On the performance of Super Abrasive Machining (SAM) on small diameter cBN wheel wear

H Bravo*, N Ortega2, R Polvorosa3 and I Zamakona1

1 ITPAero S.A., Parque Tecnológico de Bizkaia 300, 48170 Zamudio, Spain
2 Faculty of Engineering of Bilbao, Plaza Ingeniero Torres Quevedo, 1, 48013 Bilbao, Spain
3 CFAA, Parque Tecnológico de Bizkaia 202, 48170 Zamudio, Spain

*Corresponding author: h.bravo.ehu@gmail.com

Abstract: Electroplated cBN wheels have increased their importance in industry, mainly in camshaft, crankshaft and gearbox grinding in the automotive sector and in grinding of aeronautical turbine parts made from nickel superalloys. Possible new applications include Integrated Blade Rotors (IBRs), whose importance is increasing in new aeroengine configurations. Electroplated cBN wheels form retention without trueing or dressing and low wear make them suitable for this usage. However, few information is available about wear and resulting surface finish characteristics in the small diameter wheels needed for this application. In this study, data about wheel topography and wear and surface finishing of resulting surfaces is shown. Also, some hypothesis about the reasons for the higher-than-expected resulting surface finish are exposed.

Keywords: Grinding, Electroplated cBN, Surface finish, Wheel topography.

1. Introduction

Grinding with electroplated cubic boron nitride (cBN) wheels is a technology widely used for manufacturing of aeronautical parts [1-4]. Electroplated cBN wheel comprises a single layer of cBN abrasive grains adhered to the wheel by an electroplated nickel bond. This type of grinding wheel, contrary to the more conventional ones, is not dressed neither trued to restore its surface [5]. This characteristic reduces the possible strategies to control surface roughness resultant of cutting process. Only cutting process parameters, type of coolant and initial wheel topography could be used to obtain required surface finish values.

Integrated Blade Rotors (IBRs) is one of the components in an aeronautical turbine in which cBN grinding looks more promising [2,6]. cBN wheels combine good thermal behaviour, high specific material removal rates (MRR') and extended tool life, being an existing option for the machining of Nibase Superalloys as the ones used in this type of parts [7]. These process characteristics could mean an advantage against some of the techniques currently used. This advantage could come from a part integrity point of view against welding; from tool life and maximum MRR’ point of view in the case of milling; or from both when considering EDM/ECM techniques. However, information about IBRs surface finishing values obtained by SAM is limited [6].

Environmental concerns are upweighting the use of emulsions instead of net oils as cutting fluid. However, multiple studies demonstrate that electroplated cBN wheels life is decreased by using emulsions [8,9]. Also cutting forces are increased, hindering to achieve the dimensional accuracy needed
[9]. On the other hand, most of available studies are carried out using wheel diameters larger than the ranges allowed by blade spacing in IBRs manufacturing [6].

In this article, wheel wear and topographical characteristics and achieved surface finishing obtained by means of the use of cBN grinding is analysed. To do it, a wheel diameter in the allowed range for IBR’s manufacturing was used. Tests were performed with both net oil and emulsion as cooling fluid through a set of different cutting conditions.

2. Experimental setup
Surface grinding test part machining was carried out in an instrumented five axis Hermle C52 U MT machining centre. Two different coolant fluids were used, CUT-MAX 529-15 straight cutting oil and an oil-in-water emulsion of HOCUT 4940 with a concentration of 7.5%, both manufactured by Houghton.

Electroplated cBN wheels supplied by Diprotex were used in all tests. Nominal grain size of the wheels was 76 µm. The wheels were cylindrical ball-end-shaped with ds=12 mm diameter and 20 mm long. Ball radius was 6 mm (see figure 1(a)). With the aim of guaranteeing the same initial grinding conditions, a brand-new wheel was used for each test.

To achieve desired wheel speeds a high frequency Jäger S62-M280.07 S5 spindle with a maximum rotating speed of 80000 rpm was employed. Machining disposition for the experiment can be seen in figure 1(b).

![Figure 1. (a) Used tool. (b) Machining test disposition showing Jäger spindle.](image)

Test consisted of grinding multiple Inconel 718 stabs of 250x9.5x5.5 mm. Inconel 718 was chosen for being widely used in the manufacturing of turbine parts. Also, for its physical, chemical, and mechanical similitudes with other Ni-based superalloys used in turbine parts, being the former the most common. Chemical composition and mechanical properties of Inconel 718 can be found in table 1.

| Ni  | Cr  | Co  | Fe  | Nb  | Mo  | Ti  | Al  | B   | C   | Mn  | Si  | Others |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 52.5| 19  | 1   | 17  | 5   | 3   | 1   | 0.6 | 0.01| 0.8 | 0.35| 0.35| 1.79   |
| Hardness | Young’s Modulus | Tensile Strength | Density | Specific Heat | Melting Temp. | Thermal Conduct. |
| 42 HRc | 206 GPa | 1.73 GPa | 8470 kg/m³ | 46 J/(kg·K) | 1550 K | 15 W/(m·K) |
Test were conducted in up mode at a fixed radial depth of cut \((a_e=0.3 \text{ mm})\). The relation \(a_e/d_s\) was chosen so that the specific material removal rates \((MRR')\) was considered acceptable for the type of application which was being simulated.

Five different wheel velocities \((v_s=37.7, 40.84, 43.98, 47.12, 50.27 \text{ m/s})\) and five workpiece velocities \((v_w=0.55, 1.08, 1.63, 1.92, 2.45 \text{ mm/s})\) were combined to cover a range of \(MRR'\) representative of the process. A detailed description of the parameter combination set during tests can be found in table 2. Aggressiveness parameter \((\text{Aggr})\) was used to compare these grinding conditions with the ones used to manufacture this type of nickel base alloys currently. Aggressiveness parameter \((\text{Aggr})\) is calculated as shown in equation (1).

\[
\text{Aggr} = 1000 \times \frac{v_w}{v_s} \times \sqrt{\frac{a_e}{d_s}}
\]  

(1)

Table 2. Test machining parameters.

| Test Number | Wheel Direction | \(d_s\) (mm) | \(v_w\) (mm/s) | \(v_s\) (m/s) | \(a_e\) (mm) | \(MRR'\) (mm\(^3\)/mm/s) | \(\text{Aggr}\) |
|-------------|----------------|-----------|--------------|-------------|-----------|----------------|----------|
| Test 1-1'   | Upgrinding     | 12        | 2.45         | 37.70       | 0.3       | 0.74           | 10.3     |
| Test 2-2'-A | Upgrinding     | 12        | 1.92         | 40.84       | 0.3       | 0.58           | 7.42     |
| Test 3-3'   | Upgrinding     | 12        | 1.63         | 43.98       | 0.3       | 0.49           | 5.87     |
| Test 4-4'   | Upgrinding     | 12        | 1.08         | 47.12       | 0.3       | 0.33           | 3.63     |
| Test 5-5'   | Upgrinding     | 12        | 0.55         | 50.27       | 0.3       | 0.17           | 1.73     |

Test number 1-5 comprised 15 passes with shown conditions and net oil as cooling fluid. Test number 1'-5' were similar but using oil in water emulsion. In test A, test 2' conditions were used to execute consecutive passes till power consumption reached the maximum nominal power of the spindle, this is, 1.2 kW.

A tri-axial force transducer piezoelectric dynamometer Kistler 9255 and OROS® OR35 analyzer were used to measure forces. Power consumption was measured using a Load Controls UPC-230 power cell and an analog digital converter. Signal analysis was performed through Daqlab software.

Wheel surfaces were photographed and mapped using a Leica DCM confocal microscope. A manual Mitutoyo Surfertest SJ210 and a Mitutoyo Formtracer SV-C3200 were used for test piece roughness measurement.

Lateral side of the test parts was machined at the end of each test. Wheel was axially offset to mark the step between used and unused wheel area. This step was then measured using the Mitutoyo Formtracer in profilometer configuration.

Figure 2. Evolution of \(R_a\) of test parts after 10675 mm\(^3\) removed material, except for test 1, 4275 mm\(^3\) removed material.
3. Results

No relationship was found between Ra and machining parameters \( v_w \) and \( v_s \) at the tested \( a_c \) with this kind of wheels. Also surface roughness was better when using emulsion than net oil for the same combination of parameters and the same removed materials as shown in figure 2.

As the amount of removed material increases, the surface roughness decreases (see figure 3). This decrease has initially a high gradient until reaching a steady state value for any cutting condition. After reaching that point, the improvement of surface roughness is negligible independently of the additional amount of material removed, as Test A shows in figure 4.

\[ R_a \] for different emulsion test conditions.

\[ R_a \] for test 2’ and test A.

\( S_z \) is defined as the sum of the largest peak height value and the largest pit depth value within the defined area. \( S_z \) can be used to determine the wheel depth which is actively cutting. As the cBN grains on the wheel suffer wear, the number of islands at \( S_z \) depth increases (see figure 5). Also, their mean height decreases. This is reflected in the machined surface by an improvement of the resulting \( S_a \) which is defined as the arithmetical mean height of the measured surface.

Wheel wear and the resulting increase of cBN cutting edges in a narrower depth of the wheel seems to be the main driver of surface roughness improvement at this range of cutting conditions. Anyway, these values are always higher than standard values presented in the available bibliography for cBN grinding [10-12]. Although MRR’ used in those studies are in the same ranges of the ones used in this study, wheel diameter used in those studies were common for the industrial applications, and times higher than the one used in this work.

Two factors could be considered to explain this effect.

- Low number of grains in each longitudinal section of the wheel.
- Higher grain on each longitudinal section eliminating all or most material.
Low number of grains in each section decrease the probability of finding equal or almost equal tip grain height along the cutting surface of the wheel and its related to the lower radius of the wheel, therefore the lower perimeter length.

An approximation to the theoretical height difference from the valley and the top of material left by a rotating grain after a complete rotation can be easily calculated. Considering both grain and material non deformable this difference can be calculated as the sagitta of a circumference of radius (r) equal to wheel radius at a chord (l) equal to the displacement of the centre of the wheel in a complete rotation with equations (2) or (3).

\[ s = r - \sqrt{r^2 - \left(\frac{l}{2}\right)^2} \]  \hspace{1cm} (2)

Or for small values of sagitta:

\[ s \approx \frac{l^2}{8r} \]  \hspace{1cm} (3)

In the condition with the faster displacement between centres of our experiments \( v_w = 2.45 \text{ mm/s} \) at \( v_c = 37 \text{ m/s} \), or 60000 rpm for a \( r = 6 \text{ mm} \) wheel. The associated chord is 2.45 µm and the sagitta 0.0000625 µm. For comparison purposes, for Upadhyaya [12] test conditions, \( v_w = 8.5 \text{ mm/s} \) at \( v_c = 45 \text{ m/s} \), or 4831 rpm for a \( r = 89 \text{ mm} \) wheel, associated chord is 59.5 µm, and sagitta 4.97 µm, which is about 80000 times higher than our values. These values are much lower than the reals ones, due to wheel deflection, adjacent grains effect and other local effects not being considered in this study, but valid from a qualitative point of view. When measuring the surface roughness in the direction of cut, this effect is exhibited by an extremely low roughness value as shown in figure 6.

**Figure 5.** Sa compared with removed material. Two examples of wheel surface at Sz depth are shown.

**Figure 6.** Surface roughness (Ra) in the cutting direction for (a) test 1' (0.085 µm) (b) test 3' (0.066 µm) and (c) test 5 (0.091 µm).
The number of islands increases with the depth until occupy approximately from 60% to 70% of the total packaging allowed for this size of grain. Considering round grains of diameter equal to 76 µm, in a 1×1.5 mm area, a matrix of 13×20 grain or 260 grains is the maximum allowable quantity. Measurement results seen in figure 7 showed a maximum between 150 and 180 grains for 5 of the 6 analyzed wheel topographies. At the depth this quantity appears, any island can be considered a complete grain. This is not the case in the upper sections of the wheels, in which multiple islands can be related to multiple independent cutting edges of the same grain. Wheel used for test 1’ shows higher values in the middle sections. Our opinion is this deviation in the number of islands could be related to rest of debris or of graphite used for easing confocal measurements trapped in the lower areas around the grains.

Total area occupied by those areas increases following a second-degree polynomial curve as shown in figure 8, being this increase faster when using emulsion than net oil. This result is in line with the hypothesis of increased grain wear being the main driver of the improvement of surface finish when machining with emulsion instead of oil for the same amount of removed material.

**Figure 7.** Number of islands at a given depth.

**Figure 8.** Evolution of total area occupied by cBN at different depths.

4. Conclusions
In the analysed conditions no correlation between machining parameters and surface roughness was found. On the other hand, utilization of oil emulsions instead of net oil improves the surface roughness of the resulting surface for the same conditions and amount of material removed.
At the beginning of wheel life, cutting edge number in the height from the upper to the lower point machined in the part surface, determined by $S_z$ is low, with a high mean height. This causes surface finish values doubles the ones obtained after these top cutting edges are worn and height of grain tops along the wheel surface equalizes.

Increase of wheel wear when using emulsion instead net oil as cooling fluid [8] affects positively the surface finish. This increase causes an increase of the number of active grains and contact area in the active depth of the wheel, thus improving surface finish.

Acknowledgements
The authors thanks to the following people for their cooperation with the preparation of this paper. Asier Fernandez for his help with tests and resource availability planification. Sheila Gomez for her help driving the Hermle and helping with measurements during the realization of the tests. Guillermo Gonzalez and Aitor Gomez for the Leyca confocal photos and mapping. Izaro Ayesta and Jon Ander Ealo for the preparation of specimens for measurement.

We also would like to thank I.T.P.Aero S.A. for their support to this work under the umbrella of CFAA research activities. Authors would also like to thank the PhD and specialists from the University of the Basque Country for their support and advice, and the CDTI for their support through Booster2 project.

References
[1] Aronson R B 1994 CBN Grinding: A Tempting Technology Manufacturing Engineering 112 pp 35–39
[2] Chung Y W 2012 Arbitrary surface flank milling & flank SAM in the desing and manufacturing of jet engine fan and compressor airfoils Proceedings of the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition (Denmark) vol 5 pp. 21–30
[3] Klocke F, Soo S L, Karpuschewski B, Webster J A, Novovic D, Elfizy A, Axinte D A and Tönissen S 2015 Abrasive machining of advanced aerospace alloys and composites CIRP Annals 64 (2) pp 581–604
[4] González-Barrio H, Calleja-Ochoa A, Lamikiz A and López de Lacalle L N 2020 Manufacturing Processes of Integral Blade Rotors for Turbomachinery, Processes and New Approaches Applied Sciences 10 (9) p 3063
[5] Shi Z and Malkin S 2003 An Investigation of grinding with electroplated CBN wheels CIRP Annals 52 (1) pp 267–270
[6] González H, Calleja A, Pereira O, Ortega N, Lopez de Lacalle L N and Barton M 2018 Super abrasive machining of integral rotary components using grinding flank tools Metals 8 (1) p 24
[7] Patil D V, Ghosh S, Ghosh A, Chattopadhyay A K and Chattopadhyay A B 2007 On grindability of Inconel 718 under high efficiency deep grinding by monolayer cBN wheel International Journal of Abrasive Technology 1 (2) pp 173–186
[8] Tawakoli T, Westkaemper E, Rabiey M and Rasifard A 2007 Influence of the type of coolant lubricant in grinding with CBN tools International Journal of Machine Tools and Manufacture 47 (5) pp 734–739
[9] Fusse R Y, França T V, Caiati R E, Silva L R D, Aguiar P R D and Bianchi E C 2004 Analysis of the cutting fluid influence on the deep grinding process with a CBN grinding wheel Materials Research 7 (3) pp 451–457
[10] Jackson M J, Davis C J, Hitchiner M P and Mills B 2001 High-speed grinding with CBN grinding wheels—applications and future technology Journal of materials processing technology 110 (1) pp 78–88
[11] Caggiano A and Teti R 2013 CBN grinding performance improvement in aircraft engine components manufacture Procedia CIRP 9 pp 109–114
[12] Upadhyaya R P and Fiecoat J H 2007 Factors affecting grinding performance with electroplated CBN wheels CIRP annals 56 (1) pp 339–342