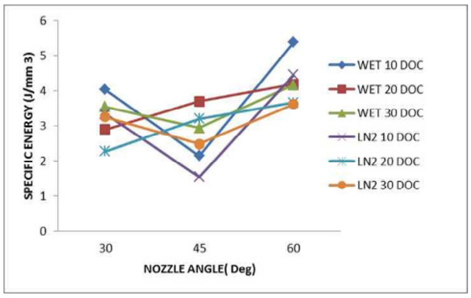


Fig. 3. Variation in the specific energy (i.e., different levels of DOC with various angles of inclination under wet and cryogenic coolants).

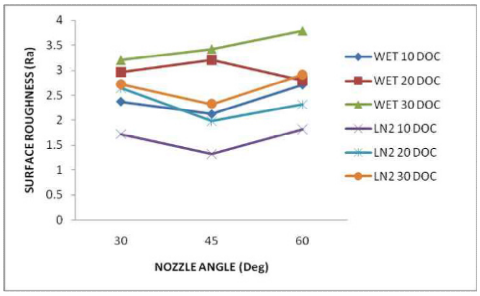


Fig. 4. Variation in the R_a (i.e., different levels of DOC with various angles of inclination under wet and cryogenic coolants).

machining.

3.1 Effect of grinding force

This study shows that cryogenic cooling environment has lower grinding force under selected experimental conditions compared with that of a conventional coolant. Cryogenic grinding at a higher DOC (30 µm) shows a reduction of 15% in tangential force and 5% in normal force over conventional grinding. The grits at a higher DOC have increased contact with the work material; hence, the friction at the contact area is increased. The application of a cryogenic coolant reduces temperature, and the work material at low temperature becomes less ductile and leads to grinding force reduction.

Fig. 2 indicates that the application of cryogenic cooling reduces the grinding forces at various nozzle angles (i.e., 30°, 45°, and 60°). The tangential forces are reduced by 21% at 30°, 15% to 27% at 45°, and 13% to 17% at 60° over those of the wet coolant at different levels of DOC. The normal forces are reduced by 3% to 8% at 30°, 4% to 12% at 45°, and 1% to 5% at 60° over the wet coolant at different levels of DOC. The grinding forces from the positioned nozzle angle were much reduced at 45° over 30° and 60°. The amount of the fluid that reaches the interface region at the nozzle angle of 45° was improved. This improvement enhanced lubrication and reduced grinding zone temperature.

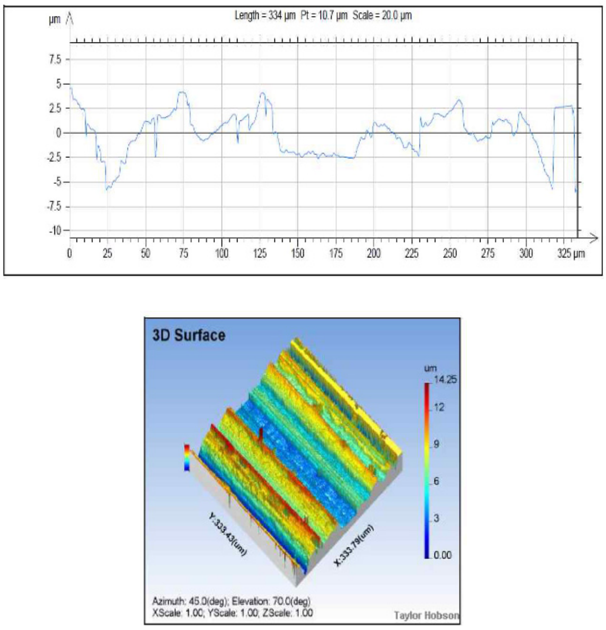
Reduction in the grinding zone temperature increases the mechanical strength of grit particles and further leads to minimized wear and breakage of the grit. The sharpness and retention of the grit offers positive effects on grinding force. A high-speed grinding process generates rapid chip formation and produces adiabatic heat at the contact area [2]. Therefore, the entire grinding energy is converted into heat. Approximately 8% to 28% of the specific energy is reduced by the application of LN_2. Fig. 3 shows that that the specific energy was higher in the lower DOC and lower in the higher DOC because of rubbing and ploughing actions.

3.2 Effect of R_a

In the grinding process, R_a depends on the cutting edge of grit particles. The extent of R_a in cryogenic cooling was less than that in wet coolants because of the controlled temperature at the grinding zone. A reduction of 32% of R_a over conventional grinding is found at a higher DOC (i.e., 30 µm) in cryogenic grinding. An increase in the DOC leads to an increase in the machining temperature, thereby resulting in the softening of work materials.

The softening promotes the flow of material from the work piece. Hence, small particles from the work material stick around the grit particles of the wheel. The application of cryogenic cooling controls the temperature at the contact region and reduces material flow around the grit particles.

Fig. 4 presents that R_a at different levels of DOC are reduced from 11% to 27% at 30°, 15% to 38% at 45°, and 17% to 33% at 60° over the wet coolant. The maximum improvement in R_a is realized at the nozzle angle of 45°. The nitrogen at the tip of the grit provides improved lubrication. Hence, the



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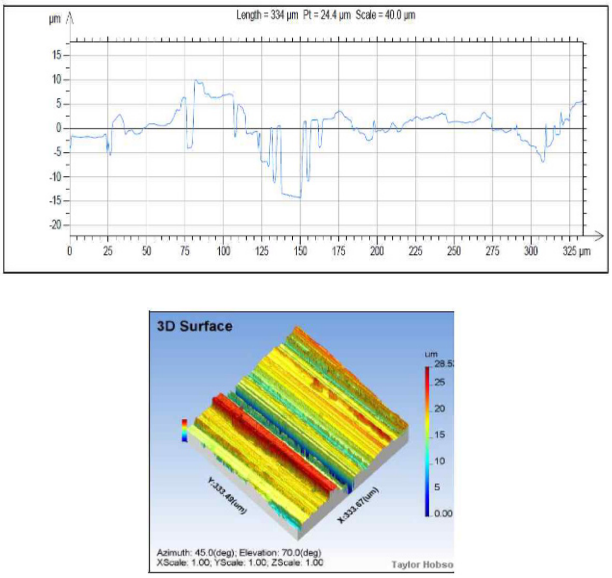
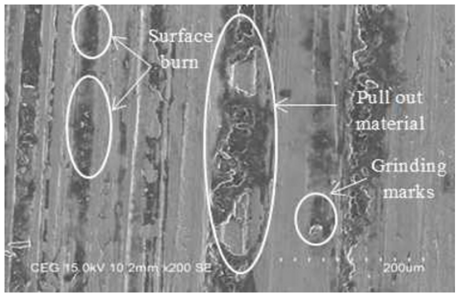


(b)

Fig. 5. Surface profile and the 3D view of the ground surface when grinding Ti-6Al-4V (a) wet; (b) cryogenic conditions (i.e., DOC = 30 µm, nozzle angle = 45°).

sharpness and retention of grit are extended, and premature breakage is also reduced. Fig. 5(a) shows the characteristic surface profiles and corresponding 3D surface topographies of the ground surface under a conventional coolant. The profile shows more ups and downs because of the blunt edge of the grit particles. The roughness profile clearly indicates the surface defects produced because of grit dullness and frequent breakages. Hence, increased tearing and burned surface were found on the ground component.



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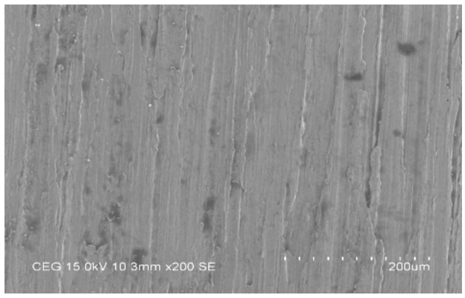


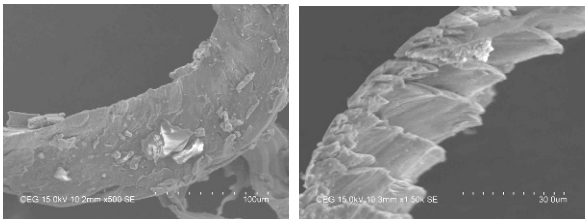
(b)

Fig. 6. SEM images of the surfaces ground when grinding Ti-6Al-4V (a) wet; (b) cryogenic conditions (i.e., DOC = 30 µm, nozzle angle = 45°).

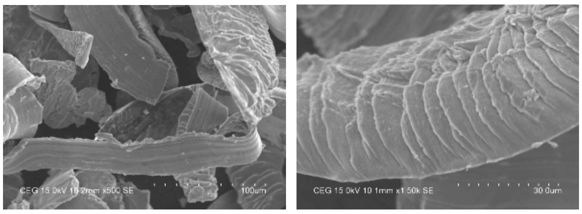
The mechanical property of the grit and the work material was affected by high heat developed at the grinding zone. The oil-based coolant was less effective in controlling temperature. Hence, frequent grit breakage takes place. The surface profile of the ground component in Fig. 5(b) shows minimal ups and downs with cryogenic cooling owing to minimal defects. The application of LN_2 reduces temperature at the grinding zone and prevents premature grit breakage by reducing friction between the grit and work material. Sharp grits generate smooth profiles and few surface defects.

3.3 Study of surface and chip morphology

Fig. 6(a) shows the SEM images of the ground surface generated in wet cooling. More surface burns and grinding marks were found as a result of the poor lubrication effect of an oil-based coolant. Fig. 6(b) shows that the ground surface under cryogenic cooling is free from defects because of the controlled oxidation reaction on the machined surface. The cryogenic coolant covers the grinding zone and acts as a barrier to atmospheric gases. Moreover, the application of the cryogenic coolant improves the hardness of the work material and reduces the adhesiveness of the work material on the grit. Fig. 7(a) shows that the chips under conventional grinding are irregularly shaped and long with burning edges because of the high temperature. Small grit particles were present on the surface of the chip. Hence, more friction and shearing action occurred in the grinding zone. Fig. 7(b) shows that cryogenic grinding produces regular shapes with smooth surface. Chips are uniformly segmented because of the controlled temperature at the interface region.



(a)



(b)

Fig. 7. SEM images of the chips taken during grinding Ti-6Al-4V (a) wet; (b) cryogenic conditions (i.e., DOC = 30 µm, nozzle angle = 45°).

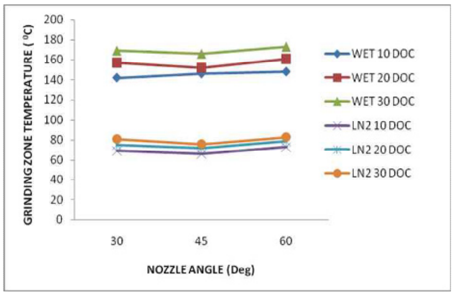


Fig. 8. Variation in the grinding zone temperature (i.e., different levels of DOC with various angles of inclination under wet and cryogenic coolants).

3.4 Effect of grinding zone temperatures

The friction generated during machining is converted to heat in the contact area. The critical condition of the work piece quality is avoiding thermal damage on the ground component by heat reduction. Thus, the reduction of heat generated in the grinding zone is critical to avoid thermal damage. Fig. 8 shows the significant reduction of the grinding zone temperature by applying cryogenic cooling. The grinding zone temperature gradually increases with an increased DOC. A reduction of 54% of the grinding zone temperature at a higher DOC is observed over conventional grinding. The maximum reduction in the grinding zone temperature is realized at the nozzle angle of 45°. The gaseous form of the cryogenic coolant reduces the friction between grit and work material. The reduction in the grinding zone temperature is due to improved lubrication and penetration of the cryogenic coolants.

4. Conclusions

Experiments were performed on the grinding of Ti-6Al-4V under two different environments (i.e., wet and cryogenic coolants) with an electroplated cubic boron nitride grinding wheel. The major conclusions are as follows:

(1) Cryogenic cooling produced a reduction of 8% to 27% in tangential force and 3% to 12% reduction in normal force compared with wet cooling. The maximum reduction in the grinding force occurred at the nozzle angle of 45°.

(2) The R_a in cryogenic cooling was reduced by up to 38% compared with wet cooling. Low unevenness was found on the ground surface because of the increased mechanical strength of the grit particles.

(3) Grinding zone temperature was reduced by up to 55% when a cryogenic coolant was used because of the lubrication effect by LN_2.

(4) The ground surface in the cryogenic environment possessed few defects even at a higher DOC because of controlled temperature at the grinding zone.

(5) The grinding performance at a nozzle angle of 45° was improved. Hence, the angle could be the optimal angle for delivery.

References

[1] S. Paul, P. P. Bandyopadhyay and A. B. Chattopadhyay, Effects of cryo-cooling in grinding steel, *J. Mtls. Proc. Tech*., 37 (1993) 791-800.

[2] S. Malkin and C. Guo, *Grinding technology: Theory and application of machining with abrasive*, Industrial Press, New York (2008).

[3] G. Manimaran and M. P. Kumar, Investigation of liquid nitrogen (LN_2) as coolant in grinding AISI D3 steel, *Advanced Material Research*, 341-342 (2012) 400-405.

[4] S. Paul and A. B. Chattopadhyay, The effect of cryogenic cooling on grinding forces, *Int. J. Machine Tools and Manuf*., 36 (1996) 63-72.

[5] M. Yokogawa and K. Yokogawa, Improving grinding performance of CBN wheels by dual - fluid supply method, *Int. J. Jpn. Soc. Precis. Eng*., 27 (1) (1993) 11.

[6] M. Dhananchezian and M. P. Kumar, Cryogenic turning of the Ti-6Al-4V with modified cutting tool inserts, *Materials and Manufacturing Process*, 26 (2011) 781-785.

[7] N. B. Fredj and H. Sidhom, Effects of the cryogenic cooling on the fatigue strength of the AISI 304 stainless steel ground components, *Cryogenics*, 46 (2006) 439-448.

[8] G. Manimaran and M. P. Kumar, Effect of cryogenic cooling and sol-gel alumina wheel on grinding performance of AISI 316 Stainless steel, *Archives of Civil and Mechanical Engineering*, 13 (2013) 304-312.

[9] S. Ravi and M. P. Kumar, Experimental investigation of cryogenic cooling in milling of AISI D3 tool steel, *Materials and Manufacturing Processes*, 27 (2012) 1017-1021.

[10] D.-H. Ko1, D.-C. Ko, H.-J. Lim, J.-M. Lee and B.-M. Kim, Prediction and measurement of relieved residual stress by the cryogenic heat treatment for Al6061 alloy: mechanical properties and microstructure, *Journal of Mechanical Science and Technology*, 27 (7) (2013) 1949-1955.

[11] S. Paul and A. B. Chattopadhyay, Effects of cryogenic cooling by liquid nitrogen jet on forces, temperature and surface residual stresses in grinding steels, *Cryogenics*, 35 (8) (1995) 515-523.

[12] V. V. Vemula and T. A. Khan, Study on grindability of Ti-6Al-4V using solid lubricants, *International Journal on Emerging Technologies*, 3 (1) (2012) 109-114.

[13] G. Guo, Zhiqiangliu, Q. An and M. Chen, Experimental investigation on conventional grinding of Ti-6Al-4V using SiC abrasive, *International Journal of Advanced Manufacturing Technology*, 57 (2011) 135-142.

[14] D. M. Turley, Factors affecting surface finish when grinding titanium and a titanium alloy (Ti-6Al-4V), *Wear*, 104 (1985) 323-335.

[15] R. Ji, Y. Liu, Y. Zhang, B. Cai, X. Li and C. Zheng, Effect of machining parameters on surface integrity of silicon carbide ceramic using end electric discharge milling and mechanical grinding hybrid machining, *Journal of Mechanical Science and Technology*, 27 (1) (2013) 177-183.

[16] W. Ding, J. Xu, Z. Chen, H. Su and Y. Fu, Grindability and surface intergrity of cast nickel based superalloy in Creep feed grinding with brazed CBN abrasive wheels, *Chinese Journal of Aeronautics* (2010) 501-510.

[17] T. Tawakoli, M. J. Hadad, M. H. Sadeghi, A. Daneshi, S. Stockert and A. Rasifard, An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubricant - MQL grinding, *Int. J. Machine Tools and Manuf.*, 49 (2009) 924-932.

[18] U. Teicher, A. Ghosh, A. B. Chattopadhyay and K. Kunanz, On the grindability of Titanium alloy by brazed type monolayered superabrasive grinding wheels, *Int. J. Machine Tools and Manuf.*, 46 (6) (2006) 620-622.

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