High-speed grinding with CBN grinding wheels — applications and future technology

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Received 15 September 1999; received in revised form 7 September 2000; accepted 20 September 2000

Abstract

The basic mechanisms and the applications for the technology of high-speed grinding with CBN grinding wheels are presented. In addition to developments in process technology associated with high-speed machining, the grinding machine, coolant system, and the grinding tool also need to adapt to high-speed machining. Workpiece-related factors influencing the results of machining are also discussed. The paper concludes with a presentation of current research and future developments in the area of high-speed grinding, and the development of high-speed CBN camshaft grinding.

Keywords: High-speed grinding; CBN grinding wheels; Aluminium oxide

1. Introduction

More than 25 years of high-speed grinding have expanded the field of application for grinding from classical finish machining to high-performance machining. High-speed grinding offers excellent potential for good component quality combined with high productivity. One factor behind the innovative process has been the need to increase productivity for conventional finishing processes. In the course of process development it has become evident that high-speed grinding in combination with preliminary machining processes close to the finished contour enable the configuration of new process sequences with high-performance capabilities. Using the appropriate grinding machines and grinding tools, it is possible to expand the scope of grinding to high-performance machining of soft materials. Initially, a basic examination of process mechanisms are discussed that relates the configuration of grinding tools and the requirements of grinding soft materials. The effect of an effective and environmentally friendly coolant system is also investigated in addition to the effect of workpiece-related variables on the suitability of using high-speed grinding techniques.

2. Theoretical basis of high-speed grinding

In view of the random distribution of cutting edges and cutting-edge shapes, statistical methods are applied to analyse the cutting mechanism in grinding. The mean undeformed chip thickness, \( h_{cu} \), and the mean chip length, \( l_{cu} \), are employed as variables to describe the shape of the chip. The undeformed chip thickness is dependent on the static density of cutting edges, \( C_{stat} \), and on the geometric and kinematic variables [1,2]:

\[
h_{cu} = k \left( \frac{1}{C_{stat}} \right) \frac{1}{\gamma} \frac{\nu_w}{\nu_s} \frac{a_e}{d_{eq}} \]

where \( \nu_w \) is the workpiece speed, \( \nu_s \) the grinding wheel speed, \( a_e \) the depth of cut, \( d_{eq} \) the equivalent grinding wheel diameter, and \( \alpha, \beta, \gamma \) are greater than zero. On the basis of this relationship, it can be established that an increase in the cutting speed, assuming all other conditions are constant, will result in a reduction in the undeformed chip thickness. The workpiece material is machined with a larger number of abrasive grain contacts. At the same time, the number of cutting edges involved in the process decreases. This leads to the advantages promised by high-speed grinding which is characterised by a reduction in grinding forces, grinding wheel wear, and in workpiece surface roughness. Consequently, increasing the speed of the grinding wheel can lead
to an increase in the quality of the workpiece material, or alternatively, an increase in productivity. The process technology depends on the characteristics and quality requirements of the workpiece to be machined.

As the cutting speed increases, the quantity of thermal energy that is introduced into the workpiece also increases. An increase in cutting speed is not normally accompanied by a proportional reduction in the tangential grinding force, and thus results in an increase in process power. Reducing the length of time the abrasive grain is in contact with the workpiece can reduce the quantity of heat into the workpiece. An increase in the machining rate of the process is necessary for this to happen, where the chip thickness is increased to the level that applies to lower cutting speeds without overloading the grinding wheel.

Experimental results [3] illustrate that increasing the cutting speed by a factor of two while maintaining the same metal removal rate leads to a reduction in the tangential force but, unfortunately, leads to an increase in the amount of work done. Owing to constant grinding time, there is an increase in the process energy per workpiece and, subsequently, in the total thermal energy generated. When the material removal rate is also increased the rising tangential force results in a further increase in grinding power. The quantity of thermal energy introduced into the workpiece is lower than the initial situation when the same-machined workpiece volume applies despite the higher cutting speed and increased metal removal rate. These considerations show that machining productivity can be increased using high-speed grinding without having to accept undesirable thermal effects on ground components.

There are three fields of technology that have become established for high-speed grinding. These are

1. High-speed grinding with CBN grinding wheels.
2. High-speed grinding with aluminium oxide grinding wheels.
3. Grinding with aluminium oxide grinding wheels in conjunction with continuous dressing techniques (CD grinding).

Material removal rates resulting in a super proportional increase in productivity for component machining have been achieved for each of these fields of technology in industrial applications [4,5] (Fig. 1). High equivalent chip thickness of between 0.5 and 10 μm are a characteristic feature of high-speed grinding. CBN high-speed grinding is employed for a large proportion of these applications. An essential characteristic of this technology is that the performance of CBN is utilised when high cutting speeds are employed.

3. Grinding tools for high-speed grinding

CBN grinding tools for high-speed machining are subject to special requirements regarding resistance to fracture and wear. Good damping characteristics, high rigidity, and good thermal conductivity are also desirable. Such tools normally consist of a body of high mechanical strength and a comparably thin coating of abrasive attached to the body using a high-strength adhesive. The suitability of cubic boron nitride as an abrasive material for high-speed machining of ferrous materials is attributed to its extreme hardness and its thermal and chemical durability.

High cutting speeds are attainable above all with metal bonding systems (Fig. 2). One method that uses such bonding systems is electroplating, where grinding wheels are produced with a single-layer coating of abrasive CBN grain material. The electro-deposited nickel bond displays outstanding grain retention properties. This provides a high-level grain projection and large chip spaces. Cutting speeds of 280 m s⁻¹ are possible [6]. The service life ends when the abrasive layer wears out.

Fig. 1. Main field of applications for high-speed grinding [4–6].
The high roughness of the cutting surfaces of electroplated CBN grinding wheels has disadvantageous effects. The high roughness is accountable to exposed grain tips that result from different grain shapes and grain diameters. Although electroplated CBN grinding wheels are not considered to be dressable in the conventional sense, the resultant workpiece surface roughness can nevertheless be influenced within narrow limits by means of a so-called touch-dressing process. This involves removing the peripheral grain tips from the abrasive coating by means of very small dressing infeed steps in the range of dressing depths of cut between 2 and 4 μm, thereby reducing the effective roughness of the grinding wheel [7].

Multi-layer bonding systems for CBN grinding wheels include sintered metal bonds, resin bonds, and vitrified bonds. Multi-layer metal bonds possess high bond hardness and wear resistance. Profiling and sharpening these tools is a complex process, however, on account of their high mechanical strength. Synthetic resin bonds permit a broad scope of adaptation for bonding characteristics. However, these tools also require a sharpening process after dressing. The potential for practical application of vitrified bonds has yet to be fully exploited. In conjunction with suitably designed bodies, new bond developments permit grinding wheel speeds of up to 200 m s⁻¹. In comparison with other types of bonds, vitrified bonds permit easy dressing while at the same time possess high levels of resistance to wear. In contrast to impermeable resin and metal bonds, the porosity of the vitrified grinding wheel can be adjusted over a broad range by varying the formulation and the manufacturing process. As the structure of vitrified bonded CBN grinding wheels results in a subsequently increased chip space after dressing, the sharpening process is simplified, or can be eliminated in numerous applications. Fig. 3 shows a typical microstructure of a vitrified CBN grinding wheel.

The selection of the appropriate grade of vitrified CBN grinding wheel for high-speed grinding is more complicated than for aluminium oxide grinding wheels. Here, the CBN abrasive grain size is dependent on specific metal removal rate, surface roughness requirement, and the equivalent grinding wheel diameter. As a starting point when specifying vitrified CBN wheels, Fig. 4 shows the relationship between CBN abrasive grain size, equivalent diameter, and specific metal removal rate for outside diameter grinding operations. However, the choice of abrasive grain is also dependent on the surface roughness requirement and is restricted by the specific metal removal rate. Table 1 shows the relationship between CBN grain size and their maximum surface roughness and specific metal removal rates. The workpiece material has a significant influence on the type and volume of vitrified bond used in the grinding wheel. Table 2 shows the wheel grade required for a variety of workpiece materials that are based on crankshaft and camshaft grinding operations. Considering the materials shown in Table 2, chilled cast iron is not burn sensitive and has a high specific grinding energy owing to its high carbide content. Its hardness is approximately 50 HRc and the maximum surface roughness achieved on machined camshafts is 0.5 μm (Rₐ), therefore a standard structure bonding system is used that is usually between 23 and 27 vol.% of the wheel. The CBN grain content is usually 50 vol.%, and wheel speeds are usually up to 120 m s⁻¹. Nodular cast iron is softer than chilled cast iron and is not burn sensitive. However, it does tend to load the grinding wheel. Cam lobes can have hardness values as low as 30 HRc and this tends to control wheel specification. High stiffness crank and camshafts can tolerate a 50 vol.% abrasive structure containing 25 vol.% bond. High loading conditions and high contact re-entry cam forms require a slightly softer wheel where the bonding system occupies 20 vol.% of the entire wheel structure. Low stiffness cam and crankshafts require lower CBN grain concentrations (37.5 vol.%) and a slightly higher bond volume (21 vol.%). Very low stiffness nodular iron components may even resort to grinding wheels containing higher strength bonding.
systems containing sharper CBN abrasive grains operating at 80 m s\(^{-1}\). The stiffness of the component being ground has a significant effect on the workpiece/wheel speed ratio. Fig. 5 demonstrates the relationship between this ratio and the stiffness of the component. Steels such as AISI 1050 can be ground in the hardened and the soft state. Hardened 1050 steels are in the range 62–68 HRc. They are burn sensitive and as such wheels speeds are limited to 60 m s\(^{-1}\). The standard structure contains the standard bonding system up to 23 vol.%. Whereas the abrasive grain volume is contained at 37.5 vol.%. Lower power machine tools usually have grinding wheels where a part of the standard bonding system contains hollow glass spheres (up to 12 vol.%) exhibiting

Table 1

<table>
<thead>
<tr>
<th>CBN grain size</th>
<th>Surface roughness, (R_a) ((\mu)m)</th>
<th>Maximum specific metal removal rate, (Q_{w_{\text{max}}}) ((\text{mm}^3\text{mm}^{-2}\text{s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B46</td>
<td>0.15–0.3</td>
<td>1</td>
</tr>
<tr>
<td>B54</td>
<td>0.25–0.4</td>
<td>3</td>
</tr>
<tr>
<td>B64</td>
<td>0.3–0.5</td>
<td>5</td>
</tr>
<tr>
<td>B76</td>
<td>0.35–0.55</td>
<td>10</td>
</tr>
<tr>
<td>B91</td>
<td>0.4–0.6</td>
<td>20</td>
</tr>
<tr>
<td>B107</td>
<td>0.5–0.7</td>
<td>30</td>
</tr>
<tr>
<td>B126</td>
<td>0.6–0.8</td>
<td>40</td>
</tr>
<tr>
<td>B151</td>
<td>0.7–0.9</td>
<td>50</td>
</tr>
<tr>
<td>B181</td>
<td>0.8–1</td>
<td>70</td>
</tr>
</tbody>
</table>

Fig. 3. Microstructure of a vitrified CBN grinding wheel. The abrasive grains stand proud of the vitrified bond and are approximately 125 \(\mu\)m in diameter.

Fig. 4. Chart for selecting CBN abrasive grit size as function of the equivalent grinding wheel diameter, \(D_e\), and the specific metal removal rate, \(Q_w\).
comparable grinding ratios to the standard structure system. These specifications also cover most powdered metal components based on AISI 1050 and AISI 52100 ball bearing steels. Softer steels are typically not burn sensitive, but do tend to ‘burr’ when ground. Maximum wheel and work speeds are required in order to reduce equivalent chip thickness. High pressure wheel scrubbers are required in order to prevent the grinding wheel from loading. Grinding wheel specification is based on an abrasive content in the region of 50 vol.% and a bonding content of 20 vol.% using the standard bonding system operating at 120 m s\(^{-1}\). Tool steels are very hard and grinding wheels should contain 23 vol.% standard bonding system and 37.5 vol.% CBN abrasive working at speeds of 60 m s\(^{-1}\). Inconel materials are extremely burn sensitive, and limited to wheel speeds of 50 m s\(^{-1}\) and have large surface roughness requirements, typically 1 \(\mu m\) (\(R_a\)). These grinding wheels contain porous glass sphere bonding systems with 29 vol.% bond, or 11 vol.% bond content using the standard bonding system.

In addition to the need to select the appropriate bonding system for grinding wheels in accordance with the requirements of the application concerned, the strength of the body of the grinding wheel requires optimisation with high cutting speeds. In the case of very high cutting speeds, conventional grinding wheel designs involving a rectangular body and a bore often leads to excessive and irregular extensions of the body and cracking of the abrasive coating. In order to eliminate the possibility of high-speed grinding wheels failing, the material and the geometry of the body must be able to cope with very high cutting speeds. A further aim of the body of the grinding wheel must be to reduce the magnitude of centrifugal forces by optimising the shape of the body of the grinding wheel without impairing operational safety. Excessive stress in the body of the grinding wheel is to be avoided, and the smallest possible extension of the body is tolerated. A reduction in mass is also necessary to move critical natural frequencies of the system in the direction of higher rotational speeds. Developments in high-speed grinding wheel design have focused on re-designing and optimising the shape of body for both vitrified CBN [8,9] and electroplated CBN grinding wheels [10].
4. High-speed machine tool development

The advantages of high-speed CBN grinding can only be realised in an effective manner if the machine tool is adapted to operate at high cutting speeds. In order to attain very high cutting speeds, grinding wheel spindles and bearings are required to operate at speeds in the order of 20 000 rpm. The grinding wheel/spindle/motor system must run with extreme accuracy and minimum vibration in order to minimise the level of dynamic process forces. Therefore, a high level of rigidity is required for the entire machine tool. Balancing of high-speed grinding wheels is also necessary at high operating speeds using dynamic balancing techniques. These techniques are required so that workpiece quality and increased tool life is preserved.

Another important consideration is the level of drive power required when increases in rotational speed become considerable. The required total output is composed of the cutting power, $P_c$, and the power loss, $P_l$:

$$P_{\text{total}} = P_c + P_l \quad (2)$$

The cutting power is the product of the tangential grinding force and the cutting speed:

$$P_c = F_t v_c \quad (3)$$

The power loss of the drive is comprised of the idle power of the spindle, $P_L$, and power losses caused by the coolant, $P_{KSS}$, and by spray cleaning of the grinding wheel, $P_{SSP}$, thus

$$P_l = P_L + P_{KSS} + P_{SSP} \quad (4)$$

The power measurements shown in Fig. 6 confirm the influence of the effect of cutting speed on the reduction of cutting power. However, idling power has increased quite significantly. The grinding power, $P_c$, increases by a relatively small amount when the cutting speed increases and all other grinding parameters remain constant. However, this means that the substantial power requirement that applies at maximum cutting speeds results from a strong increase in power is due to rotation of the grinding wheel, the supply of coolant, and the cleaning of the wheel.

The quantities and pressures of coolant supplied to the grinding wheel and the wheel cleaning process are the focus of attention by machine tool designers. This is shown in Fig. 7 [11]. The power losses associated with the rotation of the grinding wheel are supplemented by losses associated with coolant supply and wheel cleaning. The losses are dependent on machining parameters implying that machine settings and coolant supply need to be optimised for high-speed grinding.

In addition to the advantage of effectively reducing the power required for grinding, optimisation of the coolant supply also offers ecological benefits as a result of reducing the quantities of coolant required. Various methods of coolant supply are available such as the free-flow nozzle that is conventionally used, the shoe nozzle that ensures "reduced quantity lubrication", and the mixture nozzle that ensures "minimum quantity lubrication". The common task is to ensure that an adequate supply of coolant is presented at the grinding wheel–workpiece interface [12]. The systems differ substantially regarding their operation and the amount of energy required supplying the coolant.

A shoe nozzle, or supply through the grinding wheel, enables coolant to be directed into the workpiece–wheel contact zone. A substantial reduction in volumetric flow can be achieved in this way. In comparison to the shoe nozzle, supply through the grinding wheel requires more complex design and production processes for the grinding wheel and fixtures. An advantage of this supply system is that it is independent of a particular grinding process [13]. Both systems involve a drastic reduction in supply pressures as the grinding wheel effects acceleration of the coolant. A more effective reduction in the quantity of the coolant results in 'minimal quantity coolant' supply amounting to several millilitres of coolant per hour. As the cooling effect is reduced, dosing nozzles are used exclusively to lubricate the contact zone. Lubricating systems for use with high-speed...
speed grinding wheels have been reviewed by Treffert [3] and Brinksmeier et al. [14].

5. Factors affecting quality

The aim of high-speed CBN grinding is to substitute conventional machining operations such as milling, turning, and surface broaching. The high-speed grinding process focuses on machining large volumes of material in the shortest possible time. This may lead to workpiece quality becoming impaired as the equivalent chip thickness increases in proportion to grinding forces [10,15] (Fig. 8). The machine tool must be able to absorb such large forces. It is possible to reduce the amount of heat in the grinding process using high grinding wheel speeds. However, practical experience to date shows that not all workpiece materials permit high-speed grinding [4]. The mechanical characteristics of the material to be ground have a profound affect on the chip-forming process and the resulting process forces and temperatures. When extremely tough and heat resistant materials such as nickel-based alloys are involved, the process work increases to such an extent that it is not always possible to avoid microstructural damage to the surface zone of the workpiece. These materials can be ground more effectively using the CD process.

6. Developments in camshaft grinding

During the last 25 years increasing demands on automotive and diesel engine manufacturers in North America have led to ever-greater fuel economy requirements in engine design. One major fuel saving was to reduce engine friction by the use of roller tappets rather than using flat tappet followers. Roller tappets place higher loads on the camshaft that has led to the development of stronger camshaft materials. Camshafts are now fabricated from hardened forged steel or powdered metals rather than traditional cast irons.
In 1985, a major American car manufacturer made significant improvements to their 3.8 l V6 engine design to improve both fuel economy and performance. The improvements included roller tappets, tubular steel camshafts, roller rocker arms, and sequential electronic fuel injection. The 3.8 l camshaft was designed for the special requirements of the V6 engine and modifications included a cam lobe geometry with a negative radius of curvature of less than 300 mm. This design presented severe manufacturing difficulties as a result of the small grinding wheel size required in generating a re-entry profile.

Steel camshafts proved more difficult to grind than cast iron materials because of the risk of ‘burning’ and cracking caused by surface phase transformations. Kocsis and Stine [16] reported that to grind the lobes of a steel camshaft in a comparable time to that of a cast iron camshaft required continuous dressing to maintain a sharp grinding wheel. The alternative approach was to use relatively soft wheel grades that wear rapidly. Production cam lobe grinders at that time all used conventional aluminium oxide abrasive wheels with usable diameter ranges of 450–600 mm or 600–750 mm to give an acceptable wheel life (grinding ratios between 8 and 15). Unfortunately, this was not cost effective for grinding the 3.8 l re-entry profile camshaft because the maximum wheel diameter allowable was 400 mm. Conventional abrasive wheels would therefore have given an unacceptable wheel change frequency. A radically different approach was required: the solution was vitrified CBN.

6.1. Machine tool development

Towards the end of the 1970s and at the beginning of the 1980s saw several developments in machine tool design in terms of greater stiffness, accuracy, and flexibility. Hydrostatic bearing systems provided increased stiffness for slideways and wheel spindles and greater damping at very high wheel speeds. At the same time intense effort was given to incorporating computer numerical control to these machines. On grinders prior to 1980, moving the wheel head following a master cam generated the camshaft lobe profile. Incorporation of ball screws and a.c. servomotors combined with greater computing power allowed the master cam to be eliminated by generating the profile numerically. These innovations provided sub-micron accuracy of the slide movements that allowed better control of metal removal as a function of position around the cam lobe and for each revolution of the camshaft. These developments were all pre-requisites for the use of vitrified CBN.

Manufacturers in Japan were the first to recognise the full potential of using CBN and to demand machines capable of applying the product economically. The first camshaft lobe grinder designed specifically for CBN described in the literature was manufactured by Toyoda Machine Works and used resin-bonded grinding wheels. The first CBN camshaft grinder was supplied to Caterpillar in North America and was reported by Hanard [17].

The Toyoda GCB7-63 had several innovative features including hydrostatic slideways and wheel spindle, CNC profile generation, variable work speed drive to control metal removal rate around the cam lobe, and an acoustic touch sensor to determine the relative position of the wheel and diamond truer. The wheels were 600 mm in diameter and, being resin bonded, required a post-truing conditioning process using a dressing roll with loose abrasive grains. The conditioning process and the relatively low resilience of the resin bond were recognised as process limiting factors. The GCB7-63 operated at a wheel speed of 50 m s\(^{-1}\).

At the same time, Suzuki [18] described the first applications of a CBN camshaft lobe grinder dedicated to grinding with vitrified CBN grinding wheels. The machine, a GCH 32, was described in detail by Tsujichi [19] and had a fixed wheel speed of 80 m s\(^{-1}\). Toyoda Van Moppes, a joint venture between Toyoda Machine Works and Unicorn, developed the wheels. Each wheel consisted of a thin-segmented rim of vitrified material bonded onto a steel core with a measured burst speed of 250 m s\(^{-1}\) [20]. The vitrified bond eliminated the need for conditioning with a dressing roll that provided a greater wheel life than the resin-bonded wheel. The wheel diameter was 350 mm diameter and therefore capable of grinding smaller re-entry profiles than conventional grinders. An acoustic touch sensor was incorporated to determine the relative position of grinding wheel and truing disc, and to minimise dressing errors due to thermal movements within the machine.

6.2. Application development

A major car manufacturer decided to purchase 16 Toyoda GCH 32/63B CNC master less camshaft lobe grinders using vitrified CBN grinding wheels to grind their V6 re-entry profile camshaft. The purchase was the largest installation of CBN cam lobe grinders in the world, at that time, and initiated the seminal technological and engineering research and development experiment to determine the viability of CBN for cylindrical grinding. The workpiece material was a 12 lobe camshaft manufactured from AISI 1050 plain carbon steel which was induction hardened to 55 HRc with a minimum effective case depth of 1.5 mm. The surface finish requirement was 0.8 \(\mu m (R_{\nu})\) after grinding and were then tape polished.

The grinders were installed on a central coolant supply with light duty soluble oil at 3% concentration with a volume flow rate of 50 gal min\(^{-1}\) at 40 psi pressure. The grinders were supplied with air scrapers, normal and tangential jets, and exit jets to fully utilise the available coolant. An additional high-pressure coolant nozzle at 400 psi with a fluid delivery of 2 gal min\(^{-1}\) was placed above each grinding wheel to act as a scrubber and to cool the wheel.

The wheels were trued with a 100 mm diameter single-layer diamond rotary disc in conjunction with an acoustic touch sensor. A steel roll was provided for conditioning a new wheel if necessary. Grinding damage was measured...
Several design modifications were made and each truing disc from machine to machine due to excessive manual dressing. Problems were encountered regarding the correct diamond distribution to touch sense when the coolant was switched off. Problems in the presence of coolant, therefore, precautions were taken within truing cycles. The touch sensor gave good repeatability to diameter, and a number of various automatic and manual monitoring information such as wheel diameter, truing disc controller provided a wide range of diagnostic and process length to determine accuracy and repeatability. The CNC wheel testing a lengthy procedure.

Producing improvements in component quality; this made considered part of the grinding process that helped in quality camshafts. This approach meant that the wheel was approach taken by the customer was one of producing high 50% due to improved manufacturing techniques. The development of a higher strength bonding system. In addition to these developments, CBN wheel costs fell by over \( \frac{\text{specification}}{\text{total abrasive cost}} \times 100 \% \). Barkhausen noise to detect grinding burn (metallurgical change in the surface layers). Confirmation of burn was made by etching the cam lobes with 2% nital.

### 6.3. High-speed process performance

The initial performance of the CBN process was not cost effective for production in terms of either cycle time or wheel life. Significant process development was required over a 5-year period with close support from the machine tool manufacturer.

The primary problem was burning of the cam lobe in the region of the flank where wheel/cam lobe contact area is greatest, and where the instantaneous metal removal rate is highest. Production experience using vitrified CBN on camshafts prior to using steel materials had been gained grinding cast iron camshafts where the grinding power and the risk of burning was greatest immediately after dressing, and decreased as the wheel self-conditioned during grinding. A steady rise in surface roughness was accompanied after self-conditioning. For steel camshafts, it was found that the grinding power increased with time after dressing in general production even when accompanied with a small rise in surface roughness. Each part of the grinding system had to be investigated in some depth in order to eliminate grinding burn in order to create a cost-effective process.

**Wheel specification.** The initial wheel specification had a relatively dense structure, which was replaced within the first few months with an ultra-porous wheel capable of grinding the camshaft in the required cycle time without burning the component. This particular grinding wheel specification gave a life of 3000 camshafts that was later increased to 8000 (at \( 80 \text{ m s}^{-1} \) wheel speed) due to the development of a higher strength bonding system. In addition to these developments, CBN wheel costs fell by over 50% due to improved manufacturing techniques. The approach taken by the customer was one of producing high quality camshafts. This approach meant that the wheel was considered part of the grinding process that helped in producing improvements in component quality; this made wheel testing a lengthy procedure.

**Truing.** The truing process was investigated at some length to determine accuracy and repeatability. The CNC controller provided a wide range of diagnostic and process monitoring information such as wheel diameter, truing disc diameter, and a number of various automatic and manual truing cycles. The touch sensor gave good repeatability to within \( \pm 2 \text{ \mu m} \). The sensor initially gave incorrect readings in the presence of coolant, therefore, precautions were taken to touch sense when the coolant was switched off. Problems were encountered regarding the correct diamond distribution in the truer in order to ensure consistent wear throughout its life. This was identified by a large variation in wheel life from machine to machine due to excessive manual dressing. Several design modifications were made and each truing disc was X-ray inspected for a period of time until the right distribution was achieved. The final truing disc specification had a wear factor of typically one fifth of the amount of CBN removed from the wheel. The wear factor currently represents less than 4% of the total abrasive cost.

**Coolant delivery.** The coolant delivery system consisted of three main components, namely

1. **Upper main coolant nozzle.** A nozzle arrangement with normal and tangential jets. The use of this type of system is effective at breaking the air layer around the wheel at low coolant velocity but is known to be sensitive to position (\( \pm 2 \text{ \mu m} \)) [21].

2. **Lower main coolant nozzle.** This nozzle was good at cooling and the grinding zone was subjected to excessive wear by chip flow. The nozzles were initially manufactured from steel but were replaced with a carbide material.

3. **High-pressure wheel cleaning.** Satow [22] was the first to report on the use of high-pressure flushing systems for use with CBN. The benefit of using the high-pressure flushing system was to cool the grinding zone and to prevent wheel loading. The machine operator was able to determine when the coolant filter required changing based on Rollscan grinding burn level.

### 6.4. Grinding operation

The process for grinding steel camshafts is unusual in that to achieve an acceptable cycle time, burn can be knowingly induced during the initial roughing portion of the grinding cycle. The depth of this burn is controlled to such an extent that it can be removed during the finishing portion of the cycle. In addition to CNC control, the velocity, acceleration, and jerk at each degree around the cam lobe can be varied to allow for changes in the wheel/cam lobe contact length and to maximise the average metal removal rate per revolution.

The main problem encountered was that the grinding wheels could not be worked hard enough during the roughing cycle to self-condition without inducing too great a depth of burn to be removed during the finishing cycle. Consequently, after dress, the power increased from part to part as the number of wear flats on the grinding wheel increased. Wear flat formation generated significant levels of frictional heat that decreased the number of camshafts per dress. Attempts to modify the wheel structure decreased the amount of frictional heat generated at the cost of high wheel wear. By comparison, cast iron camshafts are not burn sensitive which means that they can be ground at a much higher metal removal rate.

As part of a continuous improvement in design of this particular engine, sinusoidal wave (chatter) tolerance was altered in order to improve engine noise. The major contributor to this problem was determined to be the grinding wheel and truing disc speed ratio. The ratio was changed but led to a reduced number of parts per dress from 60 to 30. In
1992, Toyoda Machine Works made machine modifications to reduce the speed to 60 m s\(^{-1}\). This had a double effect: initially, it eliminated the sinusoidal wave problem, and secondly, it dramatically reduced burn levels such that the number of parts per dress was increased to 170. By 1993 all cam grinders were operating at a wheel speed of 60 m s\(^{-1}\) and at 120 parts per dress. At this point the CBN abrasive cost fell below that of comparable processes without re-entry cam profiles that used conventional wheels (Fig. 9).

7. Results

There is no doubt that the technological and engineering research and development carried by the car manufacturer in conjunction with Toyoda Machine Works and Unicorn was one of the greatest influences for new grinding technology utilising vitrified CBN.

The rewards are self-evident (Fig. 9) in that the abrasive cost per cam lobe has decreased every year since installation. The use of vitrified CBN provided the car manufacturer with a viable method of manufacture for grinding camshafts with a re-entrant cam lobe profile, and within 5 years reduced abrasive costs to below those of conventional abrasives. However, other benefits include:

- Of the four million camshafts ground since 1989, only one defective camshaft has been returned from an engine in the field. This was traced back to a machine power failure due to lightening.
- Grinding machines average an up time of greater than 95%.
- One wheelwright is required to change wheels on a two-shift operation.

The results above show that CBN is not necessarily cost effective at higher wheel speeds but that the optimum wheel speed is a function of the peculiarities of the camshaft geometry and the material it is made from. Further research is being carried out at Unicorn in conjunction with car manufacturers in order to develop optimum wheel specifications for new camshaft materials. Recent developments in CBN abrasive research have also led to a variety of new abrasive grits which are reported to grind with lower power and remain sharper for a longer period of time than current CBN abrasives (Fig. 10).

In addition to development work carried out by grinding wheel manufacturers, it should be pointed out that the growth of vitrified CBN grinding technology has been advanced by machine tool manufacturers who have played significant role in developing the US and European market for novel cam lobe, crank pin, angle head, and multi-wheel grinding applications.

Additional applications will develop for vitrified CBN high-speed grinding technology as a result of developments in near-net-shape technology. Rough and finish machining of hardened components in one grinding operation enables the user to reduce machining sequences. Present research topics will enable new materials with special functional
requirements, such as powder metal high-speed steel variable-valve control (VVC) camshafts, to be machined using high-performance machining techniques [23].

8. Conclusion

It has been shown that the development of vitrified CBN grinding technology is a collaborative partnership between end user, machine tool builder, and abrasive supplier. In this particular case, the end user has been able to reduce grinding costs to below that incurred using conventional abrasives. Continued collaboration in addition to new developments in materials technology associated with abrasive products and camshafts will reduce grinding costs even further.

References
