Enhanced Product Performance Through CBN Grinding

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Abstract:

The extraordinary physical and thermal properties of CBN abrasives are a primary factor in the generation of beneficial residual compressive stresses. These residual stresses have a favorable influence on the fatigue life of components ground with CBN abrasives. This article suggests that the effects of CBN grinding should be factored into the original design of highly stressed, fatigue-prone drive train components.

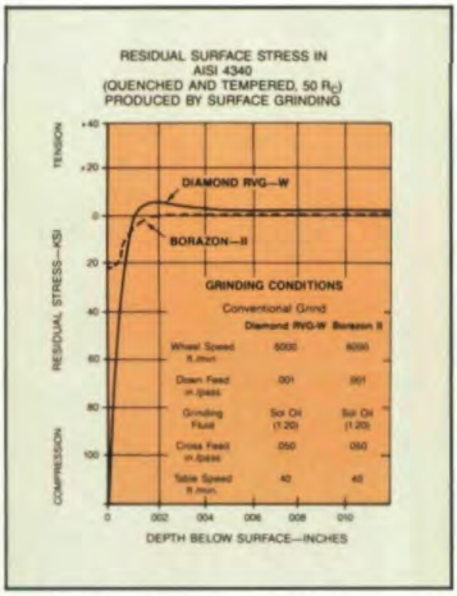

Fig. 1a – Residual stresses in SAE 4340 after grinding with CBN and diamond.

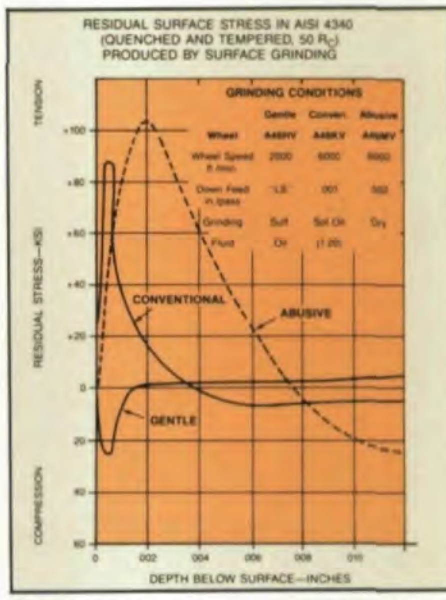

Fig. 1b – Typical residual stresses in SAE 4340 after grinding with alumina.

Introduction

Modern manufacturing processes have become an ally of the product designer in producing higher quality, higher performing components in the transportation industry. This is particularly true in grinding systems where the physical properties of CBN abrasives have been applied to improving cycle times, dimensional consistency, surface integrity and overall costs. Of these four factors, surface integrity offers the greatest potential for influencing the actual design of highly stressed, hardened steel components.

The purpose of this article is to review both the empirical studies and theoretical analyses which substantiate the surface integrity characteristics inherent with CBN grinding. In addition, some important new empirical findings of direct interest to this subject are presented and discussed.

Background

Significant evidence empirically substantiates the fact that grinding with CBN abrasives can produce a significant level of compressive residual stress in the surface of hardened steels. Most bibliographies include the work of Navarro,[1] the first to establish that both CBN and diamond abrasives produce residual compressive stresses.

Navarro's key results are shown in Figs. 1a, b and c. Figs. 1a and 1b contrast typical residual stress distributions found after grinding with CBN, diamond and aluminum oxide. The positive consequences of CBN grinding are illustrated in

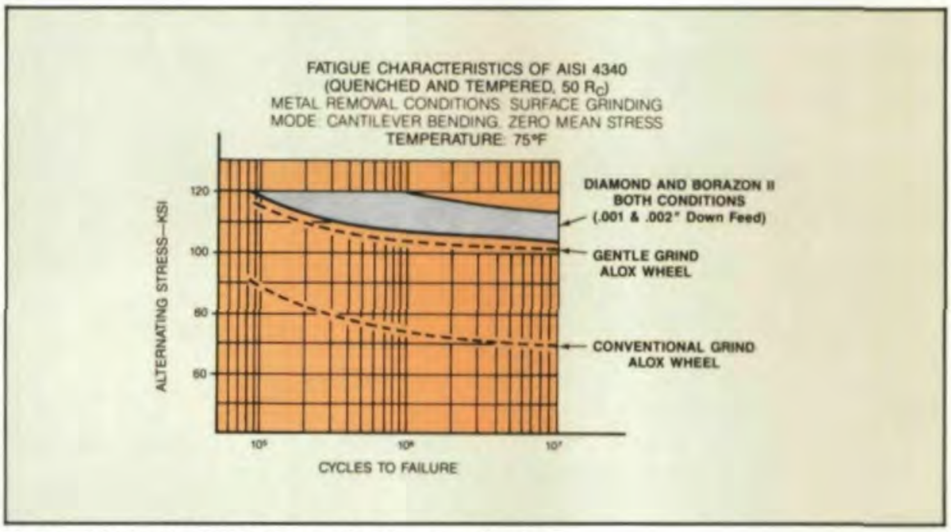

Fig. 1c – S-N data for SAE 4340 ground with various abrasives.

1c, where the bending fatigue characteristics of AISI 4340 samples ground with three different abrasives are compared. In recent years, several other studies [2-5] have served to substantiate the work first reported by Navarro.

However, little work has been done to increase our fundamental understanding of the mechanism by which these residual compressive stresses are generated. Production grinding of steel components in the metalworking industries has been dominated by the use of aluminum oxide abrasives for over 80 years. Therefore, the total context of our thinking about the grinding process is oriented around aluminum oxide abrasive grains and their specific properties. For example, "grind-

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ing" will generally leave a residual tensile stress in the surface of a workpiece, such as AISI 4340, unless special precautions are taken to avoid this phenomenon.[6] It is also generally agreed that these residual tensile stresses are created because the "grinding" process rapidly increases the temperature of the ground surface, which is then subjected to various rates of quenching, depending upon the specific nature of the operation. This process can lead to the generation of both untempered and over-tempered martensite as well as surface cracking. Expensive and tedious procedures, such as low stress grinding (LSG), nital etching or shot peening, may have to be employed in certain cases to overcome these inherent problems.

That the crucial importance of the specific thermal properties of aluminum oxide grain have been overlooked is understandable; but in view of the growing importance of CBN grinding, comparison with the extraordinary thermal properties of CBN abrasives must now be made.

Selected physical properties of CBN and aluminum oxide abrasives are shown in Table I. The density (ϱ), thermal conductivity (k), and specific heat (c) are listed along with the calculated value of thermal diffusivity. Thermal diffusivity (a thermophysical property, $k/\varrho c$), is the ratio of heat conducted versus the heat absorbed in a body.[7] In transient situations, such as the grinding process, a high value means that much heat is transmitted through the abrasive relative to the heating of the abrasive itself. As reflected in Table I, the thermal diffusivity of CBN is almost two orders of magnitude greater than that of aluminum oxide.

In order to investigate the signficance of these properties on temperatures generated in the workpiece surface, Shaw and Ramanath [8] have determined the fraction of grinding energy (R) going into the workpiece to be

$$R = \frac{1}{1 + \left\{\frac{k\varrho c \text{ abr.}}{k\varrho c_{\text{work}}}\right\}^{0.5}}$$

Thus, the fraction of heat generated in the grinding process which flows down into the work is governed by the ratio of the products, $k\varrho c$ of abrasive/$k\varrho c$ of work.

For aluminum oxide abrasive, the calculation shows R = 0.76 and for CBN, R = 0.37. These writers demonstrate that this difference in R is sufficient for the aluminum oxide grinding process to generate temperatures well in excess of the softening temperature of steel, while CBN grinding will not reach such temperature. This analysis strongly suggests that the aluminum oxide grinding process subjects the workpiece surface to a severe thermal disturbance in addition to the normal mechanical process of chip formation. CBN grinding, on the other hand, may only subject the workpiece surface to the normal mechancial disturbance with minimal thermal disturbance.

Johnson [9] illustrates the importance of the extraordinary differences in thermodynamic properties by use of a simple finite element analysis. In a typical grinding process, any single abrasive grain will be in contact with the work for only 80 microseconds. The analysis examines the temperature distribution in both an abrasive grain and a steel workpiece during the 80 microseconds after a grain at room temperature is placed in contact with a steel workpiece at 648°C. It must be noted that Johnson has not in any way attempted to simulate the complex heat generation and

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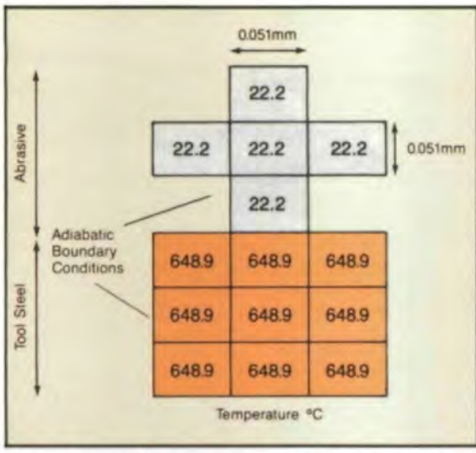

Fig. 2a – Finite element analysis model of heat transfer between workpiece and abrasive.

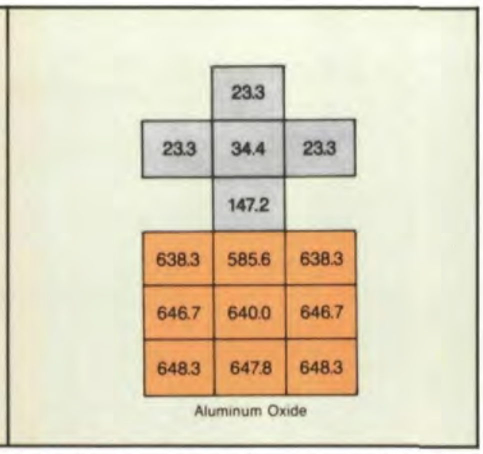

Fig. 2b – Comparison of temperature distribution after 80μsec of contact between workpiece and abrasive for three types of abrasives.

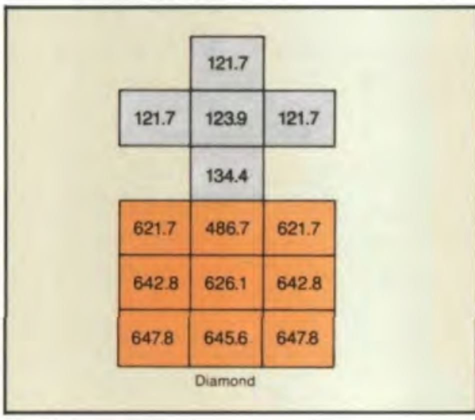

Fig. 2b

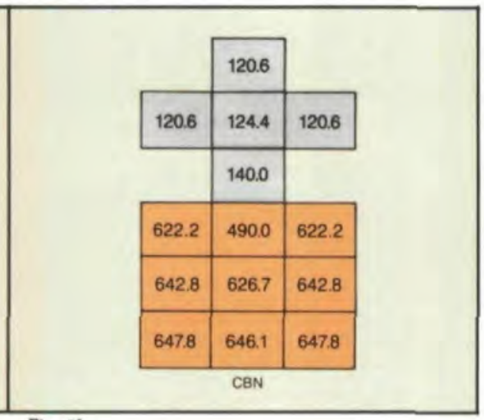

Fig. 2b

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/mm²)	4500	2100	2:1
Density, (gm/cm³)	3.45	3.97	1:1
Thermal Cond. @ (298°K),(W/m°K)	1300	35	37:1
Specific Heat @ (298°K),(J/kg°K)	506.2	774.9	2.3
Therm. Diff. @ (298°K),(m²/s) × 10⁵	74.4	1.14	65:1

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Table II
DESCRIPTION OF GRINDING WHEEL AND CONDITIONS USED IN SAMPLE PREPARATION

GRINDING WHEEL	**Size:** 12 in. × 1 in. × 5 in.
	Bond: Phenolic Resin
	Abrasive: Borazon* CBN Type II-100/120 Mesh
	Concentration: 100
GRINDING CONDITIONS	**Machine:** Cincinnati Universal Cylindrical
	Grind Mode: Plunge
	Coarse Rate: 0.060 IPM
	Fine Rate: 0.002 IPM
	Wheel Speed: 5500 SFPM
	Work Speed: 55 SFPM
	Coolant: ADCOOL #3 (1:20)

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heat transfer dynamics of the actual grinding process. The initial conditions are shown in Fig. 2a, while the temperature distribution after 80 microseconds is illustrated in Fig. 2b. This study graphically reinforces the concept developed by Ramanath and Shaw that heat is forced down into the work in the aluminum oxide case, but can flow up into the abrasive grain itself in CBN grinding.

Dodd and Kumar[10] have also studied this problem using yet a different analysis. Their work suggests that 63% of the heat generated in aluminum oxide grinding goes down into the work, while in CBN grinding, only 4% goes into the work. They have concluded that chip formation takes place at a much lower temperature in the case of CBN grinding than in the case of aluminum oxide grinding.

While none of these studies in and of themselves conclusively prove that the extraordinary thermal properties of CBN abrasives are solely responsible for the residual compressive stress phenomenon, they clearly establish that these properties *are the predominant factors*.

Experimental Investigation

Most investigators have conducted empirical residual stress studies using some form of plain surface grinding and flat workpiece specimens. This investigation will utilize cylindrically shaped specimens. In addition, most studies concentrate on the residual stresses obtained on only two or, at the most, three sample surfaces for a given combination of abrasive grain and grinding conditions. This study will utilize a total of 93 individual workpiece samples, all ground with the same CBN wheel specification. This investigation is comprised of the following steps:

1. Sample preparation – Two sets of steel cylinders, 1″ in diameter by 5″ long, have been carburized, heat treated and quenched to produce a hardness of Rc 62-64. A total of 40 cylinders of SAE 8620 and 51 cylinders of SAE 4620 have been accordingly prepared. Each sample cylinder has been cylindrically plunge ground with a one inch wide wheel containing CBN abrasive. The details of this procedure are shown in Table II. Fig. 3 illustrates the dimensions and configuration of the finished samples.

2. X-ray diffraction residual stress analysis – The surfaces of the samples prepared in Step 1 above have been analyzed

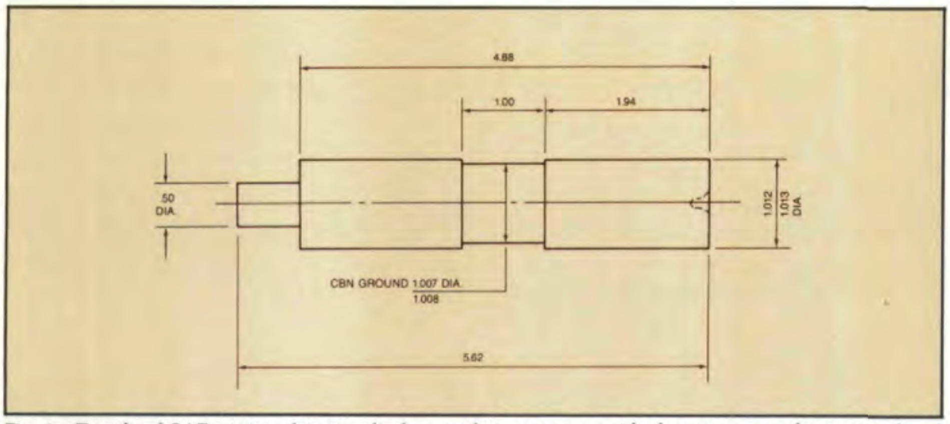

Fig. 3—Details of SAE 4620 and 8620 cylinders used to compare residual stresses – as-heat treated and CBN ground.

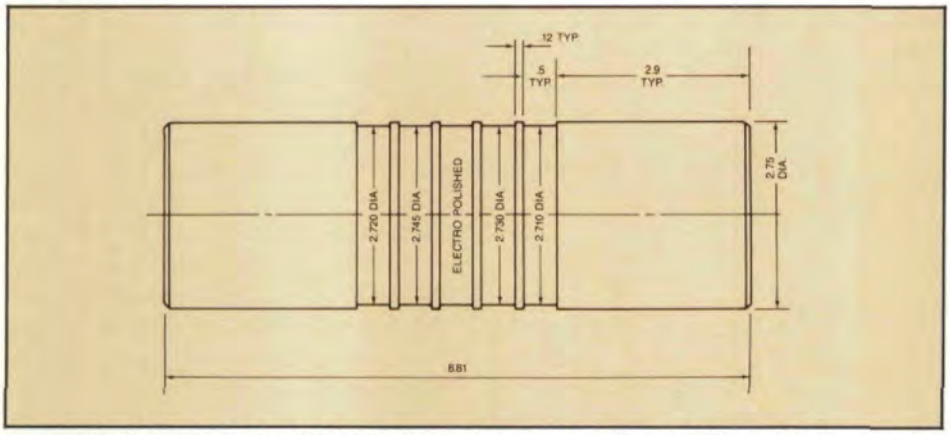

Fig. 4—Details of SAE 4620 and 8620 cylinders used to determine effect of CBN grind depth on residual stresses.

using established techniques of x-ray diffraction analysis. This analysis has been conducted on both the unground and the ground surfaces of each sample. Peripheral and longitudinal stresses have been selectively measured on the unground surfaces. The peripheral stresses in the direction of grinding and longitudinal stresses at right angles to the grinding direction have been measured on the CBN ground surfaces.

3. Effect of grinding depth on residual stresses – The amount of material to be removed in production grinding operations cannot always be precisely controlled. The slight distortions in components which have been heat treated can lead to variations in grinding depths in such cases; thus, determining how residual stress will vary as material is removed from the unground, heat treated surface is important. Therefore, another set of cylindrical samples have been plunge ground to a range of finished diameters in order to determine this effect. The configuration of such samples is illustrated in Fig. 4. The grinding conditions used to produce these *surfaces are the same as shown in Table II* except for the use of a 0.5" wide wheel.

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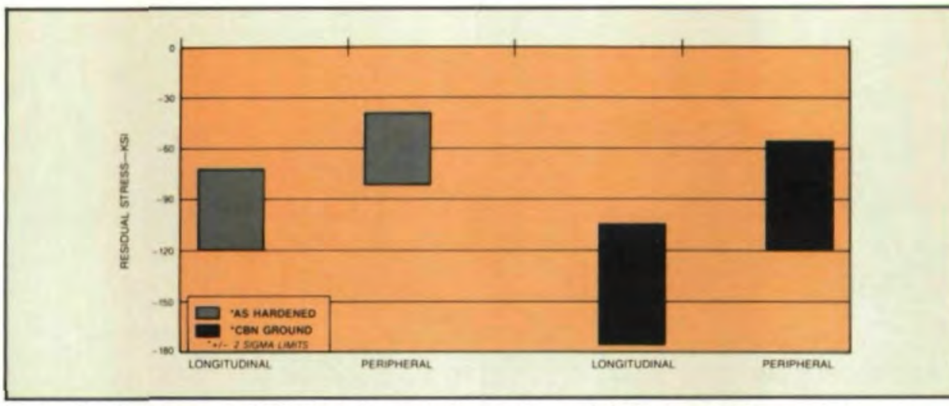

Fig. 5 – Residual stresses in SAE 4620 before and after grinding with CBN abrasives (51 samples).

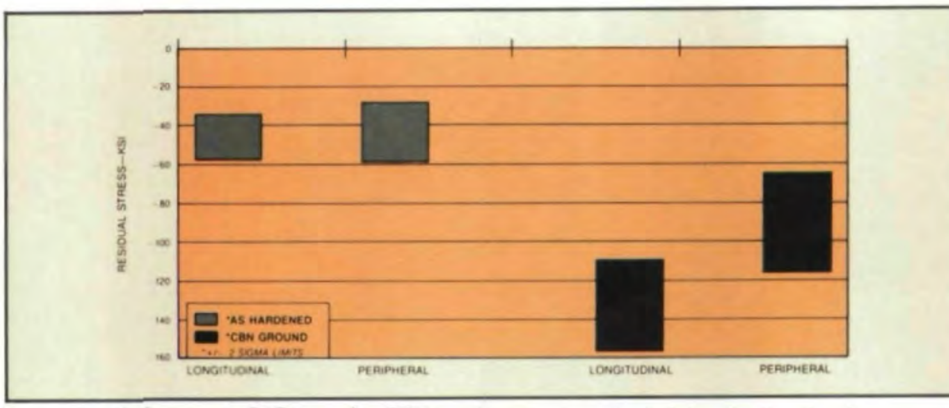

Fig. 7 – Residual stresses in SAE 8620 after CBN grinding to various depths below hardened surface.

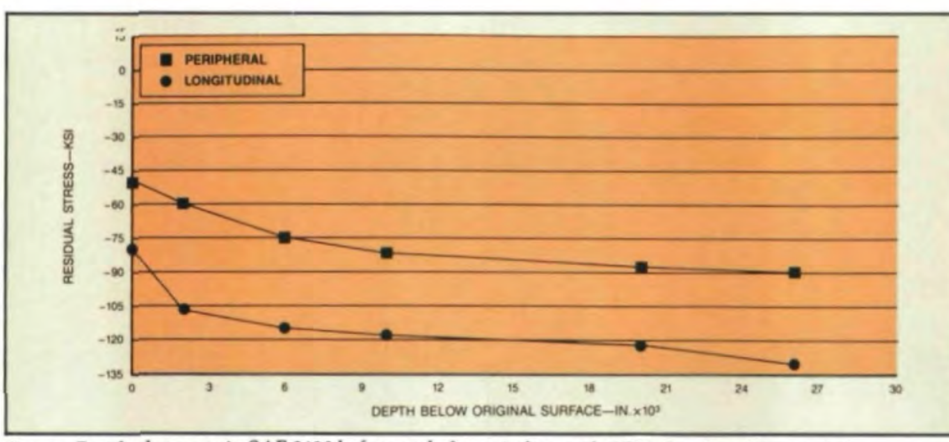

Fig. 6 – Residual stresses in SAE 8620 before and after grinding with CBN abrasives (40 samples).

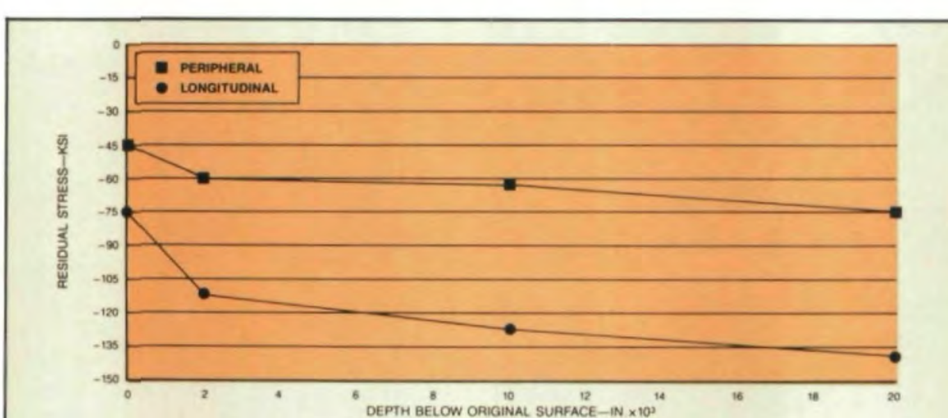

Fig. 8 – Residual stresses in SAE 4620 after CBN grinding to various depths from as-hardened surface.

Results

The results of this work are detailed as follows:

1. Residual stress analysis – The unground and ground SAE 4620 results in ±2 sigma limit bars illustrated in Fig. 5. Analysis of these results using the student "T" test for significance reveals that CBN grinding has had the following effects on the residual stress levels of the ground samples:

4620 – 95% confidence that the longitudinal stress is increased from −96250 PSI to −148600+/−5900 PSI, and the peripheral stress from −61800 PSI to −88120+/−5200 PSI.

8620 – 95% confidence that the longitudinal stress is increased from −45200 PSI to −133300+/−3600 PSI, and the peripheral stress from −43300 PSI to −92700+/−3900 PSI.

2. Effect of grinding depth on residual stress – The effect on both the SAE 8620 and SAE 4620 ground samples are shown graphically in Figs. 7 and 8. In the case of both workpiece types, the consequences of CBN grinding clearly have been to further increase the residual compressive stress as the total grinding depth is increased.

Discussion

The general character of the residual stresses which result from CBN grinding in this work is in agreement with previously reported work. This investigation, however, has shown clearly that the residual compressive stresses created by CBN grinding are additive to the inherent residual compressive stresses found on as-heat treated surfaces (Figs. 5, 6, 7, 8). This is a completely new finding which should trigger further investigation.

Recently we obtained samples of automotive transmission gears ground with an electroplated CBN wheel. Five gears were selected at random during the course of grinding a run of approximately 250,000 gears. The midflank residual stress in the radial direction has been analyzed, and the results of these analyses are shown in Figs. 9a and 9b. The residual stress distribution is developed to a depth of .008″ below the flank surface. The results show a remarkable consistency of compressive residual stress level at the flank surface. The small subsurface profile variations in the residual stress distributions will be due to variations in the heat treated profiles. Overall, these results again confirm the in-

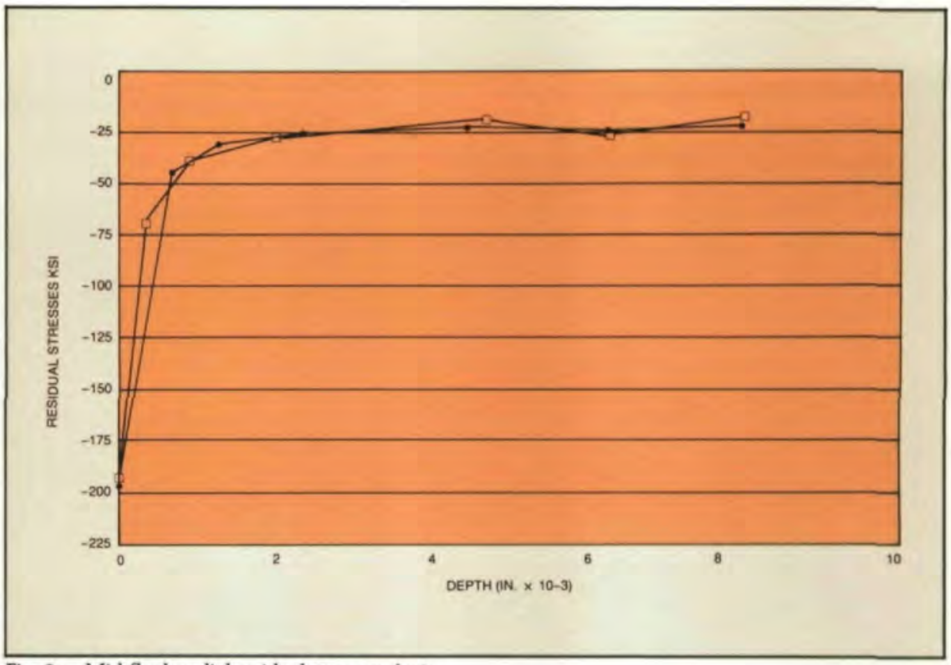

Fig. 9a – Mid-flank radial residual stress analysis.

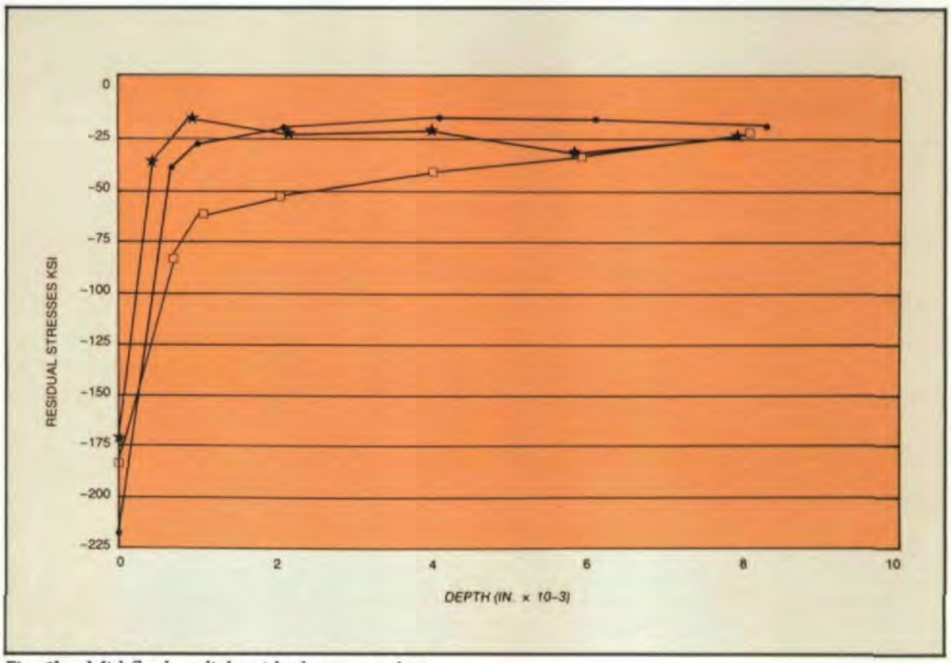

Fig. 9b – Mid-flank radial residual stress analysis.

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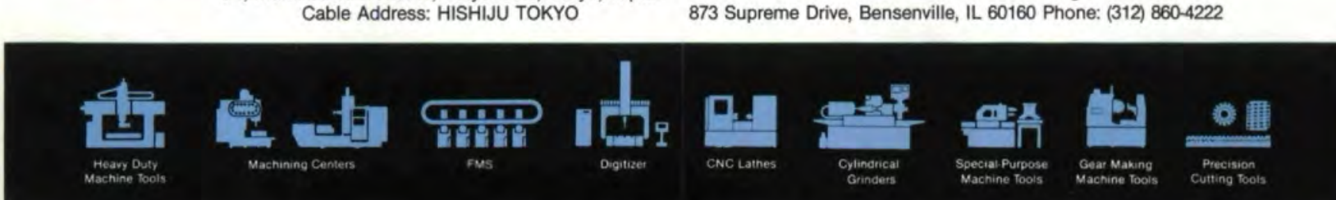

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Fig. 10

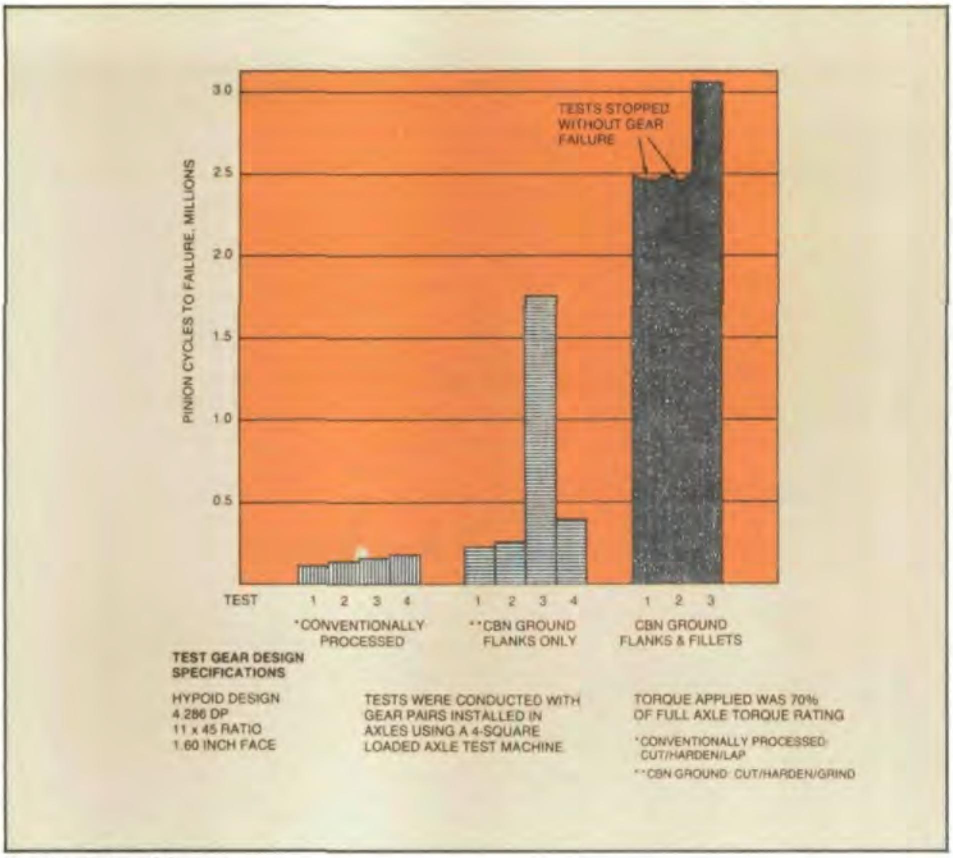

Fig. 10 – Fatigue life comparison.

herent capacity of CBN to produce significant levels of favorable residual stresses in gear components.

All of these findings tend to support the results of four-square fatigue testing of CBN ground gears reported by Kimmet.[11] This work found significant improvement in fatigue life of gears with CBN ground flanks and fillets over conventionally hardened and lapped gear sets (Fig. 10). In drawing these conclusions, Kimmet placed emphasis on the benefits of gear-to-gear uniformity and precision which result in more uniform load distribution in power transmission. In some cases, this aspect of CBN grinding may be as important or even more important than the residual stress benefits.

Yokagawa[12] has also reported increased wear resistance of the CBN ground surfaces of hardened steels over similar surfaces ground with aluminum oxide.

Honda Motor Co. has reported that the use of CBN grinding has made it possible to design and manufacture final drive gears of reduced weight and which operate at lower noise levels. These attributes derive from both the increased uniformity of tooth form and beneficial residual stresses.

Conclusions

This investigation has established that:

- CBN grinding of carburized and hardened parts can impart additional residual compressive stresses to the part surface. These stresses may be from as little as 30% greater to as much as 250% greater than the heat treated surface stresses.
- CBN grinding develops an increase in compressive residual stresses as grinding progresses from an as-heat treated surface into the case. The generation of compressive stresses has been shown in Figs. 7 and 8 to be independent of the amount of case depth removed at equivalent hardness. CBN grinding will also remove oxides, carbides and bainite from the surfaces.

The major thrust of these findings is that the beneficial effects of CBN grinding should be considered in the original design of drive train gear components. Coupled with the ability to remove all inherent distortion from the previous heat treatment process, one can also consider reducing backlash, root clearance and root configuration for ultimate beam strength. Such grinding processes offer the design engineer the confidence of knowing exactly what design loads a gear can withstand and optimizing gear size and weight in overall design to take advantage of this knowledge.

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