Technological Fundamentals of CBN Bevel Gear Finish Grinding

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INTRODUCTION

The bevel gear grinding process, with conventional wheels, has been limited to applications where the highest level of quality is required. Grinding with conventional wheels has not been used in high production applications, because of the long cycle times and resultant high manufacturing costs. A further hindrance to the wider application of bevel gear grinding has been the lack of an understanding of the fundamental principles involved in the process. Rather than basing it on applied engineering knowledge, gear grinding success has been dependent upon the experience of skilled grinding machine operators. This can make it difficult to get consistent results from day to day.

Dr. Kegg[1] has noted that the industry trend is toward higher part quality, indicating increased use of grinding, but with a diminishing supply of skilled machine operators.

In addition to these diverging tendencies, a new grinding wheel abrasive (CBN) has been introduced. Much information has been published highlighting the benefits of CBN grinding, such as reduced grinding time and overall costs, maintaining consistent geometrical tolerances and improved metallurgical integrity. Despite these promised results, CBN grinding has been slow to be implemented in high volume production applications because the additional technology also has not been well understood by many potential users.

During the past few years a significant amount of fundamental grinding research has been conducted by several researchers [2-17]. This article will show how the fundamental research has been applied to CBN bevel gear grinding. The understanding and implementation of applied grinding technology has made it possible to change the grinding machine from the mysterious black box of the past to a system having predictable and consistently repeatable results.

The combination of a new grinding tool material (CBN), new applied grinding technology, and new bevel gear grinding machines has made it possible to drastically reduce the grinding time and cost, while at the same time improving quality and consistency, making bevel gear grinding technically and economically feasible for mass production.[18]

FUNDAMENTALS OF CBN GRINDING OF HARDENED MATERIALS

CBN Physical Propeties

Elevated Temperature Hardness

Fig. 1 shows the elevated temperature hardness of the four major abrasives[12].

The temperatures encountered by the cutting points of the abrasive grains are well above room temperature, thus the elevated temperature properties are of greater significance than the room temperature properties. It can be seen that the hardness of diamond decreases at a much faster rate than the other three abrasives with increasing temperature. In addition, diamond wears rapidly by graphitization or oxidation in the presence of iron at high temperatures and is, therefore, not usually successful in grinding ferrous materials. CBN on the other hand maintains its hardness advantage over silicon carbide and aluminum oxide at all temperatures up to 1830°F (1000°C) and is chemically inert in the grinding of ferrous materials.

Grain Shape and Its Influence on the Rate of Wear Flat Development

Attritious wear, the slow gradual development of a wear

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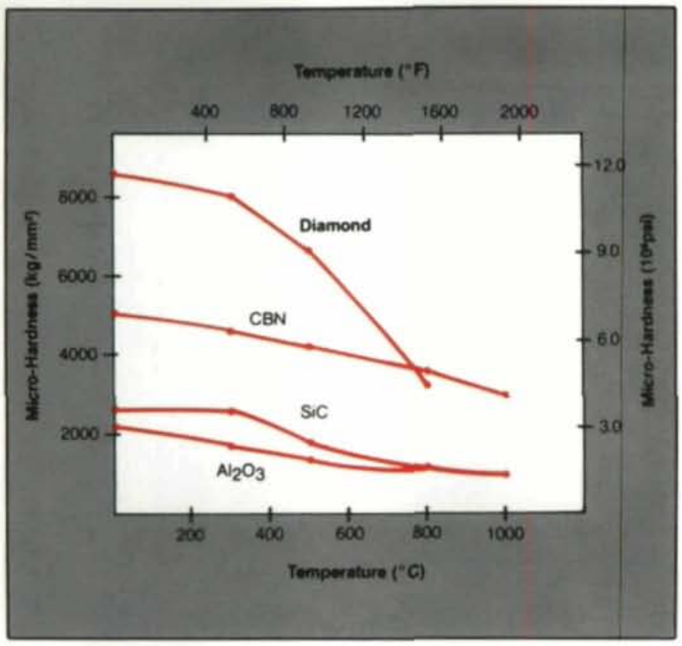


Fig. 1—Micro-Hardness of CBN in terms of the temperature in comparison to other abrasive grains.[12]

flat, limits the useful operation of a grinding wheel during finish grinding.

Fig. 2 shows photographs of an aluminum oxide and a CBN crystal. The CBN crystal has a well-defined structure, while the aluminum oxide grain does not. Aluminum oxide crystals on the average have a spherical form[19] while the CBN crystals have a block form shown in Fig. 2. It can be seen that for a given amount of crystal wear the length of the wear flat will be significantly greater for the aluminum oxide. A comparison of wear flat areas shows an even greater difference.

The size of the wear flat area has a direct effect on burning. Malkin[20] has shown that when a wear flat area of 4% of the wheel surface has developed, burning is encountered with conventional wheels. The cubic structure of CBN will allow for greater radial wear before the same size wear flat is developed.

Anisotropic Crystal Strength

Like diamond, CBN has anisotropic strength properties. This can result in a self-sharpening action under certain

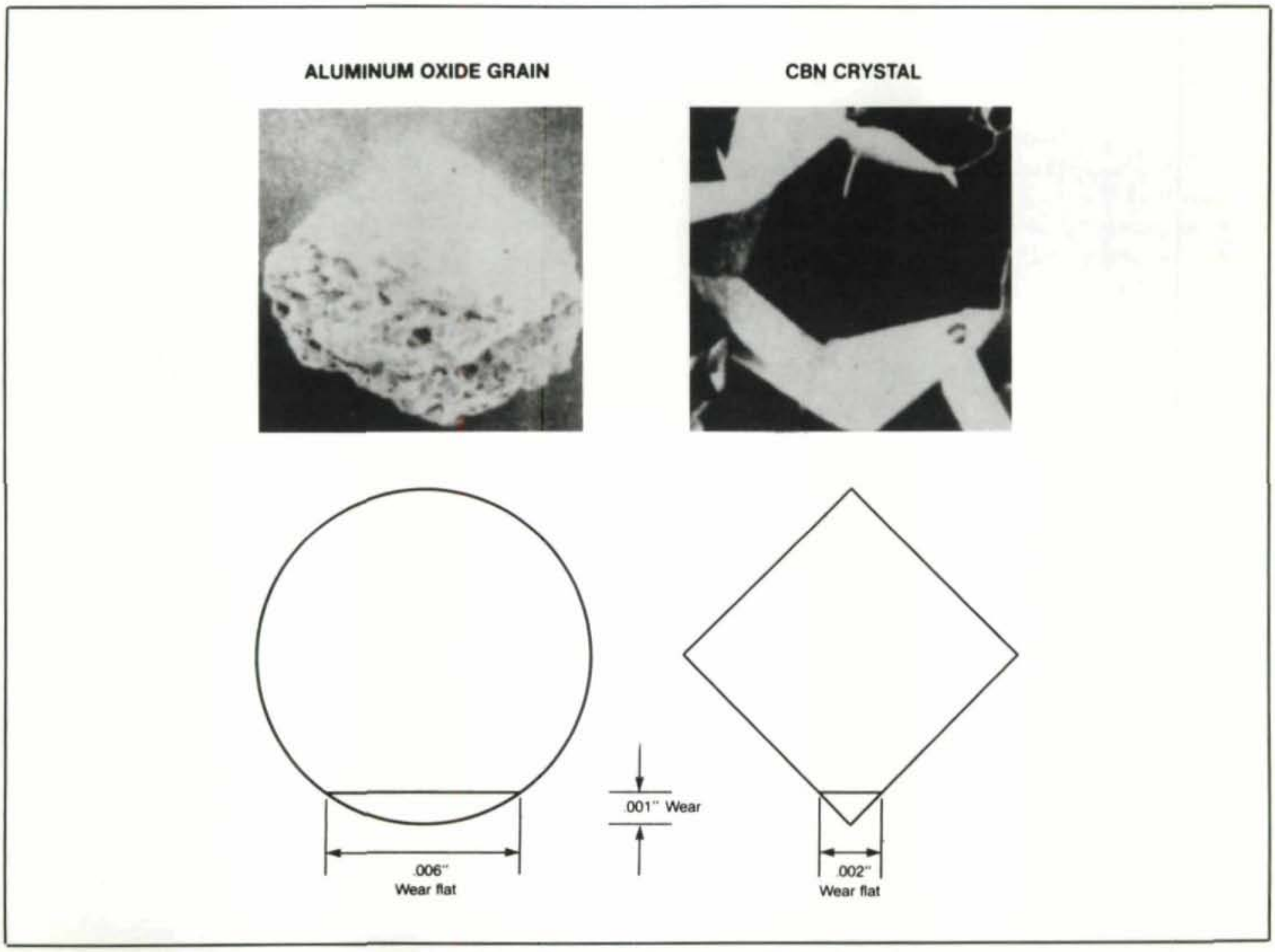


Fig. 2—Effect of Grain Shape on the Rate of Wear Flat Development.

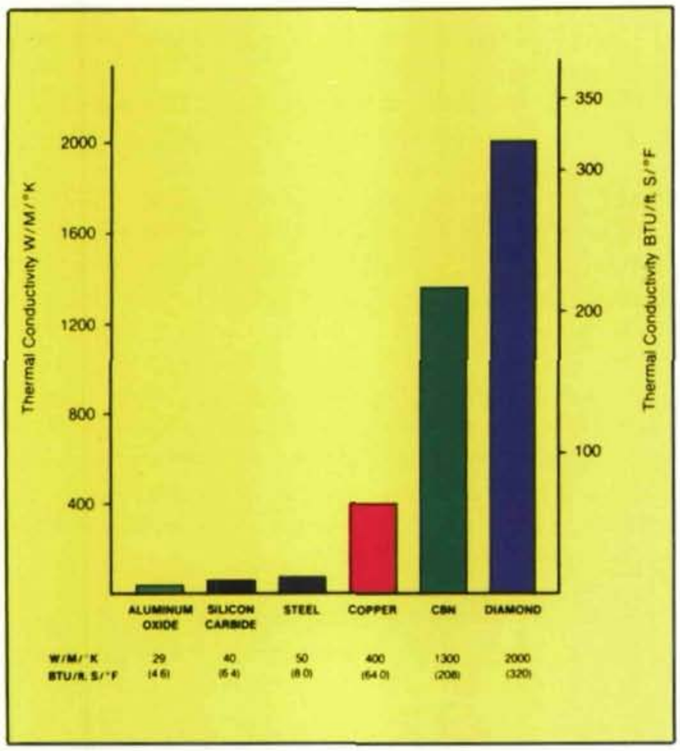


Fig. 3—Comparison of Thermal Conductivity at Room Temperature.

conditions,[14] providing a new sharp cutting edge without crystal pullout.

Thermal Conductivity

Fig. 3 shows the thermal conductivity of the four major abrasives, and of steel and copper.[21,22] The significance of this property will be shown in the next section on thermal input to the workpiece.

Grinding Characteristics of CBN vs. Conventional Abrasives

Low Thermal Input With Increased Force and Power Requirement

In CBN grinding the forces and power are higher than with conventional wheels. CBN grinding machines thus require greater spindle stiffness and power. Salje[2] has shown that at the same metal removal rate a CBN wheel required 1.25 to 2.6 times the power of an aluminum oxide wheel. This has been rather puzzling since CBN is a harder and sharper abrasive. The reason for this difference in power requirement between the two abrasives can be explained by a simple analysis of the heat flow between wheel and work in the two cases.

Fig. 4 is a schematic of the surface grinding operation. It is assumed for simplicity that all of the power consumed in grinding is dissipated as heat between wheel and work only.

$$q = q_s + q_w \tag{1}$$

where q = total heat flux in grinding
q_s = heat flux to wheel
q_w = heat flux to work

Denoting k_s, and k_w as the thermal conductivities for wheel and work, A as the wheel-work contact area and t_s, t_w as thicknesses for wheel and work across which there is an equal temperature drop, then

$$q_s \frac{t_s}{k_s A} = q_w \frac{t_w}{k_w A} \tag{2}$$

The quantity within each bracket is the thermal resistance of wheel and work respectively. Since the thickness layer from the point of view of thermal damage to work and wheel is of similar magnitude, equation[2] can be simplified as

$$\frac{q_s}{k_s} = \frac{q_w}{k_w} \tag{3}$$

From equations (1) and (3)

$$q_s = \frac{q}{1 + (k_w/k_s)} ; \quad q_w = \frac{q}{1 + (k_s/k_w)}$$

Using the room temperature thermal conductivity values from Fig. 4, in the above relationships, for the case of an aluminum oxide wheel it is seen that 63% of the total heat generated goes into the work and 37% into the wheel. In the case of a CBN wheel it is seen that only 4% of the total heat generated goes into the work while 96% ends up in the wheel. In actual practice, thermal conductivity varies with temperature for both the abrasive and the work material. Nevertheless the amount of heat input to the work will be much less with CBN than with conventional abrasives. Therefore, chips are formed at a lower temperature with CBN. Since the forces required to work a material at lower temperatures are higher, CBN grinding is accompanied by higher forces and power requirements.

It should not be misconstrued from the above analysis that thermal damage to work is not possible with CBN wheels. Thermal damage can be produced with CBN, but when the

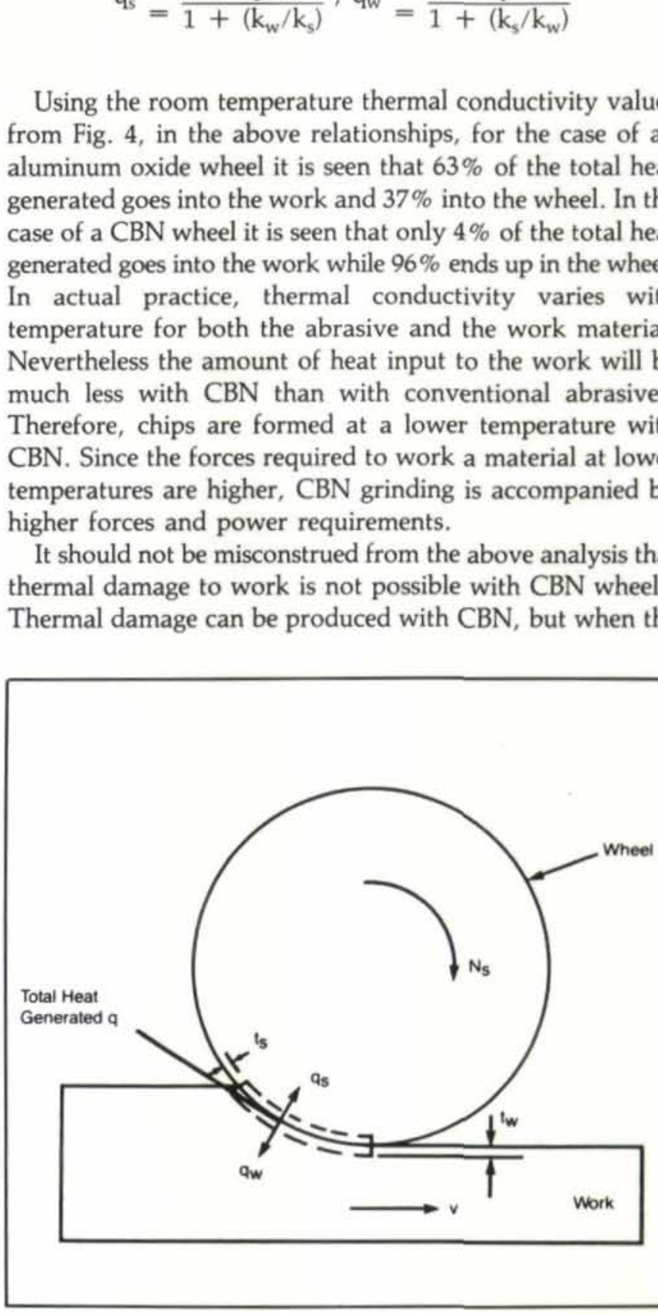


Fig. 4—Heat Distribution between wheel and worm in surface grinding

wheel is properly prepared this will happen at a much higher metal removal rate and grinding spindle power as compared to conventional wheels. On the other hand, the high heat input to the CBN wheel requires proper coolant application to increase the longevity of the wheel.

As a result of the lower heat input to the workpiece with CBN grinding wheels and a reduction in the tendency to burn, CBN wheels are normally used at higher metal removal rates than conventional wheels. This further increases the grinding forces and power. Thus, it is not unusual for the forces encountered in CBN grinding to be 4 to 10 times greater than with an aluminum oxide wheel.

Residual stresses and fatigue strength

The functional behavior of a ground component is substantially determined by the material physical properties, as well as, the residual stresses near the surface.[11,23] Residual stresses will have an effect on both the static strength and the dynamic strength (fatigue strength).

The initiation and growth of cracks can be accelerated or retarded by residual stresses. Tensile residual stresses will increase the possibility of crack initiation and growth, while compressive stresses will retard them.

The near surface residual stresses as a result of grinding can be produced by one or a combination of the following means:

thermal: heat generated during grinding;
mechanical: plastic deformation;
chemical: reactions with machining fluids and absorption of elements in the machined surface.[24]

Thermally induced residual stresses are tensile. The highly localized temperatures at the surface cause the work material to yield in compression as shown in Fig. 5. After the heat source has passed and the material cools, the plastically compressed surface material is left in tension. Snoeys[25] has found that increased maximum grinding temperatures cause higher peak residual tensile stresses. Bellows[26] has found that less abusive grinding conditions decrease the tensile residual stresses.

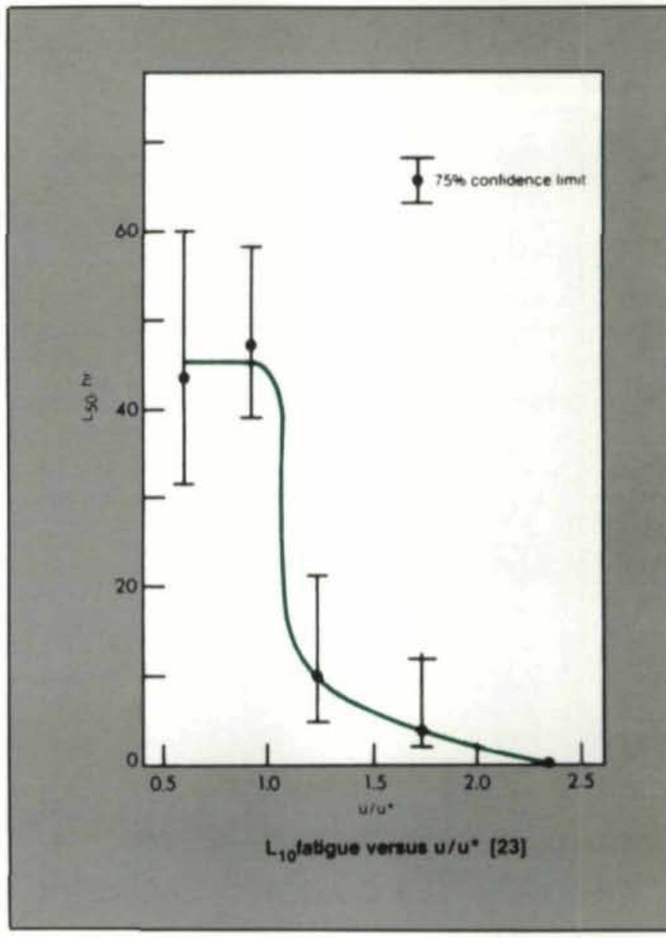


Fig. 6

The effect of various levels of thermal input on the fatigue life of bearing rings has recently been investigated.[23] In Fig. 6 it can be seen that the L10 fatigue life decreased dramatically with an increase in U/U* (the ratio of the measured specific energy to the specific energy at burning). This ratio is directly proportional to the grinding power and the grinding temperature; and points out that higher thermal input to the work surface will greatly reduce the fatigue life.

When the grinding temperature is sufficiently low, residual stresses are caused primarily by plastic deformation. This mechanical cold working of the surface material results in compressive residual stresses in a manner similar to shot peening. Also, at lower temperatures chemical reactions are less likely, or at least will often proceed at a slower rate.

Many investigators have compared the residual stresses produced by CBN and conventional wheels and have shown that CBN wheels tend to produce compressive residual stresses while aluminum oxide wheels tend to produce tensile residual stresses.[4,5,13,15,27,28,29] This difference can be explained by the previously discussed differences in thermal conductivity of the two abrasives. This proposition is further supported by the grinding tests of Ratterman[5] in which the residual stresses produced by CBN, diamond, and conventional wheels were compared. The test results showed that diamond wheel grinding produced residual compressive stresses which were larger (more compressive) than that from

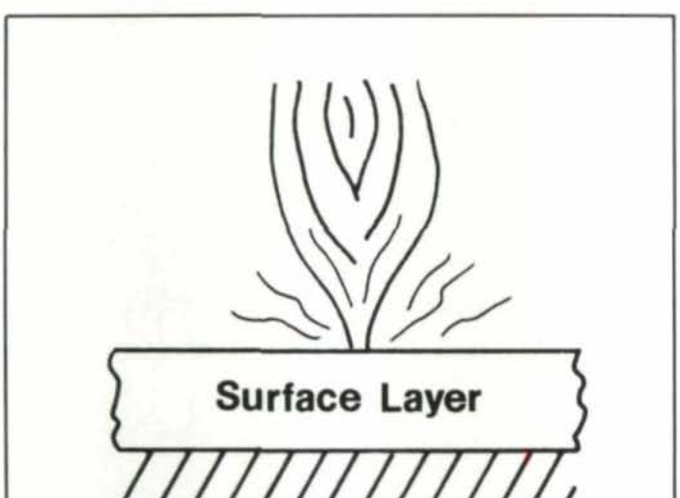


Fig. 5—Mechanism for Thermal-Plastic Induced Residual Stresses

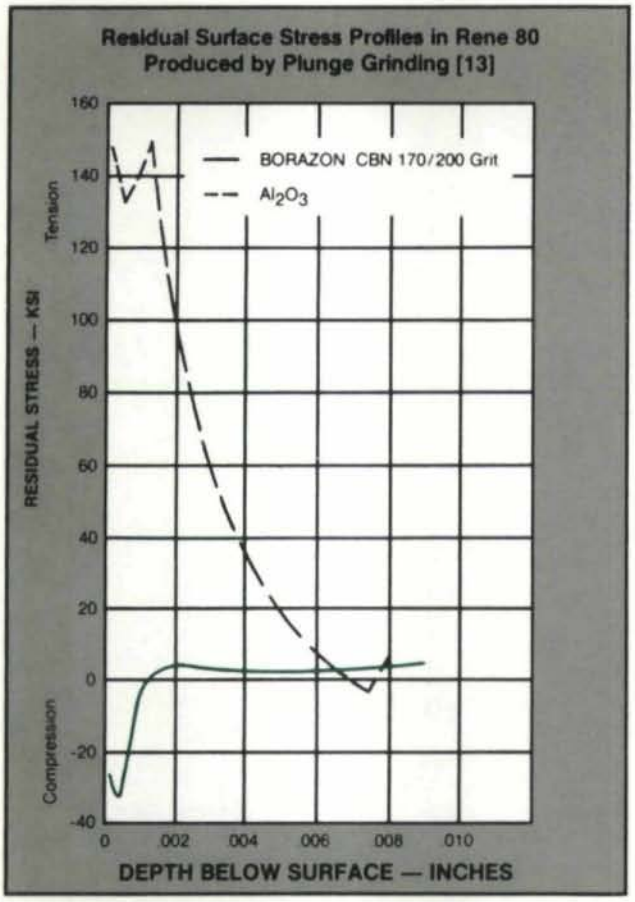
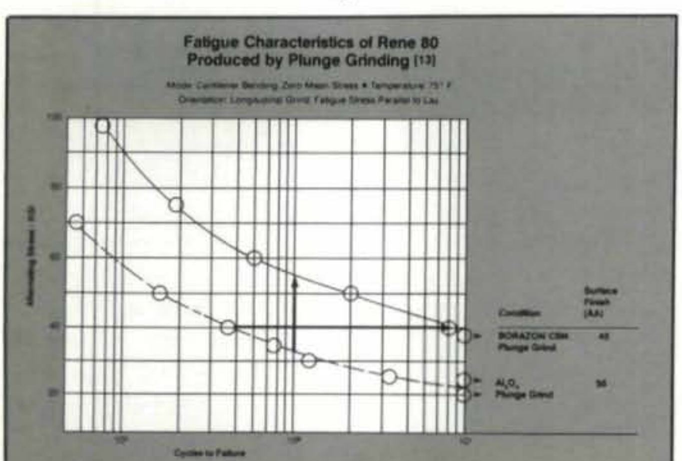


Fig. 7

CBN wheel grinding. From Fig. 3 it can be seen that diamond has a higher thermal conductivity than CBN. Therefore, in grinding with diamond the percentage of heat going into the workpiece is less than with CBN, causing greater residual compressive stresses.

Metcut Research Associates compared the residual stress and fatigue life of parts ground with CBN and aluminum oxide wheels.[13] The measured residual stresses are shown in Fig. 7 and the resulting S-N curve is shown in Fig. 8. These tests show that the bending fatigue life was increased by 27 times at an alternating stress of 40,000 lbs/in^2 or that the load carrying capacity for a life of one million cycles could be increased by 70%. Although the material in this test was not hardened steel, it clearly shows the effect of decreased thermal input.

Fig. 8



It is clear that CBN has a tendency to cause beneficial compressive residual stresses, resulting in increased fatigue life, because CBN grinds at lower temperatures. Any factor that reduces the grinding temperature will also reduce the tendency for wheel loading, chemical reactions, and wheel dulling, as well as burning and tensile residual stresses.

Furthermore, the presence of grinding burns results in metallurgical changes such as tempering (softening resulting in lower strength) and/or the formation of untempered martensite (a very hard and brittle material). These defective materials, at the point of highest stress for gear tooth bending, have a lower strength than the materials of proper hardness.

Fundamentals of CBN Grinding of Bevel Gears

Wheel Workpiece Contact Conditions

In the bevel gear grinding process the tooth profile shape is produced by the relative rolling motion that takes place between the gear or pinion and the grinding wheel. The action is as though the gear or pinion being ground were rolling with an imaginary motion generating gear of which the grinding wheel represents one tooth (see Fig. 9).

Fig. 10 is a cross section through the grinding wheel profile, showing how the wheel and the gear move together in a timed relationship to generate the tooth profile on each side of the tooth slot. At position 1 the wheel first contacts the gear tooth at the top of the outside wheel profile. As the generation continues to position 2, the wheel rolls down the profile to the pitch line. Grinding with the outside diameter of the wheel is almost completed at position 3. When both tooth profiles have been completely generated at position 4, the wheel is withdrawn from the tooth slot and returned to

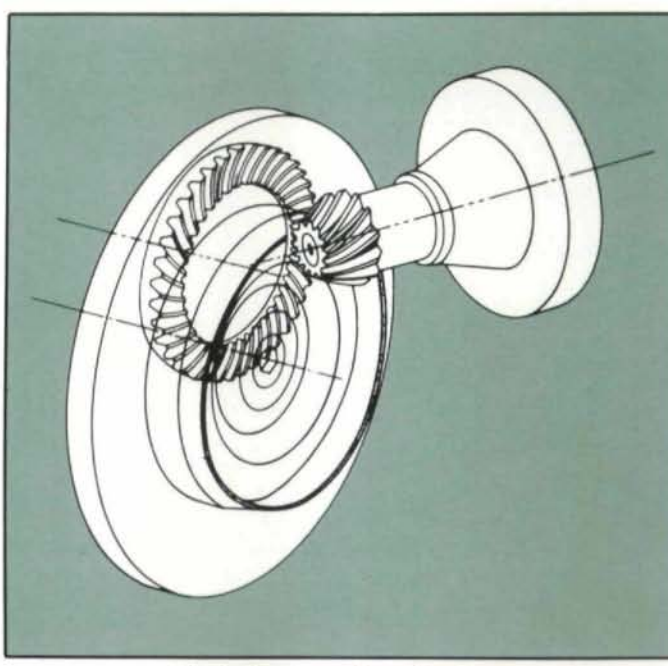


Fig. 9 – Imaginary Generating Gear.

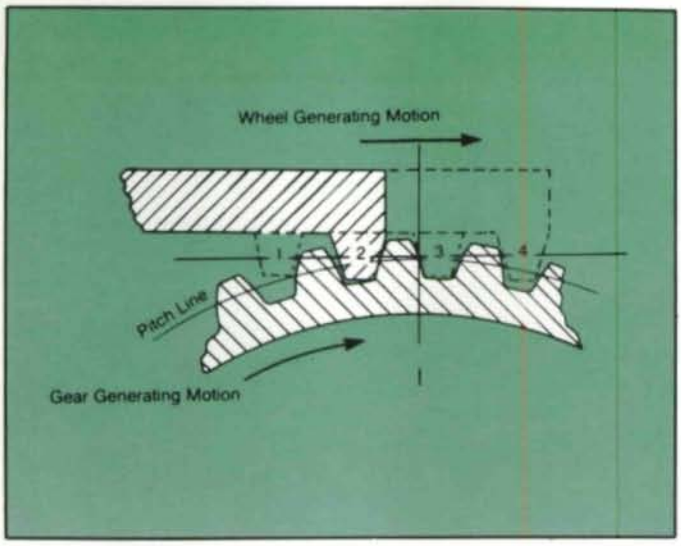


Fig. 10 – Generating Roll.

position 1, while the gear is indexed to grind the next tooth slot.

Fig. 11 shows a three-dimensional representation of how the wheel/work, contact area starts at position 1 and proceeds to positions 2 and 3. The abrasive grains cut in a direction parallel to the root line.

A lengthwise section of the tooth in position 2 (Fig. 12) shows how the gear tooth wraps around the wheel in a way quite similar to internal grinding. The contact length will be very long as shown in Fig. 13. It can be seen that when the depth of grind is .001" the contact length can be two to five times longer than when surface grinding at the same depth of grind.

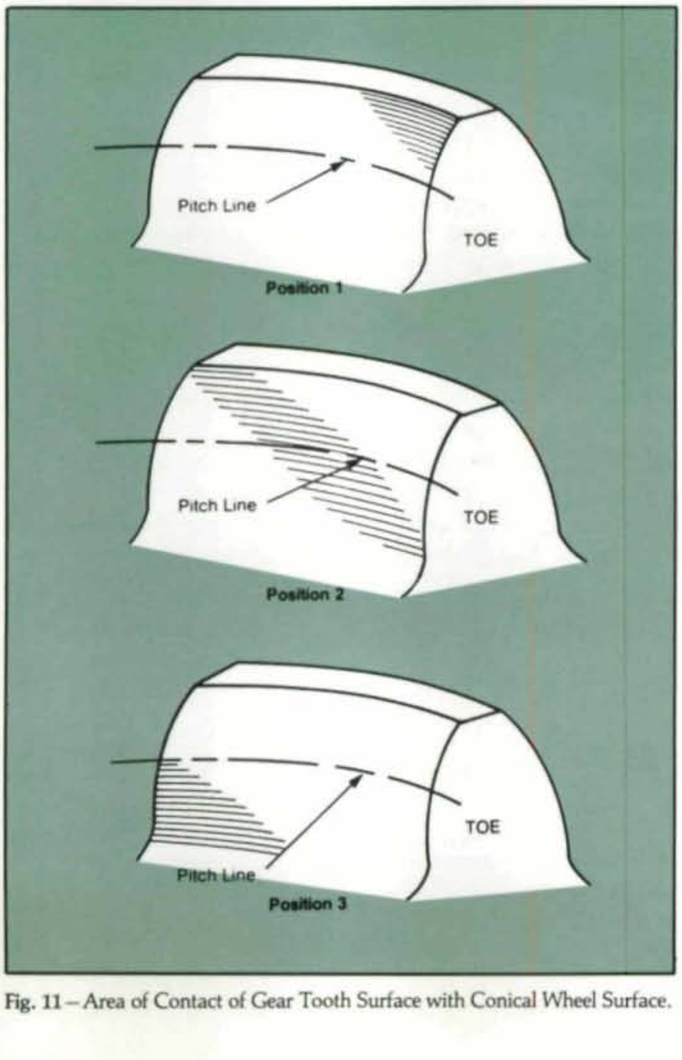


Fig. 11 – Area of Contact of Gear Tooth Surface with Conical Wheel Surface.

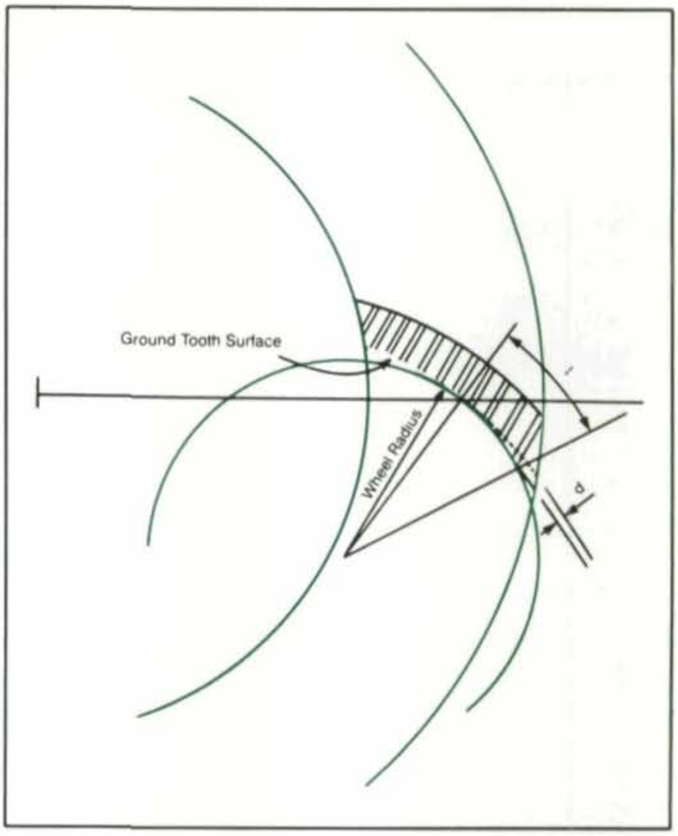


Fig. 12 – Length of Wheel – Work Contact.

When finish gear grinding is done in a single pass at .005" depth of grind, an equivalent length of contact in surface grinding would not be encountered until a depth of grind of .080" was used. This shows that bevel gear grinding contact length can be as long as that encountered in creep feed grinding.

Thermal Aspects

From Fig. 12 it can be seen that all along the contact length,[1] the distance (d) to what will soon be the ground tooth surface is very small. Thus, the heat generated in the contact zone is easily conducted to the gear tooth surface. Furthermore, due to the fact that the feed rate is limited by machine dynamics (the acceleration and deceleration of the generating system), the amount of time that the long contact length heat source is over a given point on the gear tooth is relatively long, allowing for a greater temperature rise of the work material.

The required grinding power is also increased because of the long contact length and the resulting increased amount of rubbing encountered.

These factors indicate some of the reasons why bevel gear grinding with conventional wheels has been sensitive to thermal damage and one reason why the depth of grind has been limited to .001" or less, which results in low metal removal

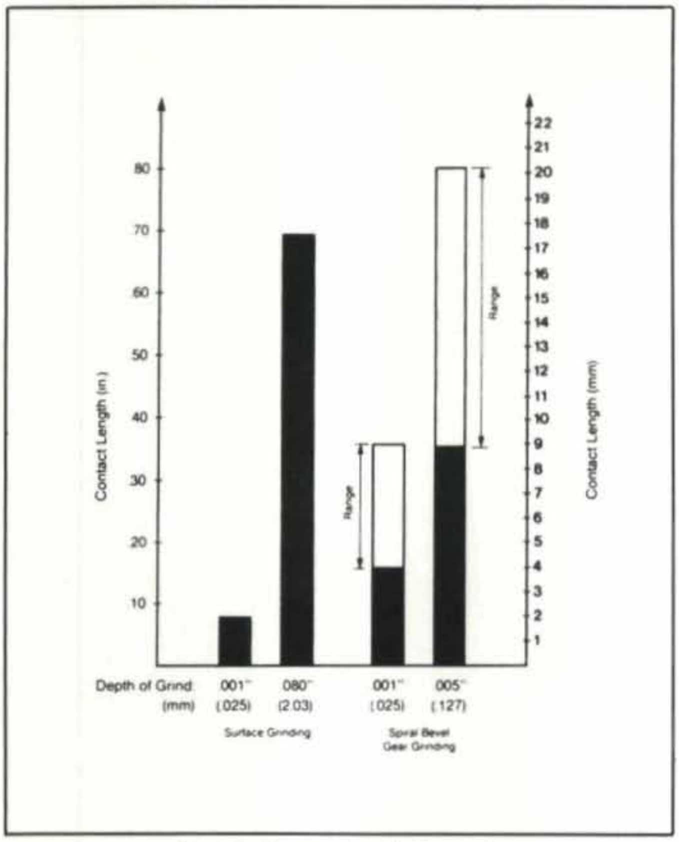


Fig. 13 – Contact Length Comparison.

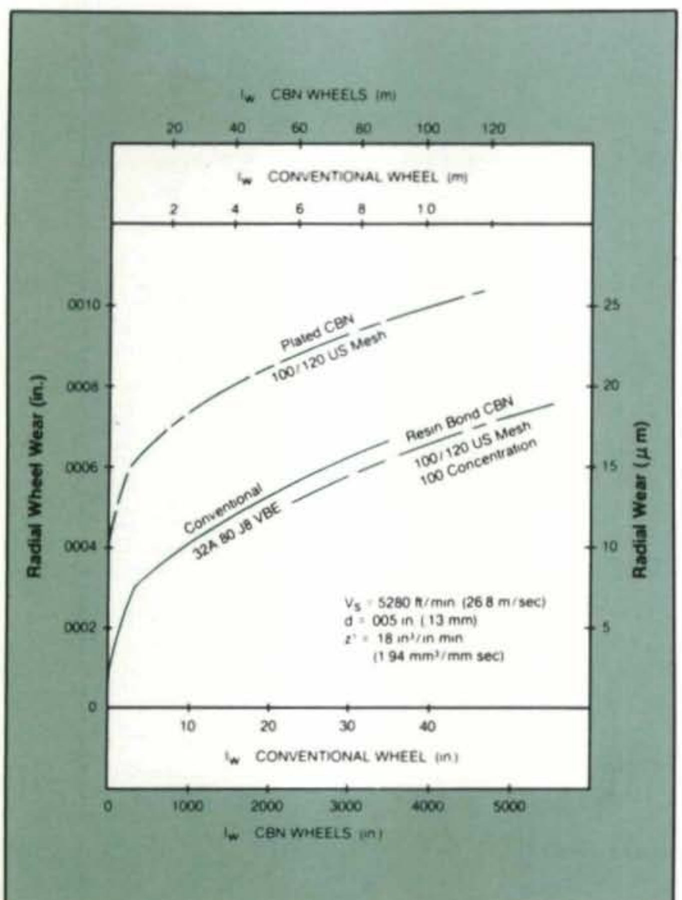


Fig. 14 – Laboratory Wheel Wear Rate Comparison.

rates and long grinding cycle times (typically 40-250 sec/tooth). The long cycle times are due to the necessity of multiple grinding passes and several wheel dressings per gear ground.

It has been found that the thermal input to the gear tooth surface can be so substantially reduced, due to the enhanced properties of CBN, discussed in the section on "Fundamentals of CBN Grinding of Hardened Materials," that all the finishing stock can be removed in a single pass without thermal damage, at a cycle time as short as 4.0 seconds per tooth. The result of the cool cutting action of CBN is also indicated by the substantially improved fatigue life of CBN ground gears as discussed later in the section on "Results of CBN Gear Grinding."

Wheel Wear Laboratory Results

The wheel wear as a function of the length of the gear tooth slot ground is shown in Fig. 14. The wear of a vitrified aluminum oxide wheel is compared to a plated and a resin bond CBN wheel. The slot length scale for the CBN wheels are 100 times the conventional wheel scale. All three wheels showed a rapid initial wear, followed by a slow steady wear rate. It can be seen that the slope of the steady wear rate for each of the wheels is about the same, which means that the CBN wheels wore at a rate 1% of the conventional wheel wear rate.

A borderline burning condition was encountered with the conventional wheel after grinding only 35" of slot length (1 pinion). After grinding 125 to 150, times the slot length with the CBN wheels, the thermal input to the pinion tooth surface was still far from the burning limit. Thus, the CBN wheels were still capable of grinding more parts.

As a result of such encouraging laboratory results and the desire to determine how this process might work in a production environment, it was decided to conduct further wheel life tests in a gear manufacturing plant.

Production Results

Grinding trials in a production environment showed that more than 90,000 inches of slot length (1.42 miles, 2050 gears) could be ground with a single plated CBN wheel, with the wheel still capable of grinding more parts. This was 20 times the amount of material ground in the laboratory tests.

This length of wheel life would represent three weeks of single shift production at 100% efficiency.

Resulting Implications

Such very long wheel life has the following important implications:

a. excellent tooth spacing can be achieved as a result of the small wheel wear per gear (in the micro inch per gear range).[18]

b. excellent consistency can be achieved from gear to gear despite variations in stock left for finishing.

c. the possibility of unmanned manufacturing with automatic loading and automatic periodic coordinate part inspection.[30]

d. a dresser is not required on the grinding machine, mak-

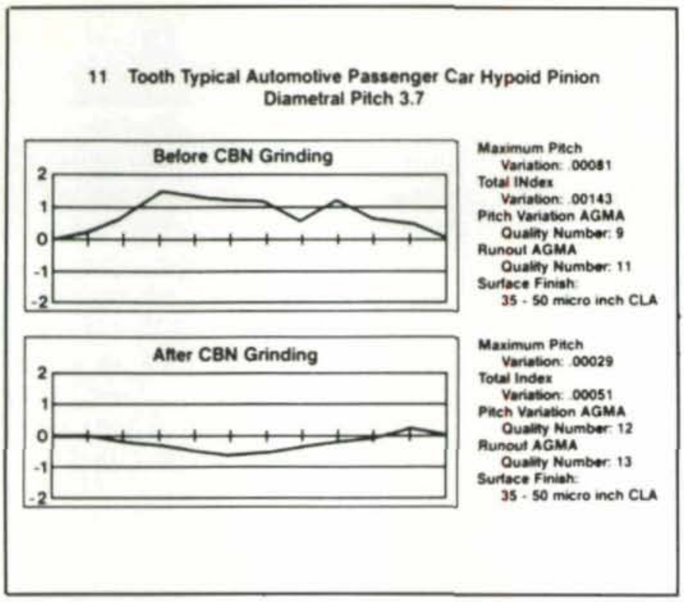


Fig. 15—Index Variation Measurements Before and After CBN Grinding.

ing the machine less complex and allowing greater machine utilization.

Results of CBN Gear Grinding

Tooth Spacing Quality

Fig. 15 shows that an automotive pinion with an AGMA quality number 9 was improved to quality number 12 by single pass CBN grinding. This shows the corrective nature of this process.

Fatigue Life

Bending fatigue life improvements of 17 times have been achieved as compared to cut hardened and lapped gear sets, the most common method used in the manufacture of land application bevel gears.[18] Current surface durability tests have shown a life improvement of 2 to 5 times for CBN ground gear sets. The benefits resulting from CBN grinding are achieved by the removal of harmful effects, such as dimensional inaccuracies of tooth position and geometry, excessive surface roughness and unwanted surface microstructural features.

Cost

Many times it has been thought that the use of CBN grinding wheels necessitated high tool cost. This has not been found to be the case with CBN finish grinding of bevel gears. Even when the production cycle time for CBN finish grinding was faster than soft finishing, the CBN wheel cost per gear was essentially the same as the cutter cost for soft finishing. By changing the gear manufacturing methods to take advantage of CBN hard finishing, one manufacturer found that the production cost per gear set was reduced by thirty percent.

Summary

This paper has attempted not only to show the possible benefits which may be derived from grinding with CBN, but also to explain the physical reasons for the observed phenomena. This knowledge permits taking advantage of the characteristics of CBN to simultaneously improve productivity and workpiece quality.

The combination of this new grinding tool material (CBN), the applied grinding technology, and new bevel gear grinding machines designed for the necessary increased requirements have now made this new process both technically and economically practical for the mass production of bevel gears.

This process appears to have great potential for becoming the dominant finishing method in the near future because it combines the benefits of better quality control and lower cost.

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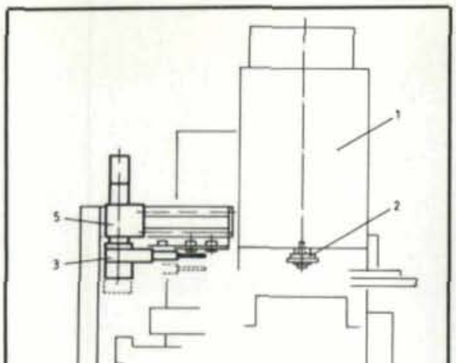
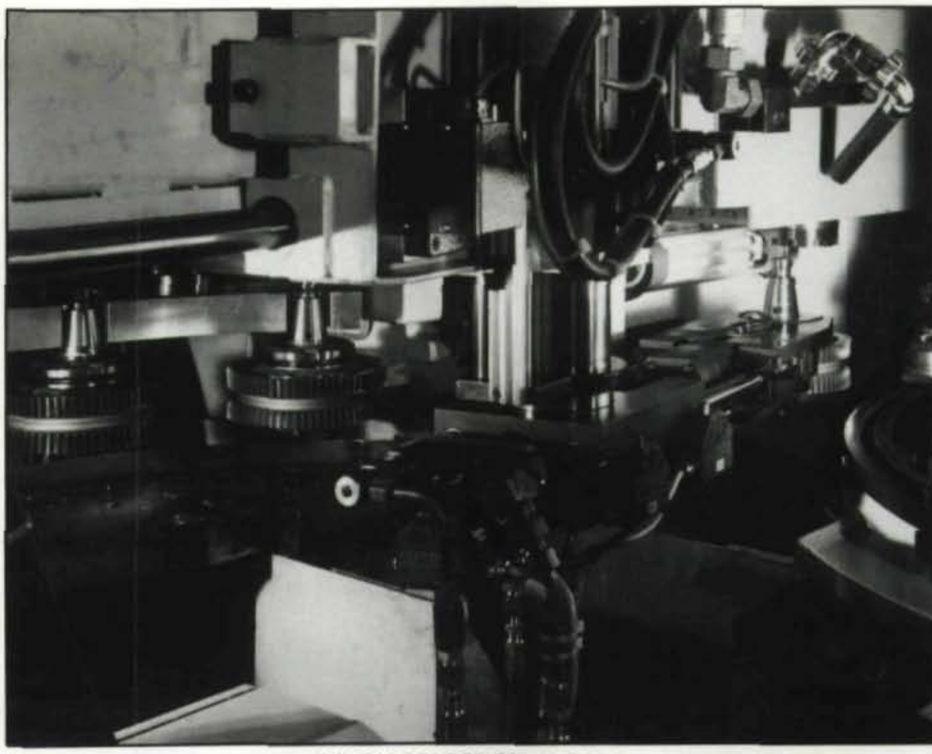


Fig. 13A & B – Automatic cutter changing unit with storage for 3 cutters.

and tools. The conventional first and second generation modern gear shaping machines are, most likely, not suitable for an FMS or FMC system. Many manufacturers say the state-of-the-art gear shaping machine is not ready for installation in an FMS or FMC manufacturing technique. Most certainly, the third generation spindle relief CNC gear shapers can, indeed, fulfill all design parameters needed for installation in an FMS and FMC applications, namely because of their special features, i.e.:

- zero setup time – automatic machine setup
- tool offset compensation
- fully automatic fixture change
- fully automatic tool change
- gear cutting flexibility – multiple gear cuttings per setup, i.e. cluster gears
- integration of a CNC post process gauging unit to the CNC control of the shaper



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