Influence of CBN Grinding on Quality and Endurance of Drive Train Components

K.V. Kumar and E. Ratterman
GE Superabrasives, Worthington, OH

Abstract:

The merits of CBN physical characteristics over conventional aluminum oxide abrasives in grinding performance are reviewed. Improved surface integrity and consistency in drive train products can be achieved by the high removal rate of the CBN grinding process. The influence of CBN wheel surface conditioning procedure on grinding performance is also discussed.

Introduction

There is a growing demand in the automotive industry to produce passenger cars and trucks with pleasing noise quality and increased load carrying capacity. Consequently, the focus of manufacturing today is on the manufacture of consistently high-quality drive train products at low cost. This, in turn, has encouraged engineers to re-evaluate the current design and production methods in relation to new process concepts, new machine tools, and cutting tool materials.

The present method of gear manufacturing typically consists of the following steps:

Soft cutting/Rough forging
↓
Finish cutting/Shaving/Rolling
↓
Heat Treatment
↓
Honing/Lapping
↓
Shot Peening (optional)

In the above method, since lapping or honing is not significantly corrective in nature, tooth distortion from heat treatment manifests itself in large runout and transmission errors. Also, the cutter marks in the tooth face and fillet regions, which act as stress raisers and reduce the surface fatigue and bending fatigue strength in the gear, are left behind.

The new approach consists of:

Rough cutting/Near Net Forging
↓
Heat Treatment
↓
CBN Finish Grinding
↓
Lapping/Honing

The final goal of this new approach, however, is to eliminate lapping and make it a three-step process. The finish grinding operation following heat treatment ensures correct tooth geometry and minimizes the tooth-to-tooth pitch variation and runout errors. A short cycle time lapping process is sometimes necessary to improve the noise quality of the gear set.

Based on the above approach, several types of CBN hard gear finishing machines have been introduced for spur, helical, and spiral bevel gear products. Several articles[1-6] have been published describing the CBN gear grinding technology and its advantages. In this article, the merits of CBN grinding are reviewed with some examples. The influence of wheel specification and wheel

Table I
SELECTED PHYSICAL PROPERTIES OF CBN AND ALUMINA ABRASIVES

Property/Units	BORAZON® CBN	Aluminum Oxide	Ratio
Formula	BN	Al_2O_3	
Knoop Hardness, (kg/mm.^{2})	4500	2100	2:1
Density, (gm/cm^3)	3.45	3.97	1:1
Thermal Cond. @ (298°K),(W/m°K)	1300	35	37:1
Specific Heat @ (298°K),/Jkg°K)	506.2	774.9	2.3
Therm. Diff. @ (298°K),(m^2/5) × 10^5	74.4	1.14	65:1

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surface conditioning procedures on part profile and geometry are also presented.

Background on CBN

CBN is a manufactured abrasive surpassed in hardness only by diamond. As an abrasive, it is extremely wear resistant and able to retain its sharpness for a long time. The physical properties of the tool are among the several factors that have a strong influence on increasing the material removal rate, tool life, and surface integrity of the work material. Table I gives selected physical properties of CBN and aluminum oxide (Alox) abrasives. The thermal diffusivity of CBN is almost two orders of magnitude greater than that of Alox. Thermal diffusivity is the ratio of heat conducted versus the heat absorbed in a body. A high value means that much heat is transmitted through the abrasive relative to the heating of the abrasive itself.

The thermal stability and chemical properties of CBN also influence the abrasive performance. CBN reacts with air or oxygen to form boron oxide according to:

$$2BN + 3/2O_2 = B_2O_3 + N_2$$

The boron oxide forms a solid protective layer around the CBN crystal, preventing further oxidation at < 1300°C. CBN also reacts with water and water soluble oils according to:

$$BN + 3H_2O = 2H_3BO_3 + NH_3$$

The boric acid readily dissolves in water, which promotes further degradation of CBN. Straight oil coolant is therefore recommended to get the best performance with CBN.

Johnson[7] illustrated the importance of CBN thermodynamic properties by use of a simple finite element analysis. In a typical grinding process, any single abrasive grain is in contact with the work for only 80 microseconds. The analysis examines the temperature distribution in both an abrasive grain and steel workpiece, 80 microseconds after a grain at room temperature is placed in contact with a steel workpiece at 648°C. Fig. 1a shows the initial conditions, and Fig. 1b shows the temperature distribution after 80 microseconds. The analysis shows that workpiece surface temperatures would be higher when ground with Alox than with CBN.

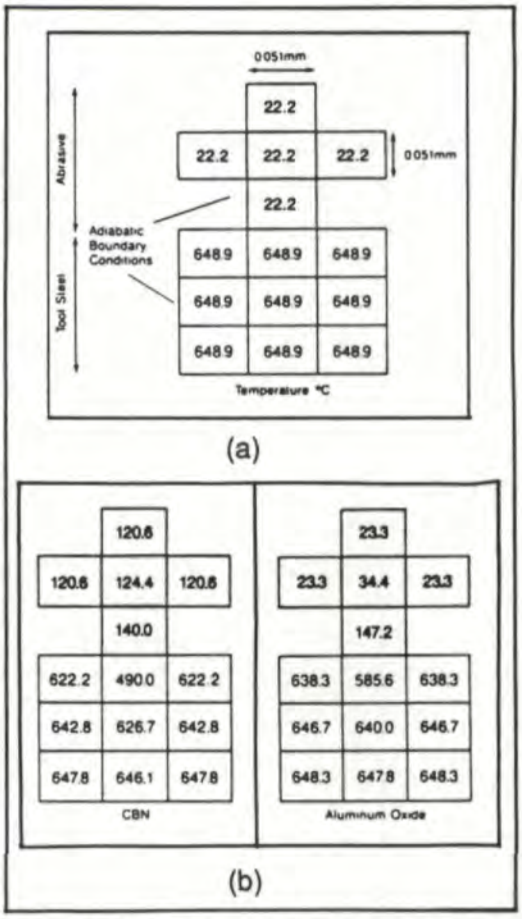

Fig. 1 – Finite element model of temperature distribution in workpiece and abrasive. a) Initial condition at time t= 0 sec. b) Comparison of temperature distribution after 80 microseconds of contact with CBN and aluminum oxide.[7]

Ramanath and Shaw[8] have determined the fraction of grinding energy (R) going into the workpiece to be

$$R = \frac{1}{1 + \left[\frac{k\varrho C_{abr.}}{k\varrho C_{work}}\right]^{0.5}}$$

Ernest Ratterman
is Manager – Application Technology Communications at GE Superabrasives, Worthington, OH. He is responsible for applying new and conventional communications technologies to superabrasive educational needs. Mr. Ratterman holds a degree in aeronautical engineering from the University of Cincinnati.

Dr. K.V. Kumar
is Manager, Advanced Application Programs at GE Superabrasives. He holds a masters degree from Carnegie Mellon Institute and a doctorate in mechanical engineering from Arizona State University. His research interests are in material removal processes, triboloby, and machine tool technology.

Where k is thermal conductivity, ϱ is density and c is specific heat. For aluminum oxide, the calculation shows R = 0.76, and for CBN R = 0.37. This analysis also suggests that the CBN grinding process will have minimal thermal disturbance and more mechanical action in chip formation. A more rigorous analysis on the thermal aspects of CBN grinding can be found in the work done by Lavine, Malkin, and Jen.[9]

CBN Wheel Specification

CBN can be classified into monocrystalline and microcrystalline types of abrasive. The microcrystalline type is tougher and less friable than the monocrystalline and requires a larger force to fracture the crystal. Monocrystalline CBN has good fracture characteristics for free cutting action in the wheel and is mainly used in gear grinding.

CBN wheels are made either by electroplating or in an impregnated bond system. The electroplated wheels are produced by attaching a single layer of abrasive particles to the steel core of the tool by electrodeposition of nickel. As the nickel is deposited onto the core, it entraps the abrasive particles in a strong mechanical grip. Impregnated bond systems are those where the abrasive particles are molded in a matrix of either phenolic resin or metal powder or glass frits.

Electroplated wheels are predominantly used in gear grinding applications as they can hold the profile geometry in extended use and are easy to fabricate. Electroplated wheels are normally specified by CBN type and the mesh size. However, to achieve the required profile accuracy and surface finish, the particles have to be screened for a narrow size range and shape.[10]

Vitrified bonded (glass frit) CBN wheels can also be used, as they are easy to shape using a CNC truing device and can hold the profile geometry in grinding. These wheels are specified by the CBN type, mesh size, concentration of CBN, volume porosity, and bond hardness. Vitrified CBN wheels have been qualified for use in form gear grinding of spur and helical gears.[11] However, it is still in the development stage of Reishauer type wheels and Gleason type cup shaped wheels.

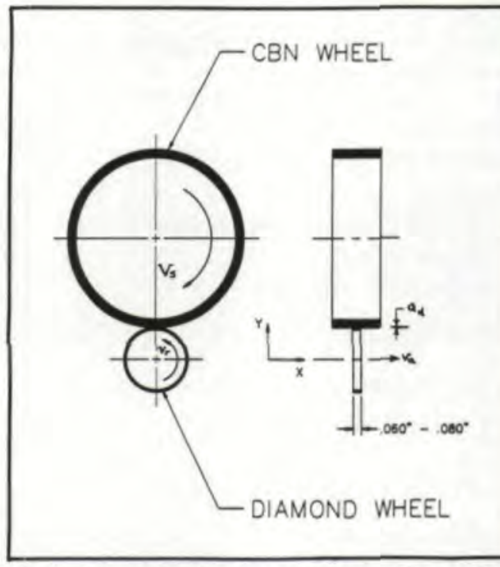

Fig. 2—Schematic of truing by the generation method. The various truing parameters are 1) Direction of rotation; 2) Speed ratio, $q = v_r/V_s$ fpm/fpm; 3) Depth of cut, a_d inch; 4) Lead, v_a inch/revolution of CBN wheel; 5) Overlap factor, u_d = actual roller width/lead; 6) Diamond wheel specification.

TABLE II – Summary of Test Conditions

A. Grinding Condition	
Work Material	AISI 52100, R_c 57-60
Grind Mode	Plunge Cylindrical Grind, Up Cut
Wheel Speed, V_s	12000 fpm
Work Speed, V_w	150 fpm
Specific removal rate, Z'	0.4 in^3/in-min.
Radial stock, d	0.05 in.
Dwell time, t_d	2 revs. of work
Volume ground, v'_w	15 in^3/in.
Coolant	Cimperial HD90, 5% Water Soluble
Wheel Specification	CBN-I, 170/200, 200 Conc., R, Vit. Bond
B. Wheel Conditioning	
Diamond Wheel	MBS-750, 40/50, 50 Conc. Metal Bond
Truing Mode	Rotary Cup Wheel, Unidirection
Diamond Wheel Speed V_r	200 fpm
Speed ratio, q	0.2, 0.6, 1.0
Radial Infeed/pass, a_d	0.0001 in.
Lead, v_a	0.006 in/rev.
Overlap Factor, u_d	10

Conditioning a CBN Wheel

Conditioning is the process of preparing a CBN wheel mounted on the spindle to the desired concentricity, profile geometry, and cutting characteristics. Typically, this entails a truing and dressing operation. Truing provides the shape and minimizes the out-of-roundness in the wheel, while dressing relieves the bond around the abrasive for a free cutting action. In resin and metal bonded wheels, truing and dressing are done as two separate operations. In the case of vitrified bonded wheels with volume porosity over 20%, conditioning is a one-step process similar to that for conventional Alox wheels.

In production grinding, the vitrified CBN wheel is conditioned by a powered rotary diamond wheel, either by plunge form truing or profile generation process. The latter method is widely used as the truing forces are low and good profile accuracy is obtained. Fig. 2 is a schematic of the various parameters involved in truing by the generation method. To illustrate the importance of these parameters, plunge cylindrical grinding tests were done on a heat treated AISI 52100 bearing steel. Table II gives the grinding conditions and conditioning parameters. The truing is usually conducted in the unidirection mode, as the radial forces are dominant to fracture the CBN crystals and obtain sharp cutting edges. Fig. 3a, 3b, and 3c show the grinding power, wheel wear, and surface finish versus volume ground. The speed ratio of 0.6 yields the best overall result in terms of power, wear, and finish. A speed ratio of 1.0 is not desirable, as the radial truing forces are at a maximum and result in a reduced diamond truing wheel life. At low speed ratio of 0.2, the normal truing force is so small that the CBN cutting edge remains dull, and there is not sufficient bond relief around the crystal. Consequently, at start of the grind, the power is high enough to cause thermal damage in the workpiece and limits the material removal rate. As a result, the wheel is used gently at the start, until it is free cutting for higher removal rates. When the speed ratio is increased to 0.6 and above, the radial truing forces are adquate to fracture or impart cracks at the working tip of the CBN and relieve the bond around it. This results in grinding without burn from the start at the desired material removal rate. The surface finish and wheel life also tend to be the best at this condition.

The influence of metal bonded diamond truing wheel specification and lead conditions on grinding power and surface finish are illustrated in Figs. 4a and 4b. The grinding power increases with smaller diamond size and higher concentration, while the surface finish is improved. The lead conditions can be varied to change the transient shape of the grinding power and surface finish at the start of grind. An optimum truing condition can be found where the grinding power and surface finish have less transient effects and are relatively stable from the start.

Electroplated CBN wheels are sometimes conditioned to get an acceptable surface finish and profile geometry. However, in doing this the wheel life is compromised by the extent of conditioning done. For electroplated wheels, conditioning is done either with a diamond wheel or a silicon carbide abrasive wheel. The direction of rotation of the diamond wheel is counter direction (upcut) to the CBN wheel, and a low speed ratio of 0.2-0.4 is used. The overlap

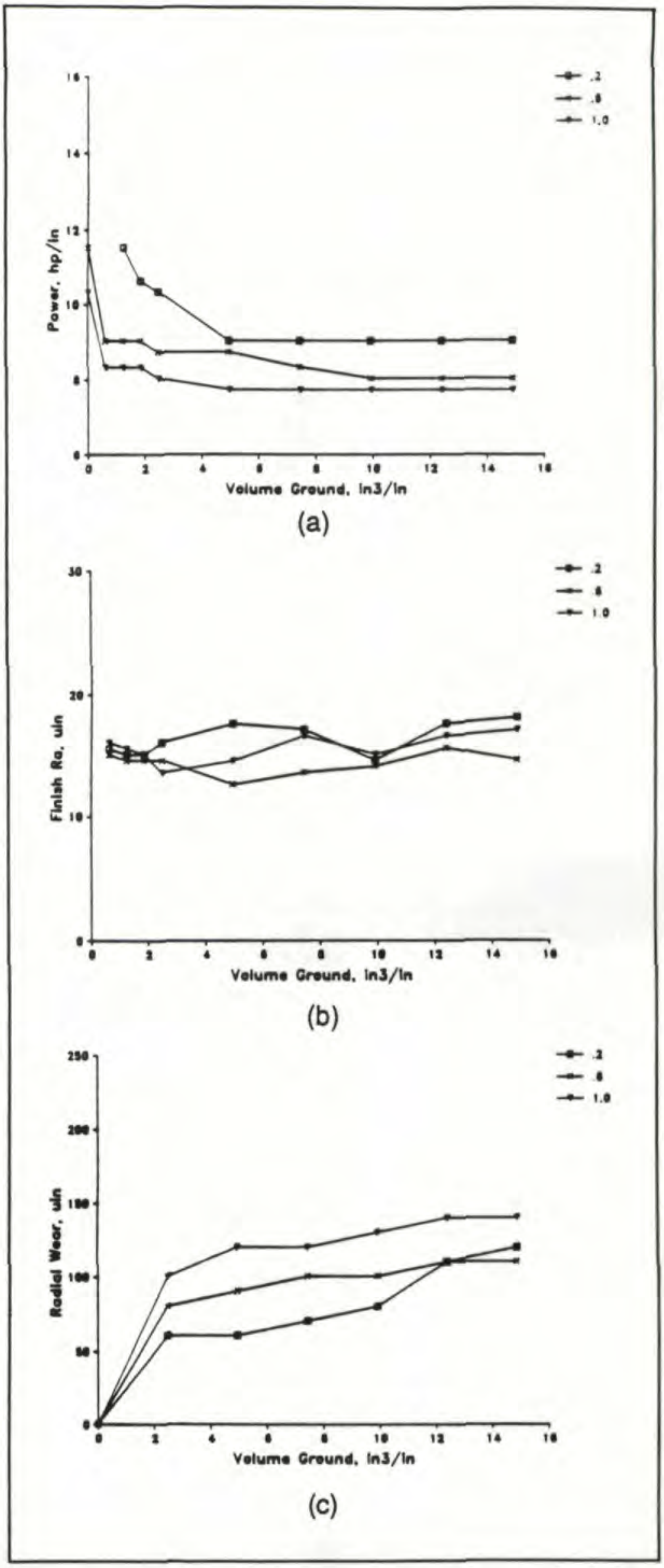

Fig. 3a, b, c—Variation of grinding power, surface finish, and radial wear versus volume ground for CBN wheel conditioned at different speed ratio. See Table II for test conditions.

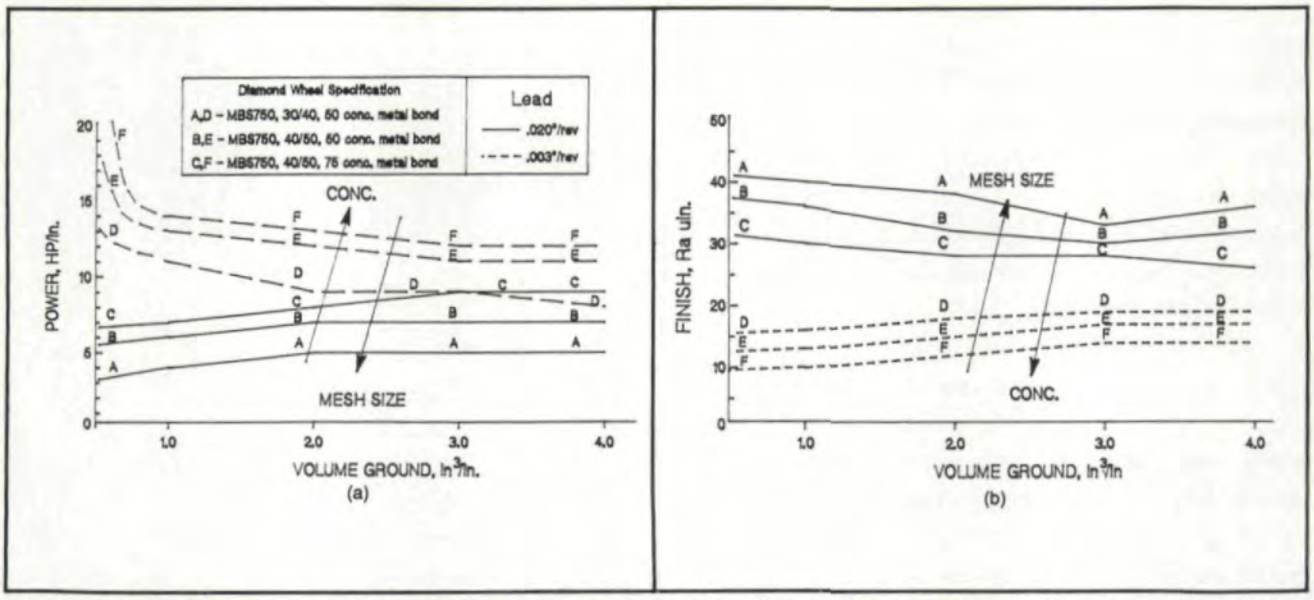

Fig. 4 – Influence of diamond wheel specification and truing lead on the variation of (a) grinding power, (b) surface finish versus volume ground. Test conditions: CBN-I, 120/140 mesh size, 175 conc. vit. bond, work: D2 steel - R_c60, $Z' = .16$ in^3/in-min., $V_s = 12800$ fpm, truing q = 0.15 unidirection, coolant - 3% Adcool #3.

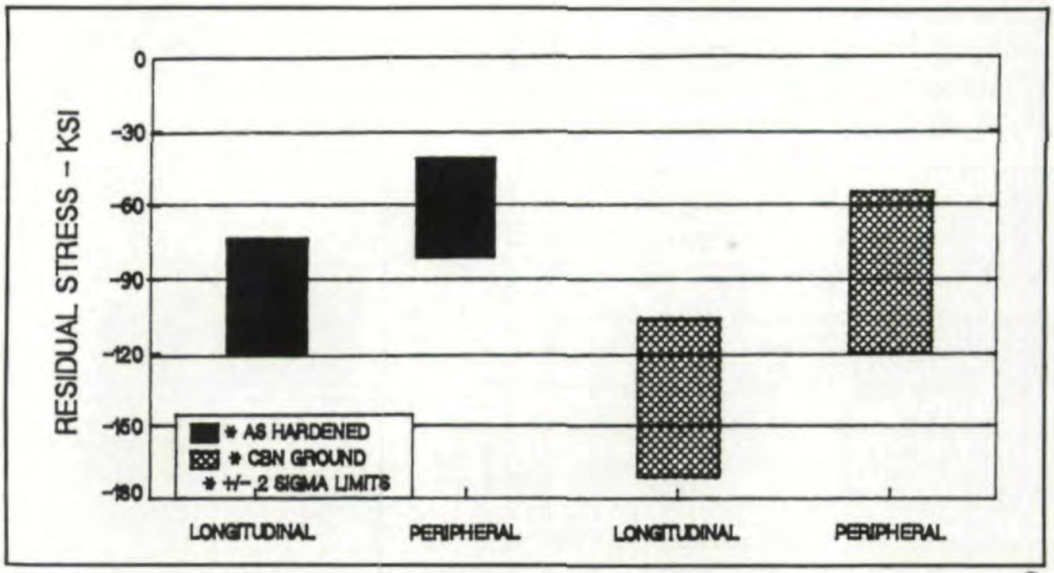

Fig. 5 – Residual stress in SAE 4620 steel before and after grinding with a resin bonded CBN wheel (51 samples).[7]

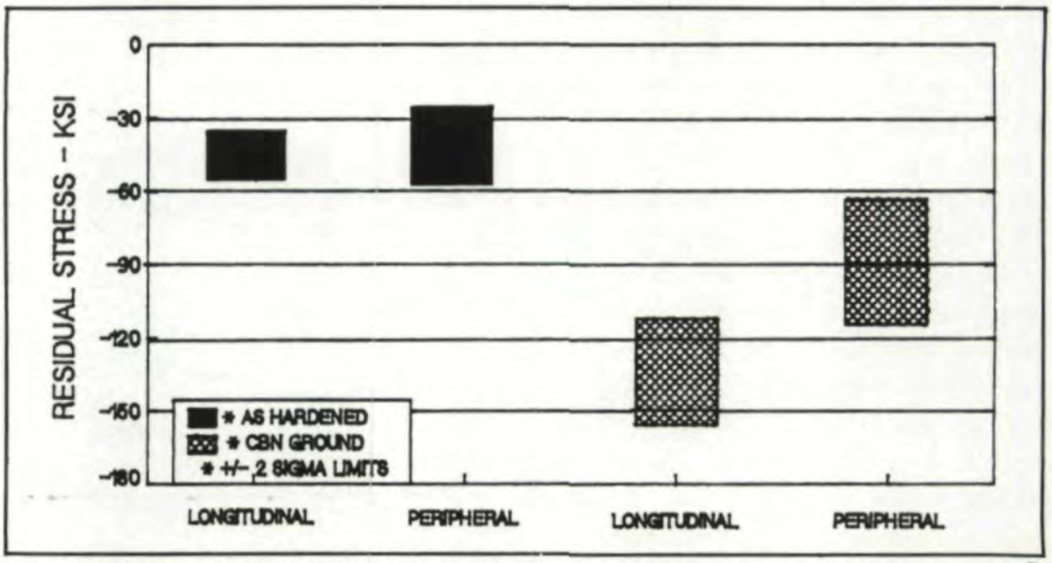

Fig. 6 – Residual stress in SAE 8620 steel before and after grinding with a resin bonded CBN wheel (40 samples).[7]

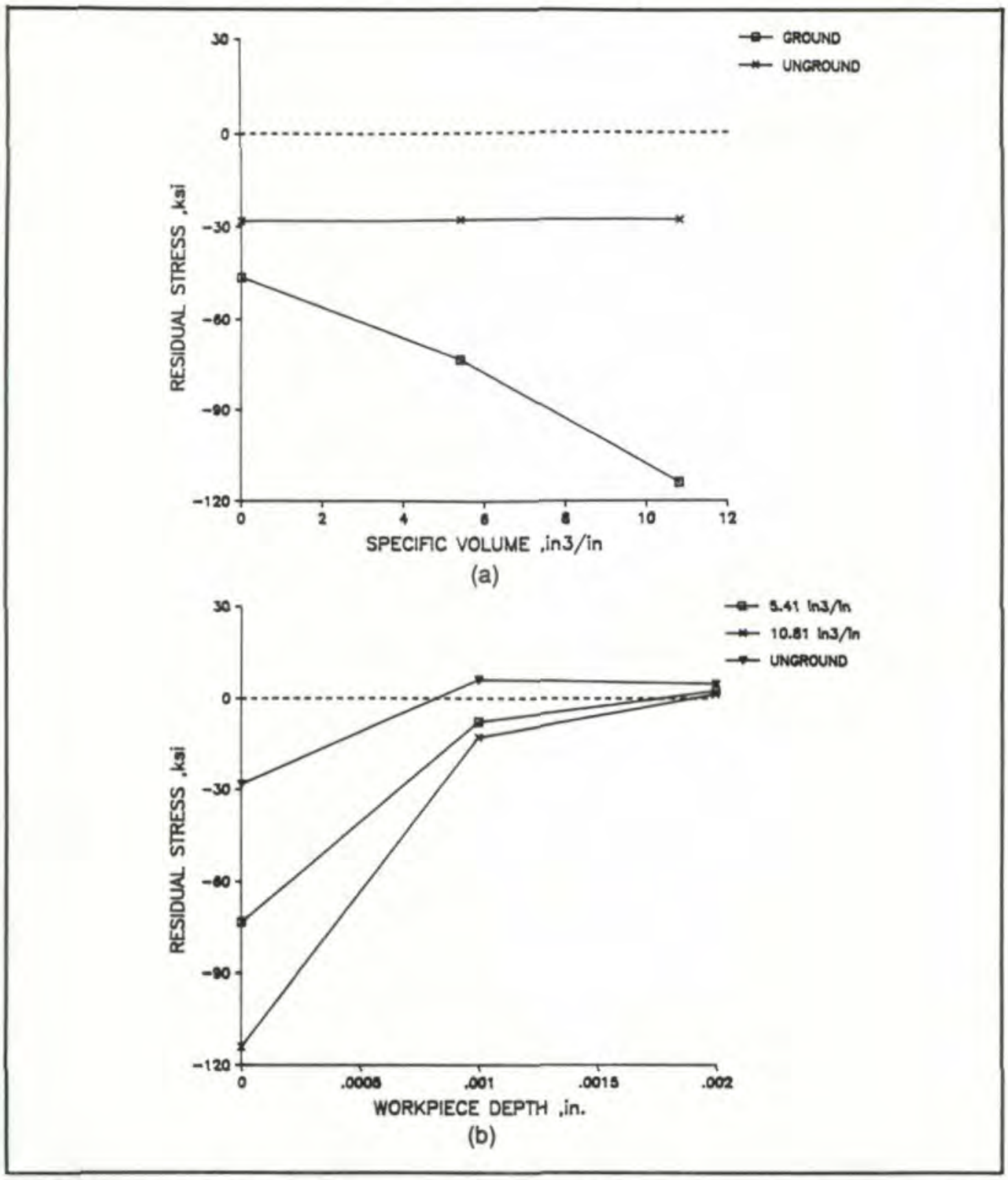

Fig. 7—a) Variation of surface residual stress versus volume ground. b) Variation in residual stress versus workpiece depth. Test condition: CBN-I, 80/100 mesh size, 200 conc., L, vit. bond, work: 8620 steel, R_c60. $V_s = 6000$ fpm $Z' = 0.45$ in^3/in-min., coolant - 5% HD90 Cimperial.

factor is kept high (50-60) to achieve a good surface finish.

Surface Integrity

Surface integrity of the workpiece generally refers to surface roughness, the state of stress, hardness variation, and the metallurgical state following a grinding or machining operation. In grinding the gear components after heat treatment, it is essential to preserve the surface integrity of the gear at high material removal rates over the life of the wheel. Reference 12 summarizes the results of several CBN grinding studies conducted on residual stress. The important observations are reviewed here.

Figs. 5 and 6 show the residual stress in SAE 4620 and 8620 steels before and after plunge cylindrical grinding with a resin bonded CBN wheel. The compressive stress in the ground part is greater than in the heat treated condition. Also, the magnitude in the direction perpendicular to grind is greater than along the direction of chip removal because higher temperatures are developed in the chip forming direction relative to the lateral direction, and the resulting thermal stresses tend to decrease the stress developed by mechanical deformation. In the lateral direction, there is no chip removal, but there is considerable mechanical working of the plowed material on the workpiece.

Plunge cylindrical grinding tests were also done with a vitrified bonded CBN wheel on 8620 case-hardened steel. Fig. 7a is a plot of surface residual stress versus volume ground, and Fig. 7b is a plot of

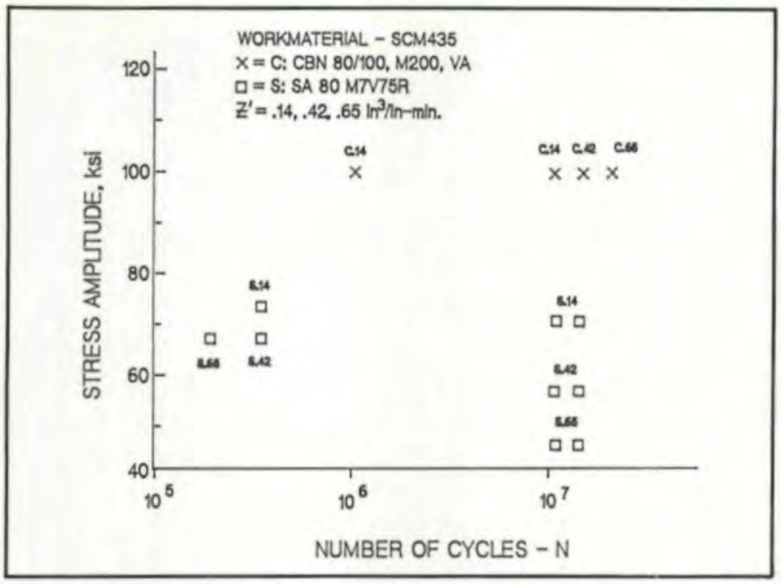

Fig. 8 – Comparison of fatigue strength of aluminum oxide and CBN ground samples at different material removal rates, from Yokogawa.[13]

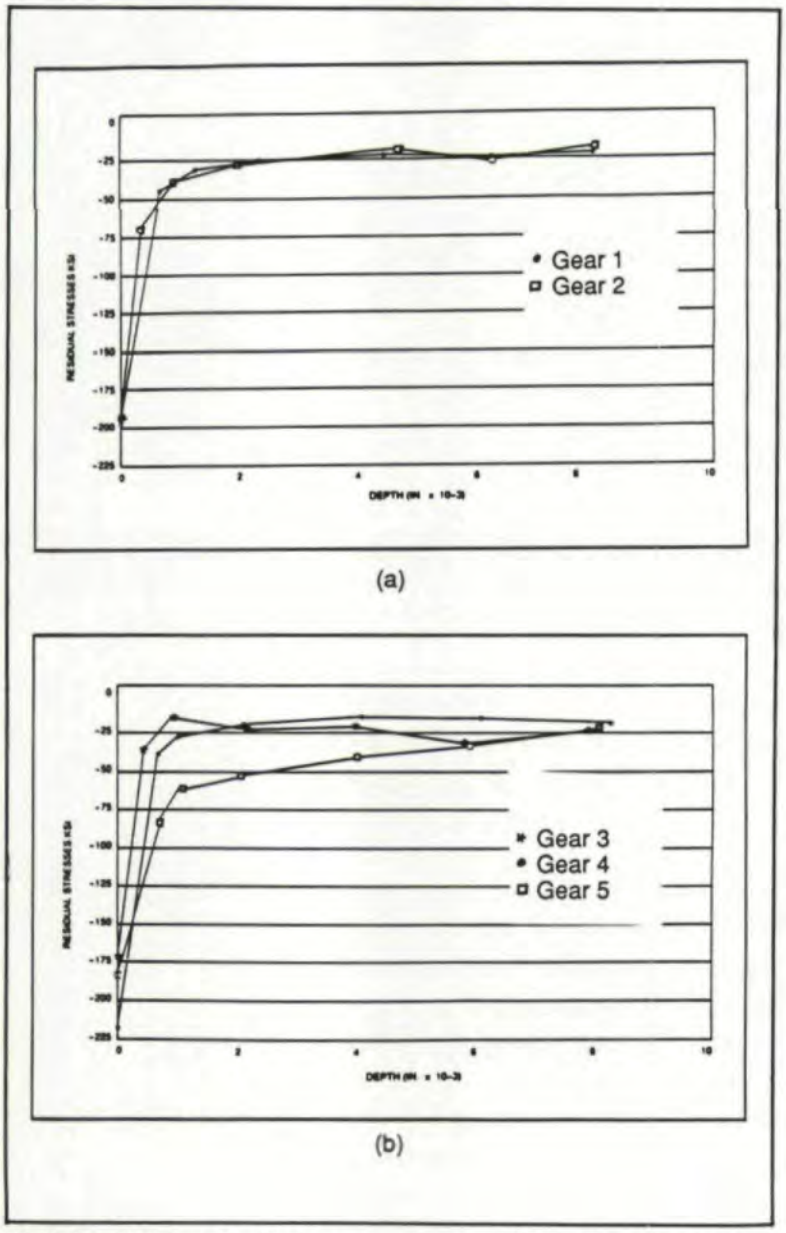

Fig. 9a, b. – Variation of residual stress measured at midflank in the profile direction versus depth, for helical gears ground with a plated CBN wheel.[7]

variation in residual stress with workpiece depth. The magnitude of compressive stress is greater than the heat treated condition and increases with the volume ground. Microhardness measurements across the cross section showed no reduction in hardness. The above results demonstrate that, regardless of the bond system used, residual compressive stress can be generated under proper grinding conditions. These results also correlate well with the physical properties of CBN abrasive described earlier.

Recently Yokogowa[13] compared the fatigue strength (rotary bending test) of Alox and CBN ground samples at different material removal rates. This is illustrated in Fig. 8. The S-N Chart shows that parts ground with the CBN wheel have a stress amplitude of 100 ksi for failure at all removal rates. By contrast, the parts ground with the Alox wheel have a lower stress amplitude for failure at all removal rates. This result clearly demonstrates that with CBN grinding, higher load carrying capacity can be achieved at shorter cycle times relative to Alox abrasives.

Although the kinematics of gear grinding are more complex than O.D. and surface grinding methods, a similar trend in the improvement of results can be observed when grinding with CBN abrasives. Residual stress measurements were made on automotive transmission gears ground with an electroplated CBN wheel in the Kashifuji gear grinding machine. Five gears were selected at random during a trial production run. The midflank residual stress along the profile direction was analyzed, and the results are shown in Figs. 9a and 9b. The residual stress distribution is developed to a depth of .008" below the flank surface. The results also show a remarkable consistency in the compressive stress level at the tooth flank surface. The subsurface profile variations in the stress is probably due to variations in the heat treated profiles and the stock removed.

All of these findings tend to support the results of four-square fatigue testing of CBN ground gears reported by Kimmet and Dodd.[2] Fig. 10 shows the fatigue life comparison of a CBN ground spiral bevel gear over a conventionally hardened and lapped gear set. The bending fatigue strength is at a maximum when the flanks and the fillets are ground. This improvement can be attributed to compressive stress as well as to other factors, such as:

a) Improved blend and shape of the fillet region, which reduce any stress risers that might occur;

b) Improved accuracy of gear tooth geometry, which reduces the dynamic loading on gear teeth;

c) Removal of impurities present from heat treatment, such as a decarburized layer and other undesirable carbide networks.

It can be deduced that the increase in strength may allow for higher load rating of a gear set or downsizing to attain the same rating.

Concluding Remarks

The merits of CBN physical properties and influence of wheel conditioning procedures on grinding performance have been reviewed. It is shown that improved surface integrity and consistency in drive train products can be achieved by the high removal rate CBN grinding process.

However, much more work needs to be done in several areas to further enhance the use of CBN in gear grinding. The various areas are

1) Consistent manufacture of electroplated wheels having acceptable accuracy, surface finish, and wheel life without conditioning the wheel;
2) Development of vitrified bonded CBN wheels and conditioning devices in the machine that can produce the desired cutting characteristics and profile accuracy;
3) Implementation of advanced coolant application methods to avoid thermal damage in the workpiece and increase the wheel life;
4) Development of machine tool and grinding process technology to overcome gear noise and in turn eliminate the lapping and honing process.

CBN grinding has the potential of revolutionizing gear production methods in an economical way, while resulting in improved quality and consistent product performance.

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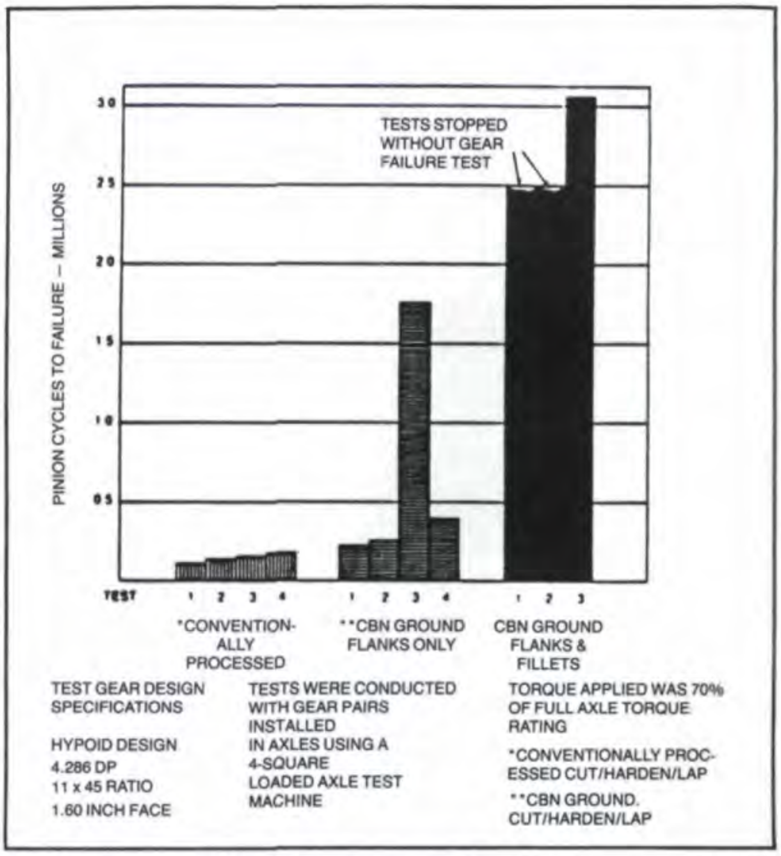

Fig. 10 – Comparison of bending fatigue strength of spiral bevel gears conventionally processed versus CBN ground.[2]

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