2nd CIRP Global Web Conference

CBN Grinding Performance Improvement in Aircraft Engine Components Manufacture

Alessandra Caggiano*, Roberto Teti

Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology,
Department of Chemical, Materials and Production Engineering, University of Naples Federico II,
P.le Tecchio 80, 80125 Naples, Italy

* Corresponding author. Tel.: +39 3289223274; fax: +39 081 7682362. E-mail address: alessandra.caggiano@unina.it.

Abstract

Cubic Boron Nitride (CBN) grinding is extensively employed in the aerospace industry as it allows to effectively grind high performance aerospace metal alloys such as nickel base superalloys. With reference to a real industrial case of CBN grinding for the manufacture of aircraft engine components, the aim of this paper is to improve the CBN wheel tool life and optimize the grinding process while taking into account economic, environmental and social sustainability issues. Different types of CBN grinding wheels fabricated using diverse deposition procedures are tested to compare their behavior during grinding of Ni base superalloys and assess their tool life in terms of number of parts successfully ground by a single wheel. Tests are also performed to investigate alternative coolant type applicability as well as grain size influence on surface integrity as these factors can significantly affect process performance, final workpiece quality and grinding wheel life.

1. Introduction

Cubic Boron Nitride (CBN) grinding is extensively employed in aerospace industry for the precision grinding of a wide range of components.

The advantages of CBN compared to other abrasives are related to high hardness, thermal stability, chemical inertness and high thermal conductivity, that make this abrasive particularly suitable to grind high performance aerospace metal alloys such as Ni base superalloys [1].

In the aircraft engine industry, grinding is employed for the final shaping of turbine vanes that require very smooth surfaces and high dimensional accuracy.

For a particular workpiece material and geometry, the selection of grinding process parameters and grinding fluid is primarily guided by the specified part quality level. In many industrial applications, the productivity of the grinding process is a secondary objective since it is very difficult to determine the effect of each input parameter on the key process responses without incurring large capital expenses for the costly and difficult-to-grind superalloy materials.

Consequently, many grinding operations are still conducted at suboptimum productivity levels without evaluating or implementing solutions that can improve the process performance [2].

However, CBN grinding wheels are rather expensive compared to other wheel types and their tool life management is an outstanding issue which can significantly improve production quality and cost. Worn tools can generate unacceptable defects, such as burns and cracks on the workpiece, and involve higher energy consumption, while their frequent substitution has a negative impact on production rate and cost [3].

With reference to a real industrial case of aircraft engine components manufacturing, the aim of this paper is to improve the CBN grinding wheel life and optimize the grinding process while taking into account economic, environmental and social sustainability issues.

A number of studies have been directed towards the investigation of grinding wheel parameters and coolant
type influence on grinding process performance, final workpiece quality and grinding wheel life [4-6].

In this research work, a first testing campaign on grinding of René 125 aeroengine components was carried out using diverse CBN grinding wheels fabricated with different galvanic bath deposition parameters resulting in diverse CBN concentrations, to compare their tool life in terms of number of parts ground by a single wheel.

Tool life and management improvements can generate significant benefits in terms of costs related to grinding wheel purchase and dressing as well as final part quality and productivity [7, 8].

A second testing campaign on grinding of René 80 aeroengine components was carried out to investigate the applicability of a semi-synthetic grinding fluid, expected to significantly improve process performance, workpiece quality and environmental impact for the grinding process under study. When using notable amounts of cutting fluids, social and environmental issues are critically involved, as fluids can be detrimental to workers, due to the formation of toxic fumes, and to the outer environment where proper disposal should be carried out [9].

In critical applications such as aircraft engine components, ground surfaces should comply with very severe surface integrity requirements to satisfy the requirements of component performance and reliability.

To guarantee the required surface integrity within the experimental tests, extensive surface evaluations are performed on the ground components.

2. Industrial Case Study

The improvement of CBN wheel tool life is studied in this work for real industrial cases of grinding processes in aircraft engine components manufacturing.

The aim is to improve the CBN wheel tool life and optimize the grinding process while taking into account economic, environmental and social sustainability.

To consider the impact of diverse factors on grinding performance, 2 experimental testing campaigns, relative to 2 different grinding processes of particular interest for the aeroengine manufacturer, were executed.

First, grinding tests using 3 CBN grinding wheels with dissimilar superabrasive concentrations were carried out to select the most suitable microgeometry for the specific application.

Then, experimental tests relative to a second grinding process were performed to verify the applicability of an alternative grinding fluid with reduced economical, environmental and social impact.

3. Experimental tests with diverse CBN concentrations

In the first testing campaign, different grinding wheel microgeometries related to various CBN concentrations (i.e. grain distribution over the wheel surface) were obtained using diverse parameters in terms of time and current of galvanic bath deposition. These wheels were tested to compare their tool life in terms of number of parts ground by a single grinding wheel.

3.1. Workpiece

The workpiece on which the grinding tests were performed is a precision investment cast René 125 turbine vane. As most materials used for aeroengine components, René 125 is a nickel base alloy able to withstand elevated temperatures while keeping its high thermo-mechanical properties and chemical stability.

3.2. Grinding wheels

The grinding wheels employed for the first experimental campaign are 3 cylindrical CBN grinding wheels with diameter 178 mm and thickness 35 mm.

The 3 wheels are characterised by the same type of superabrasive grains (CBN), equal grit size (average particle size: 181 μm) and shape, but different concentrations of abrasive material resulting in different intergranular spacing over the wheel surface.

The amount of superabrasive grains, directly related to grain spacing, usually determines the wheel life and higher concentrations give better surface finish [2].

The first tested grinding wheel, referred to as T0, is the one traditionally employed for this application by the aeroengine manufacturer, that is characterised by a concentration of 4.4 crt/cm². The second wheel, referred to as T1, presents a -15% lower concentration obtained by varying the procedure of electrolytic deposition in galvanic bath. The third grinding wheel, referred to as T2, has a -30% lower concentration compared to T0.
3.3. Experimental procedures

Experimental grinding tests were performed with the 3 different grinding wheels on a Burkhardt & Weber CNC grinding machine.

The tests consisted of creep-feed grinding operations on René 125 aeroengine components, with 6700 rev/min rotational speed, 645 mm/min feed rate and depth of cut per pass equal to 0.5 mm for the first pass and 0.2 mm for the following 8 passes (9 passes in total).

The grinding fluid was a Rhenus HM7 oil, a colourless, low viscosity, low oil mist and low emission special grinding oil, free of aromatics, chlorine and heavy metals such as lead, zinc and barium. The oil was directed on the working area with a pressure of 20 bar through 2 nozzles (Fig. 2). Moreover, an additional central nozzle was used for cooling.

Using the same process parameters, the 3 grinding wheels proved to have different tool lives.

With the T0 grinding wheel, which is the one currently employed by the aeroengine manufacturer, the maximum number of produced units per wheel was 41; thereafter, tool wear became too significant and defects such as burns and cracks occurred on the workpiece.

With the T1 grinding wheel, having a lower CBN concentration, the maximum number of parts produced per wheel was much higher, equal to 66 units.

On the other hand, with the T2 grinding wheel, having an even lower CBN concentration, 50 units per wheel were produced, which is higher than with the traditional T0 wheel, but less than with T1.

The workpiece surface was acceptable for all 3 grinding wheels, so that the selection of the most suitable CBN concentration can be made on the basis of tool life: thus, T1 appears the most convenient solution.

It is worth noticing that CBN concentration also affects the grinding wheel price, as a lower amount of the expensive abrasive grains reduces the cost.

Moreover, the significantly larger number of vanes that can be produced by a single T1 wheel compared to the traditionally employed T0 wheel would considerably reduce grinding wheel purchase and dressing costs.

As regards potential savings, with a dressing cost of 360 €/wheel and an average production of 5,000 vanes/year, the employment of T1 wheels would allow a reduction of dressing costs around 38% (16,600 €).

4. Impact of grinding fluids on sustainability

Grinding fluids have a central role in reducing friction in the wheel-workpiece contact zone (lubricating effect), removing the grinding swarf (flushing effect), and carrying away some of the thermal energy dissipated in the contact zone (cooling effect) [9-11].

Grinding fluids can be classified into 5 categories:
- Petroleum-base and mineral-base cutting oils
- Water-soluble oils
- Synthetic fluids
- Semi-synthetic fluids
- Water plus additives

The selection of the proper grinding fluid has a significant impact on the 3 dimensions of sustainability: social, environmental and economical [9].

The expected advantages that could be achieved by employing semi-synthetic grinding fluids instead of traditional cutting oils are:
- Higher heat removal and better cooling of the workpiece, allowing to boost process parameters and reduce production time.
- Improved working environment, since no toxic fumes are generated (which are common when using oils).
- Reduced fluid contamination and pollution [12].

Contamination of cutting fluids due to tramp oil, usually from hydraulic systems, or water, from any of several sources, may cause excessive variation in workpiece finish or dimensions, short tool life, or corrosion of the workpiece. With emulsions, tramp oil losses could be easily skimmed off and reused for hydraulic systems. This would reduce contamination and pollution, as oil losses are recovered and reused.
- Reduced fire hazard.
- No need to further wash the workpiece after grinding.

When using traditional oils, the workpiece required final washing to degrease and remove oil traces. This is not necessary with semisynthetic fluids, allowing the cutback of time and cost of the added operation.
- Reduced cost for oil top up. Oil top up could be carried out less frequently and with a low oil-water ratio, as the main losses are due to water evaporation.

5. Experimental tests with semi-synthetic fluid

In the second experimental campaign, the use of a semi-synthetic grinding fluid, that would allow a significant environmental, economical and social advancement, was studied with reference to another industrial case of turbine vanes CBN grinding.
Experimental grinding tests were conducted by using an innovative semi-synthetic fluid and different grinding wheels to verify the process feasibility and a suitable set-up in terms of grinding wheels and process parameters.

5.1. Experimental set-up: workpiece, wheel and fluid

The workpiece on which the experimental tests were carried out is a precision investment cast turbine vane made of René 80 nickel based alloy.

3 different cylindrical CBN grinding wheels (referred to as B126, B151 and B181), all with 125 mm diameter and 13 mm thickness, were employed. The 3 wheels differ in the abrasive grain size: average particle size was 126 \( \mu \text{m} \), 151 \( \mu \text{m} \) and 181 \( \mu \text{m} \), respectively (Fig. 3).

The grinding fluid used for the experimental tests is a semi-synthetic fluid (CIMCOOL CIMSTAR 560) with a very low mineral oil content and a 6% concentration.

Semi-synthetic fluids are mixtures of synthetic and soluble-oil components. These products, sometimes referred to as microemulsions, include synthetic dispersions and some oil-accepting synthetics.

Semi-synthetic coolants usually contain a percentage of oil in the range 5% - 30% [2] and they are used for grinding applications in which high heat removal and moderate lubricity are needed.

The advantages of these fluids include:
- Better heat dissipation than for soluble oils
- Good rust protection compared with other emulsions
- Very good rancidity resistance
- Very good acceptance by both machine operators and maintenance staff.

5.2. Experimental procedures

Grinding tests were carried out on a 5-axis compact machining centre (DMC 60 T by DECKEL MAHO). As regards the grinding process parameters, 9000 rev/min rotational speed, 4 mm depth of cut and 3 different feed rates (20 mm/min, 45 mm/min and 90 mm/min) were used for the realization of slots along the outer and inner bands of turbine vanes.

Fig. 4 shows the grinding wheel and workpiece and Fig. 5 the grinding process. Tables 1 and 2 report the number of valid test repetitions for each process condition on the turbine vane outer and inner bands.

| Feed rate | B126 | B151 | B181 |
|-----------|------|------|------|
| F20       | 2    | 2    | -    |
| F45       | 2    | 2    | 2    |
| F90       | 2    | 2    | 2    |

Table 1. Outer band grinding process conditions: no. of test repetitions

| Feed rate | B126 | B151 | B181 |
|-----------|------|------|------|
| F45       | 3    | 3    | -    |
| F90       | 3    | 3    | -    |

Table 2. Inner band grinding process conditions: no. of test repetitions

5.3. Grinding process energy efficiency improvement

In the past, energy consumption by machining and grinding processes has not been a fundamental concern for industry [13]. Grinding process improvements mostly focus on cycle time reduction, wheel savings, quality improvements. The situation is changing due to recent increase in energy demand worldwide, energy price fluctuations, and concern over global warming.
Considering the significant amount of grinding operations used by industry worldwide, improving the energy efficiency of grinding processes would have a considerable impact. Furthermore, the high energy intensity of grinding processes is also the origin of workpiece surface and subsurface damages such as burn, white layer and unacceptable residual stress.

Power consumption during the grinding tests was monitored as percentage of the maximum power allowed by the machining centre (100% corresponds to 40 kW) to compare the different process conditions in terms of energy efficiency (Tables 3 and 4).

Taking into account the power consumption, grinding wheels B151 and B181 seem to exhibit the better behavior. However, the evaluation of ground surface integrity should be carried out to select the best solution.

### 5.4. Surface Integrity Evaluation

In critical applications such as components for the aerospace industry, grinding processes are required to produce surfaces compliant with very strict surface integrity requirements to satisfy the increasing demands of component performance and reliability [2].

Several inspections were performed on the ground surfaces in order to identify surface integrity under all experimented process conditions.

#### 5.4.1. Visual Inspection

Visual inspection was carried out to identify possible causes for rejection:
- Any discoloration caused by material overheating during grinding.
- Cracks and evidence of surface melting.
- Linear discontinuities.

Visual inspection of the ground surfaces evidenced the presence of burnt areas. After workpiece cleaning, the burn traces were much reduced: some of them were still visible, although acceptable, in particular on the first slots realized with B126 and feed rate F45 and F90 (Fig. 6), while those realized with B151 and feed rate F45 and F90 appeared slightly better (Fig. 7).

#### 5.4.2. Fluorescent Penetrant Inspection

Fluorescent Penetrant Inspection (FPI) was performed to detect possible cracks generated during grinding.

The following sequence of operations for surface integrity evaluation was performed:
1. Workpiece cleaning
2. Acid attack on each slot
3. Fluorescent Penetrant Inspection (FPI)
4. Analysis of results

No crack indication was identified, indicating that no significant defect was generated during grinding tests.

Although all the ground surfaces passed the FPI investigation, further surface finish requirements, such as roughness of the ground surfaces, should be verified.

### Table 3. Outer band grinding process conditions: average power load

| Feed rate | Grinding wheel |
|-----------|----------------|
| F20       | B126 6%        |
|           | B151 3%        |
|           | B181 -         |
| F45       | B126 9%        |
|           | B151 6%        |
|           | B181 4%        |
| F90       | B126 18%       |
|           | B151 8%        |
|           | B181 8%        |

### Table 4. Inner band grinding process conditions: average power load

| Feed rate | Grinding wheel |
|-----------|----------------|
| F45       | B126 4%        |
|           | B151 3%        |
|           | B181 -         |
| F90       | B126 4.5%      |
|           | B151 5%        |
|           | B181 -         |

#### Fig. 6. Slots ground with B126 grinding wheel: some burns are visible, though they are considered acceptable

#### Fig. 7. Slots ground with B151 grinding wheel: no burns are verified

### 5.4.3. Roughness measurement

Roughness of the ground surfaces was measured by means of a roughness meter to verify the compliance with the acceptable roughness range (0.8 - 1.6 µm).

The measured average roughness values for the first surfaces generated by the 3 grinding wheels were:
- B126 \( \rightarrow \) \( Ra = 1.39 \) µm
- B151 \( \rightarrow \) \( Ra = 1.95 \) µm
- B181 \( \rightarrow \) \( Ra = 2.15 \) µm
From these values, B126 seems to be the most suitable grain size as concerns roughness tolerance values (see Fig. 8). However, B126 shows a good performance at the beginning but it is subject to a very rapid wear during processing. This means that, on the one hand, roughness rapidly decreases to values below the acceptable range and, on the other hand, grinding wheel substitution and dressing should be carried out more frequently with consequent higher costs.

The grinding wheel proving the best behavior is B151, as the roughness values, initially slightly beyond the maximum acceptable limit, gradually decrease with increasing wheel wear and fall into the acceptable range.

As concerns B181, it proved to be unsuitable for the specific application as the roughness values were always far beyond the acceptable range, even after wheel wear.

6. Conclusions and future developments

With reference to a real industrial case of aircraft engine components manufacturing, this paper investigated CBN grinding of nickel base alloy products.

The aim was to improve the CBN grinding wheel tool life and optimize the grinding process while accounting for economic, environmental and social sustainability.

Different types of CBN grinding wheels fabricated using diverse deposition procedures were tested to compare their behavior during grinding and assess their life in terms of number of parts ground per single wheel.

Moreover, alternative grinding fluid type applicability was investigated through experimental tests on a second grinding operation, with the aim to improve process performance, workpiece quality and grinding wheel life.

Power monitoring during grinding was carried out in order to evaluate the energy efficiency of the process under diverse grinding conditions.

To guarantee the required surface integrity, evaluations based on visual inspections, FPI analyses and surface roughness measurements were performed.

Further work will be focused on the design and development of nozzles to better direct the grinding fluid at the interface between wheel and workpiece, so as to maximize the lubricating action, avoid dispersion and increase the environmental and social sustainability of the process. The related sustainability aspects will be quantitatively assessed through comparative measurements of the working environment quality.

A critical factor that strongly affects grinding wheel life is chatter: further work will investigate solutions aimed at the reduction of vibrations during grinding to verify the advantage in terms of tool life improvement.

| Parameter | Measurement (µm) |
|-----------|-----------------|
| Ra        | 1.3900          |
| Rp        | 3.3028          |
| Ry        | 7.0697          |
| Rt        | 12.4224         |

Fig. 8. Roughness measurement for test with B126 grinding wheel

Acknowledgements

Ing. Luigi Cuccaro of GE Avio SpA is gratefully acknowledged for his technical contribution and for providing the experimental set-up of this research work. The Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fr-I_LEAPT) at the Department of Chemical, Materials and Production Engineering, University of Naples Federico II, is acknowledged for its support to this research activity.

References

[1] Groover, M.P., 1996, Fundamentals of Modern Manufacturing: Materials, Processes and Systems, Prentice-Hall International Ed.
[2] Lindsay, R.P., Subramanian, K., Ault, W.N., Nachman, E.S., 1998, Machining, Vol. 16, Chapter on Grinding, in "Metals Handbook", 2nd Ed., J.R. Davis, Editor, ASM International
[3] K. Wegener, H.-W. Hoffmeister, B. Karpuschewski, F. Kuster, W.-C. Hahmann, M. Rabicy, 2011. Conditioning and monitoring of grinding wheels, CIRP Annals, Vol. 60/2, pp. 757-777
[4] Salonitis, K. Chondros, T., Chryssolouris, G., 2008, Grinding wheel effect in the grind-hardening process, International Journal of Advanced Manufacturing Technology, Vol. 38/1-2, pp. 48-58
[5] Salonitis, K., Chryssolouris, G., 2007, Cooling in Grind-Hardening operations, International Journal of Advanced Manufacturing Technology, Vol. 33/ 3-4, pp. 285-297
[6] Chryssolouris, G., Tarfas, K., Salonitis, K., 2005, An analytical and Experimental Approach to Grind-Hardening, SME Journal of Manufacturing Processes, Vol. 7/1, pp. 1-9
[7] Teti, R., D’Addona, D., 2003, Grinding Wheel Management through Neuro-Fuzzy Forecasting of Dressing Cycle Time, CIRP Annals, Vol. 52/1, pp. 407-410
[8] D’Addona, D., Teti, R., 2006, CBN Grinding Wheel Inventory Sizing through Non-Shortsighted Flexible Tool Management Strategies, 2nd Int. Virt. Conf. on Intelligent Production Machines and Systems - IPROMS 2006, 3-14 July, pp. 217-221
[9] Jin, T., Stephenson, D.J., Xie, G.Z., Sheng, X.M., 2011. Investigation on cooling efficiency of grinding fluids in deep grinding, CIRP Annals, Vol. 60/1, pp. 343-346
[10] Brinksmeier, E., Minke, E., 1993, High-Performance Surface Grinding - The Influence of Coolant on the Abrasive Process, CIRP Annals, Vol. 42/1, pp. 367-370
[11] Inasaki, I., Tönnhoff, H.K., Howes, T.D., 1993, Abrasive Machining in the Future, CIRP Annals, Vol. 42/2, pp. 723-732
[12] Oliveira, J.F.G., Alves, S.M., 2006, Development of Environmentally Friendly Fluid for CBN Grinding, CIRP Annals, Vol. 55/1, pp. 343-346
[13] Oliveira, J.F.G. Silva, E.J., Guo, C., Hashimoto, F., 2009, Industrial challenges in grinding, CIRP Annals, Vol. 58/2, pp. 663-680