Comparative Load Capacity Evaluation of CBN-Finished Gears

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Abstract:

Cubic boron nitride (CBN) finishing of carburized gearing has been shown to have certain economic and geometric advantages and, as a result, it has been applied to a wide variety of precision gears in many different applications.

In critical applications such as aerospace drive systems, however, any new process must be carefully evaluated before it is used in a production application. Because of the advantages associated with this process, a test program was instituted to evaluate the load capacity of aerospace-quality gears finished by the CBN process as compared to geometrically identical gears finished by conventional grinding processes.

This article presents a brief description of the CBN process, its advantages in an aerospace application, and the results of an extensive test program conducted by Boeing Helicopters (BH) aimed at an evaluation of the effects of this process on the scoring, surface durability, and bending fatigue properties of spur gears.

In addition, the results of a x-ray diffraction study to determine the surface and subsurface residual stress distributions of both shot-peened and nonshot-peened CBN-ground gears as compared to similar conventionally ground gears are also presented.

Introduction

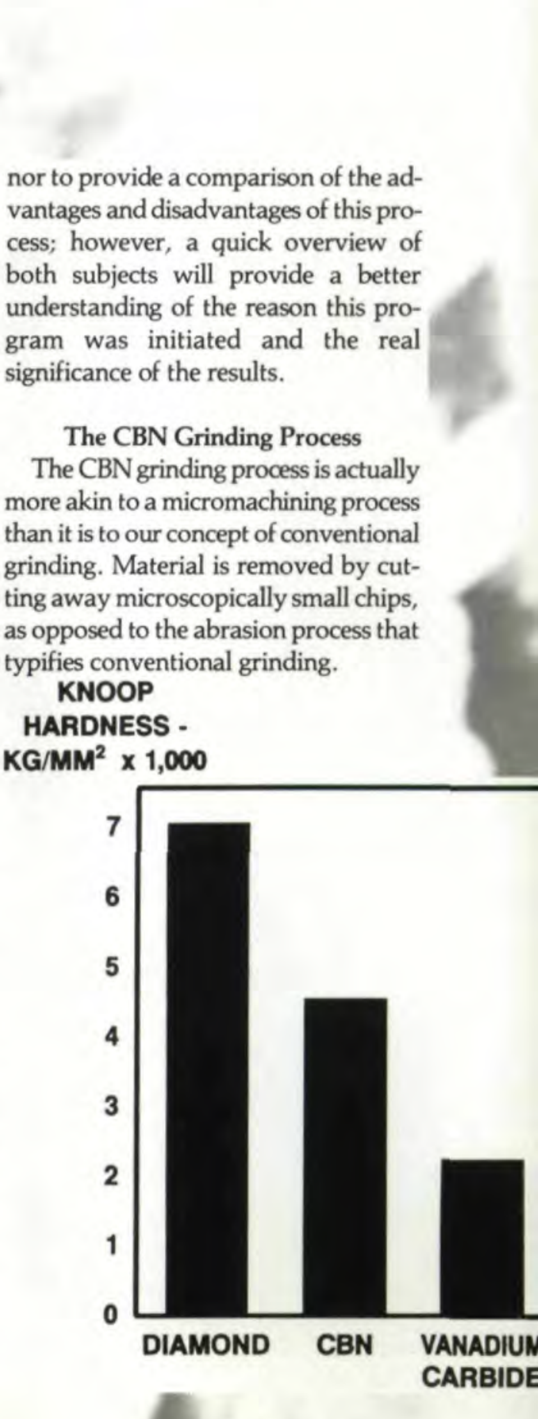
While CBN gear grinding is a relatively new technology, cubic boron nitride itself is not really a new material. It was developed more than 20 years ago by General Electric Company (under the trademark BORAZON) as a substitute for industrial diamonds. CBN is, as Fig. 1 indicates, quite hard and thus very resistant to wear. This high hardness relative to more conventional abrasives (such as aluminum oxide) used in grinding wheels, and the characteristic sharply angled shape of CBN crystals (Fig. 2)[1] combine to produce a grinding wheel that yields greatly improved performance in terms of both increased speed and consistent quality. These properties also contribute to the long life that is obtained from CBN wheels. Table I shows some of the applications of CBN; more detailed information related to the basic properties of CBN can be found in Reference 2.

Similarly, grinding with CBN is not new either; however, it is only in the last few years[3-5] that this technique has gained wide acceptance as a method for finishing precision gears. It can be applied to grinding a wide variety of gears, including spur, helical, bevel, and worms. In fact, any conventional gear-grinding process can be adapted to use CBN technology, although, as is discussed later, more than just the grinding wheel medium must change.

Our purpose here is neither to describe the basic process of CBN grinding nor to provide a comparison of the advantages and disadvantages of this process; however, a quick overview of both subjects will provide a better understanding of the reason this program was initiated and the real significance of the results.

The CBN Grinding Process

The CBN grinding process is actually more akin to a micromachining process than it is to our concept of conventional grinding. Material is removed by cutting away microscopically small chips, as opposed to the abrasion process that typifies conventional grinding.



Both the actual grinding forces and the power required are higher for CBN than for conventional grinding. As a result, while most basic grinding processes can be readily adapted to the CBN process, the requirement for greater machine and work-holding stiffness indicates that, in most cases, existing machines cannot be used.

Many different types of CBN wheels are available. CBN wheels for gear-grinding purposes can generally be classified as either plated or bonded types. Plated types essentially have single CBN particles plated over the active wheel surface. Bonded wheels use a much thicker layer of CBN crystals, mixed with a variety of bonding agents, on the active surface of the wheel. Plated wheels cannot be dressed or trued but provide long life and consistent parts. Bonded wheels may (in fact, must) be dressed and thus provide the opportunity to vary tooth geometry, but with some sacrifice in part consistency.

Fig. 1 – Hardness comparison of typical materials.

Table I. CBN Superabrasive Selection Chart

BORAZON CBN Type	Crystal Type	Mesh Size*	Wheel Bond	Recommended Applications
I	Monocrystalline; blocky shape, medium friability	40/60 to 325/400	Metal, vitreous, electro-plated	Steels hardened to Rockwell C50 and above; high-temperature superalloys with hardnesses of Rockwell C35 and above
II	Metal-coated Type I crystal	40/60 to 325/400	Resin	Same as Type I
500	Monocrystalline; blocky shape, tougher than Type I	60/80 to 325/400	Electro-plated	Same as Type I
510	Surface-treated Type 500 crystal	60/80 to 325/400	Metal, vitreous	Same as Type I; softer steels where abrasive pullout is a problem when grinding with Type I
550	Microcrystalline; irregular shape, high toughness, high thermal stability	20/30 to 140/170	Metal, vitreous	Hardened and soft ferrous alloys and cast irons
560	Metal-coated Type 550 crystal	20/30 to 140/170	Resin	Same as Type 550
570	Surface-treated Type 550 crystal	20/30 to 140/170	Electro-plated	Same as Type 550

* ASTME E-11 sieve. Types I and II CBN are also available as micron powders for fine grinding, lapping, and polishing. Data courtesy General Electric Company (from Reference 1)

Advantages

There are several reasons why CBN grinding technology is of interest to the gear designer, user, and manufacturer. Some are related to improved quality and consistency, while others are related to increased productivity and lower unit costs.

Reduced Burn Tendency. From the point of view of both manufacturing and design reliability, the fact that CBN technology promises to reduce the overall tendency to generate grinding burns is extremely attractive. Kumar[5] reports that, at room temperature, when grinding with a conventional aluminum oxide wheel, approximately 63% of the total heat generated goes into the work while only 37% goes into the wheel. By comparison, when grinding with a CBN wheel, about 96% of the total heat goes into the wheel while only 4% goes into the part. These observations are based on the thermal

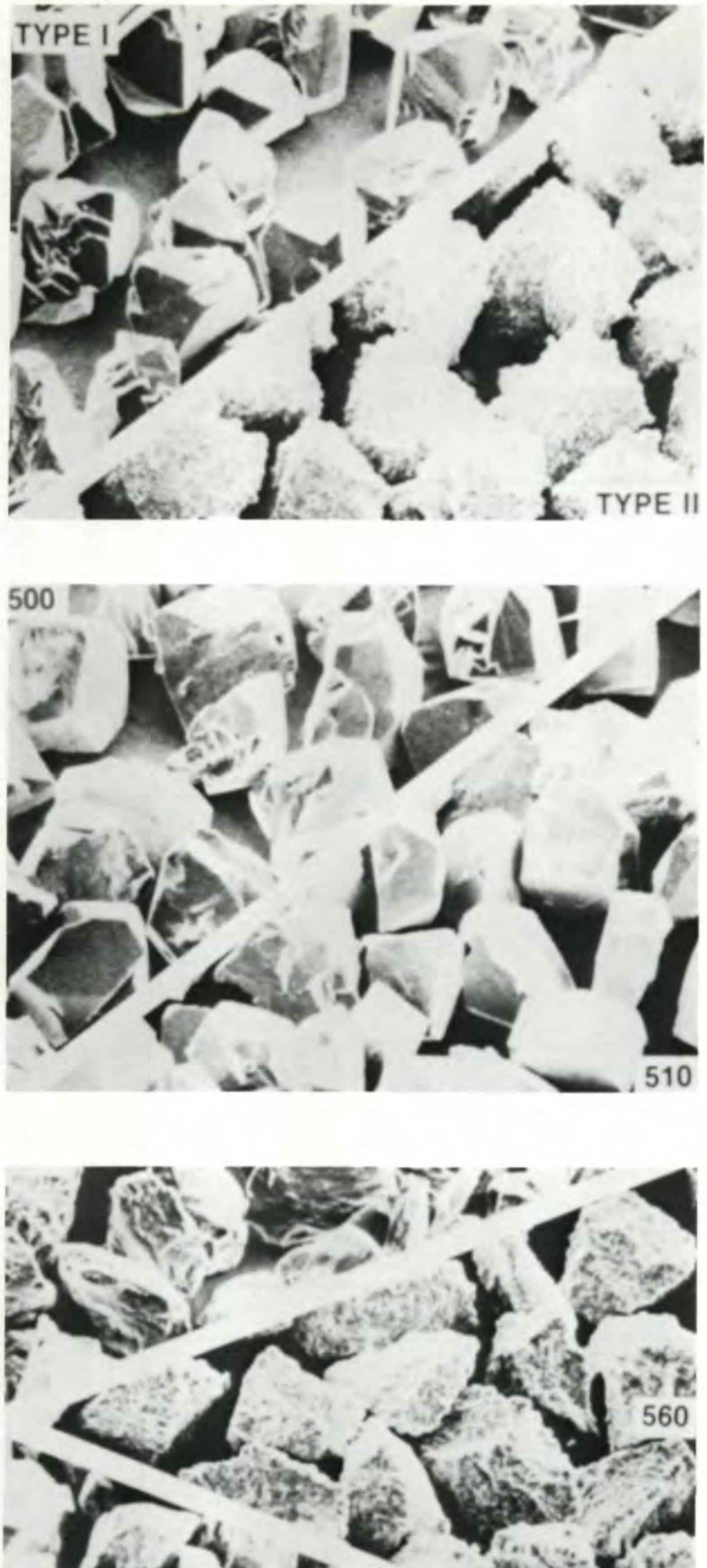


Fig. 2 – Typical crystals of cubic boron nitride.

properties shown in Fig. 3. While this comparison is reasonable, it must be noted that actual values will vary substantially for any real grinding example, depending on the gear material and the actual wheel configuration. Still, the general trend is favorable since, with less heat delivered to the gear, the tendency to burn is markedly reduced.

This should not be interpreted, as some have, as indicating that it is not possible to burn parts when grinding with CBN. It is certainly possible to burn parts; it is just less likely that burning will occur. Things can go awry and the results can be disastrous with the best of processes.

Improved Wheel Life. One of the major problems associated with producing quality parts is the deterioration of the wheel with the number of linear inches of surface ground. As the life of the wheel improves, the consistency of the parts produced will also improve. The life of a typical CBN wheel is much longer, as Fig. 4 shows, than that for a conventional wheel. In reviewing this figure, it is important to note that two abscissa scales are used, and that the one for the CBN wheel is one hundred times that for the conventional wheel. It is clear, for this experiment at least, that the wear rate of the CBN wheel is 1/50 that of a conventional wheel.

Fatigue Life and Residual Stress. One of the benefits that have been claimed for CBN is a significant improvement in fatigue life and a related improvement in the residual stress profile for CBN parts. Figs. 5 and 6, which were abstracted from data obtained from Ref-

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erence 6 as presented in Reference 5, demonstrate improvements in both fatigue life and residual stresses for test specimens made from Rene 80. While we have no reason to doubt the veracity of these data, the testing was accomplished on a material that is not typically used for gears and by a grinding method that is not typical of gear tooth grinding techniques. The overall results are, however, intriguing and certainly worth further investigation.

It is this specific area that the program reported in this article was developed to evaluate. The basic question posed at the start of this program was "How do the bending, durability, and scoring load capacities of CBN parts compare to those of identical parts properly ground by conventional techniques with aluminum oxide wheels?" It was not our intent to prove a result; rather, our intent was to investigate a phenomenon and report the results.

The Program

In order to accurately compare the performance of typical aerospace-quality gears that were finished by conventional and CBN grinding techniques, a test program was defined. The gears used in this test program, for both the conventional and CBN grinding methods, were otherwise identical, within the limits normally allowed for aerospace gearing in general. That is, their basic geometry, accuracy, material, heat treatment, and all processing other than the tooth grinding were as nearly the same as practical for both configurations. These parameters are also representative of typical BH helicopter gears so that the data may be easily transferred to actual applications.

The specific test gear configurations and test rigs used were the standard BH rigs for each type of test and thus a large amount of historical data was available for comparative purposes.

Test Gear Configuration

Two types of gears were tested as shown in Table II. Both are fully representative of typical helicopter gears except for face width. The differences in configuration are necessary to accommodate differences in the test rigs used for each test.

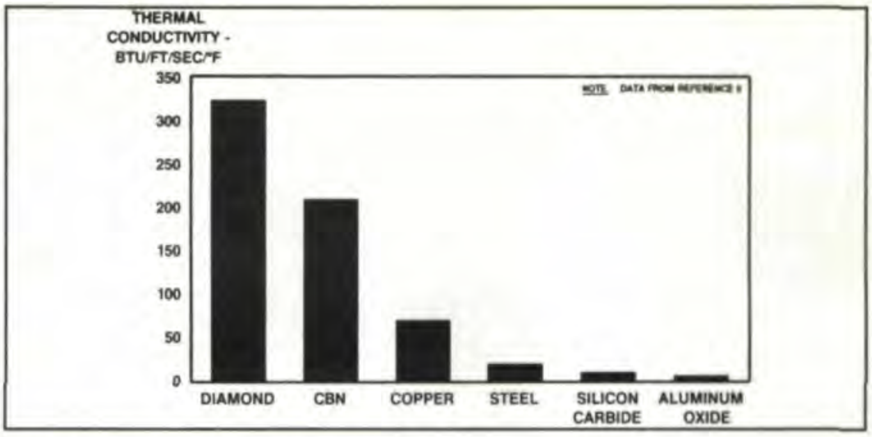

Fig. 3 – Comparison of thermal conductivity at room temperature.

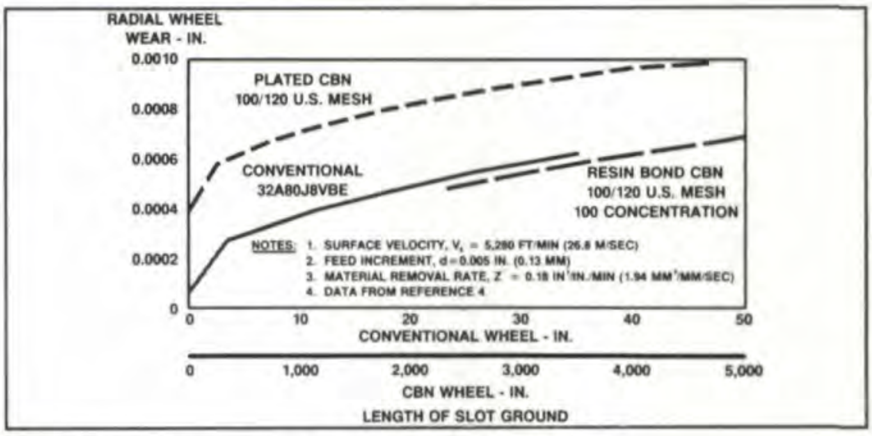

Fig. 4 – Laboratory comparison of wear rate of grinding wheels.

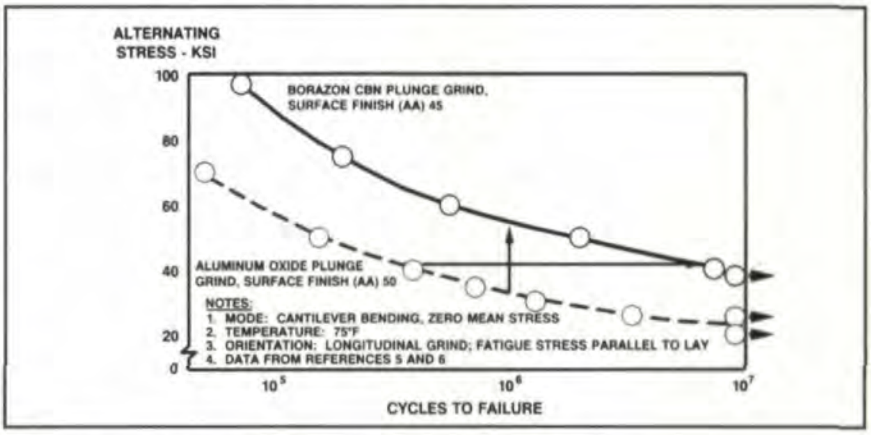

Fig. 5 – Fatigue characteristics of Rene 80 produced by plunge grinding.

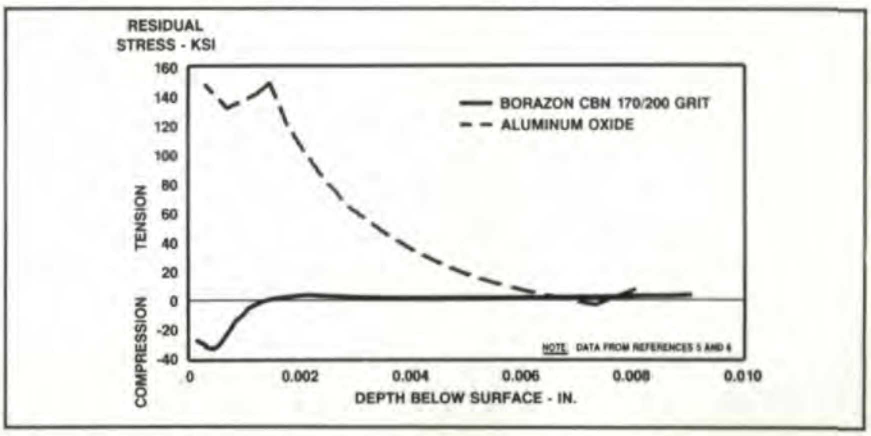

Fig. 6 – Residual surface stress profiles in Rene 80 produced by plunge grinding.

Table II. Test Gear Configurations

Parameter	Bending Fatigue	Scoring and Durability
Type	Spur	Spur
Diametral Pitch (in.)	5.3333	5.0
Pressure Angle (deg)	25.	25.
Number of Teeth	32.	30.
Quality Level, Q_n	12 - 13	12 - 13
Material	AISI 9310 DVM (BMS 7-249, Type III)	AISI 9310 DVM (BMS 7-249, Type III)
Surface Hardness	HRC 60-64	HRC 60-64
Effective Case Depth (at HRC 50) (in.)	0.035-0.055	0.030-0.045
Core Hardness	HRC 32-42	HRC 32-42
Surface Finish (max)	25 RMS	25 RMS

All gears were form-ground with full circular fillets. All CBN test specimens were shot-peened per our normal production specification. The advantage of using these specific configurations for the test parts is that they represent standardized test components that have been used for over 20 years in similar test programs; thus, the reliability of the specimens and their application to the final product are well-documented and understood. In addition, a large and varied test data history is available for comparative purposes. The small differences in pitch and case depth simply accommodate differences in the test rigs used for the bending and surface loads tests.

Test Gear Manufacture

The test gears were manufactured in accordance with normal Boeing Helicopter's standards by a qualified supplier. The results of all inspections conducted on the as-manufactured parts indicated that they were within typical expected ranges for other parts of similar size and configuration and were representative of the results for geometrically identical test gears from previous programs.

The only significant difference noted between the CBN-ground gears and previous test gears is that the surface finish on the CBN test gears hovered near the limit, typically 20-25 RMS, while most previous conventionally ground gears were found to be well below the limit on surface finish, typically 14-18 RMS.

The surface finish on the CBN parts could be improved by using a finer grade wheel (i.e., smaller CBN particles). If this is done with a plated wheel, however, wheel life may suffer somewhat. Use of a finer wheel of the bonded type will improve finish, but will sacrifice some part-to-part consistency.

Single-Tooth Bending Fatigue Testing

In order to evaluate the relative bending fatigue capacity of CBN and conventional gears, a series of carefully controlled single-tooth bending fatigue tests were run.

Test Fixture. The fixture used (Fig. 7) is the standard BH single tooth rig. It applies a unidirectional load to one tooth at a time. A total of four teeth per specimen are typically tested, although this can be increased to eight with a special adapter. The fixture is installed in a universal fatigue test machine (in this case, a Baldwin-Lima-Hamilton IV-20) capable of applying 16,000 pounds of total test load (8,000 pounds steady, plus 8,000 pounds alternating) at a frequency of 1,200 cycles per minute. The fixture is designed so that the load is applied to the test tooth at the highest point of single-tooth contact (based on a 1:1 ratio), while the reaction anvil contacts the reaction tooth at the lowest point of single-tooth contact. A constant load of 100 pounds is maintained on the test tooth at all times to prevent the impact loading that would occur if the load went through zero.

Instrumentation. The only instrumentation required for this test was that necessary to monitor test time (cycles of load application) and a crackwire signal. The crackwire provided automatic machine shutdown and test termination when the crack reached a specific, predetermined length, so that all failures were uniform. The crackwire was positioned on all gears so that a crack of approximately 0.070 - 0.080 inch would break the wire and cause an automatic shutdown.

A high-amplitude microswitch was also provided as a backup. This switch sensed abnormal movements of the machine that might occur in the event of an unexpected failure of the machine or the test specimen and automatically shut down the machine.

Calibration. Before the start of the test, the load link and one of the test gears were instrumented with strain gages. The test gear was gaged as shown in Fig. 8 so that actual gear tooth root stresses could be measured. The location of the strain gages on the test gears was determined by calculation of the critical section based on the standard AGMA approach and by examination of the failure origins from previous test gears. Since these test gears are quite thick-rimmed, the measured stresses should match those predicted by the AGMA method relatively closely. As Fig. 9 shows, there was good correlation.

Procedure. The testing procedure was quite simple. The test gear was installed in the fixture, and the height of the load anvil was adjusted to the required position (highest point of single-tooth contact) as determined by gear and fixture geometry. The load anvil was then checked for proper positioning. A steady load of 100 pounds was applied to the test tooth, and all dimensions were rechecked. The steady load was maintained approximately 100 pounds above the alternating load at all test conditions to prevent impact loading of the teeth.

Once the gear position was checked, the desired load was applied and the machine turned on. A small amount of moly grease was used at the tooth/anvil contact points to prevent fretting. During the course of the testing the specimen was checked for localized heating. At no time did the specimen

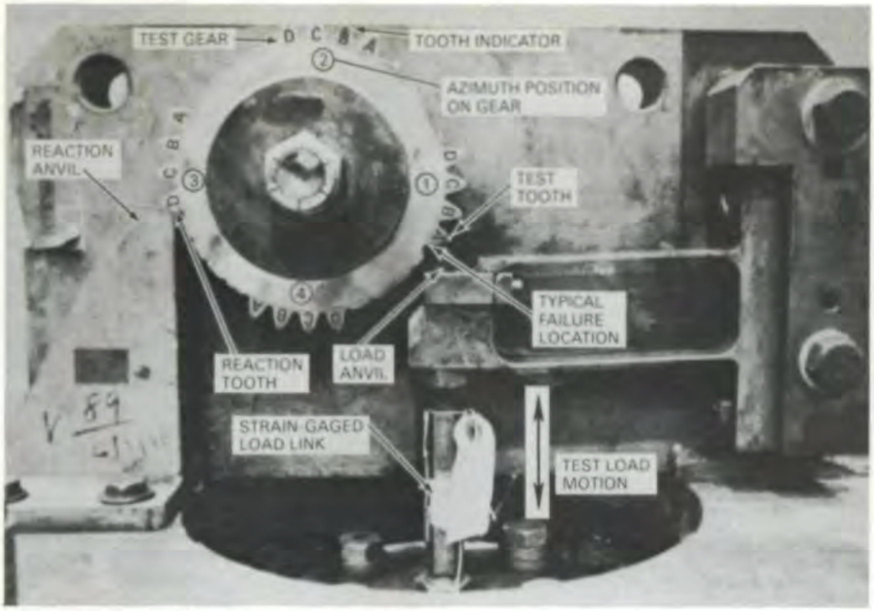

Fig. 7 – Single-tooth bending fatigue test fixture.

temperature exceed the ambient room temperature by more than 20°F. Each specimen was run at the specified load unit failure or 10 million cycles, whichever occurred first. Runouts were determined by cycle count. Failure was defined as a crack that progressed sufficiently to break the crackwire, at which point the machine was shut down automatically. This procedure insured that all failures were uniform.

Results. A total of twelve data points, eleven failures, and one runout, were obtained. The data were analyzed in accordance with standard BH statistical methods.[7] The results of this analysis are presented in Fig. 10. In order to provide a basis for comparison, similar data for two previous test programs, using identical gears, but convention-

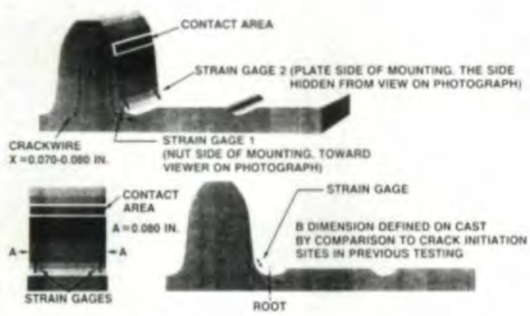

Fig. 8 – Strain gage and crackwire placement.

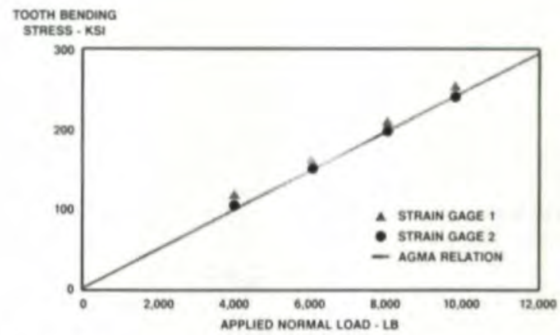

Fig. 9 – Single-tooth bending calibration and correlation.

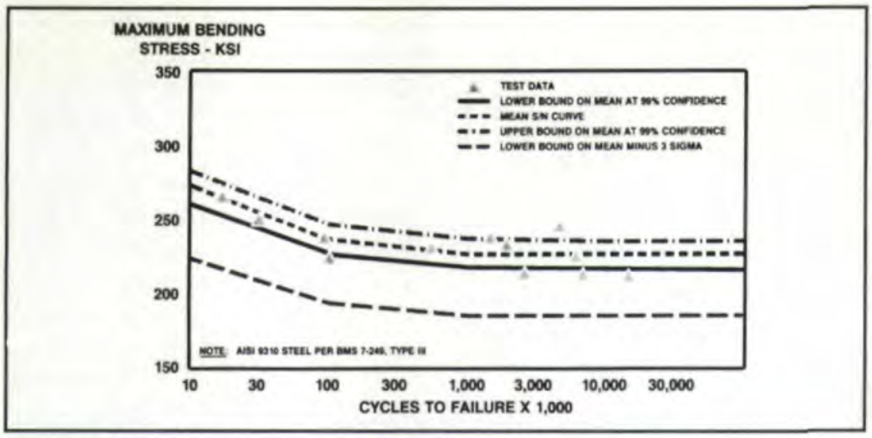

Fig. 10 – Single-tooth bending fatigue data for CBN-ground gear.

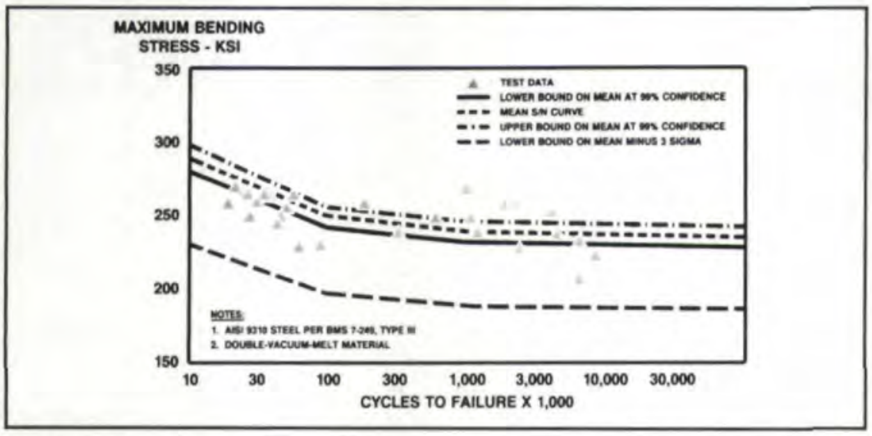

Fig. 11 – Single-tooth bending fatigue data for conventionally ground gear of vacuum-carburized steel.

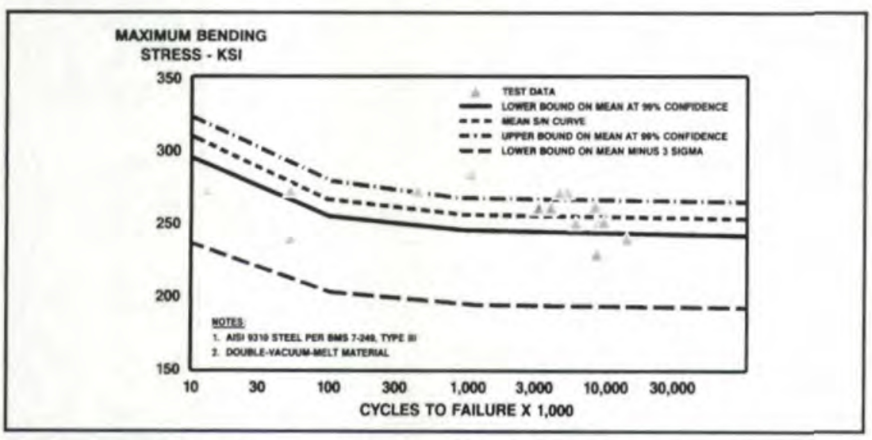

Fig. 12 – Single-tooth bending fatigue data for conventionally ground gear of gas-carburized steel.

Fig. 13 – Rig for rotating surface durability and scoring test.

Fig. 14 – Gear research test facility.

ally ground with aluminum oxide wheels, are shown in Figs. 11 and 12. While the mean endurance limits for these three tests vary somewhat, the mean-minus-three-sigma (standard deviation) limits are remarkably similar. Much information that is not at first obvious is conveyed by these three charts.

Durability and Scoring Testing

Test Rig. The test rig used for both the durability and scoring test phases of this program is shown in Figs. 13 and 14. This four-square, locked-in-torque rig is capable of testing spur or helical gears on 6-, 10-, or 16-inch center distances. Two test configurations at each center distance, overhung and straddle-mounted, are possible with this rig. When mounted in the overhung configuration, as shown in Fig. 13, the gears are wholly contained within a housing that is external to all other rotating components. This allows the test gear lubrication system to be fine-tuned exactly to the configuration being tested. The test oil thus lubricates nothing but the test gears, so cross-contamination is avoided. Precise control of flow, pressure, and temperature, as well as oil jet impingement on the test gears themselves, is carefully maintained.

The stand is capable of testing up to a pitch-line velocity of 10,000 feet per minute at more than 50,000 in.-lb of pinion torque. All gears and bearings, both test and slave, are pressure-jet lubricated with MIL-L-23699 oil. Power is supplied by a 100-hp motor running at 3,600 rpm. Variations in shaft speed are provided by changing the timing pulley configuration between the motor and the test stand input shaft.

Each gearbox on the rig (two slave and one test) is lubricated with a separate, completely self-contained oil system. Each system consists of both pressure and scavenge pumps with in-line heat exchangers, pressure and temperature sensors, and a very-high-capacity fine filtration system (3, 12, 25 micron; 12 used for this testing). The test gearbox is also equipped with an in-line, high-capacity heater that allows the actual oil inlet temperature at the test gear jet to be controlled within 5°F.

Instrumentation. The major variable in both the scoring and durability testing is shaft torque; thus, shaft torque measurement is provided. In addition, the stand is instrumented to provide information on oil flow rate, pressure, temperature (into and out of the test unit), and run time. Vibration measurement is also available, but was not used in this testing.

Calibration. Before the start of the test program, the instrumented shaft that is used to measure torque is calibrated (actually calibrated twice since a redundant torque bridge is provided for reliability). The oil flow and temperature sensors to the test gear set are also calibrated and certified.

In addition, all gearboxes are drained, flushed, and refilled with the test lubricant to insure that the oil systems are free of any possible contaminants from previous testing.

Procedure. At the start of the test, all oil lubrication pumps were started and run until a stable temperature condition was observed. At that point, the desired torque was applied to the pinion shaft within an accuracy of 5%.

The specific test conditions for the scoring and durability tests were slightly different as Tables III and IV show.

The durability tests were run for 7 million cycles or until failure, whichever occurred first. Failure was determined by the occurrence of a minimum of one pit, at least 1/16 by 1/16 inch in size, on at least three nonadjacent teeth. A gear that completed 7 million cycles was considered a runout.

The scoring tests were run according to the procedure outlined in Fig. 15. Testing continued by this procedure until failure; thus the scoring testing produced no runout points.

Durability Results. A total of ten data points, eight failures, and two runouts, were obtained. As was the case with the bending data, these data were analyzed in accordance with standard BH statistical methods.[7] The results of this analysis are presented in Fig. 16. In order to provide a basis for comparison, similar data for a previous test program, using identical gears, but conventionally ground with aluminum oxide wheels, are shown in Fig. 17. While the mean endurance limits for these two tests vary considerably, the mean-minus-three-sigma (standard deviation) limits almost overlie one another.

Scoring Results. A total of ten scoring data points were obtained from this

Table III. Durability Test Conditions

Pinion Speed	3,600 rpm
Oil Inlet Temperature	135°F
Oil Jet Pressure	45 psi
Oil Jet Flow	0.32 gpm

Table IV. Scoring Test Conditions

Pinion Speed	3,600 rpm
Oil Inlet Temperature	200°F
Oil Jet Pressure	45 psi
Oil Jet Flow	0.32 gpm

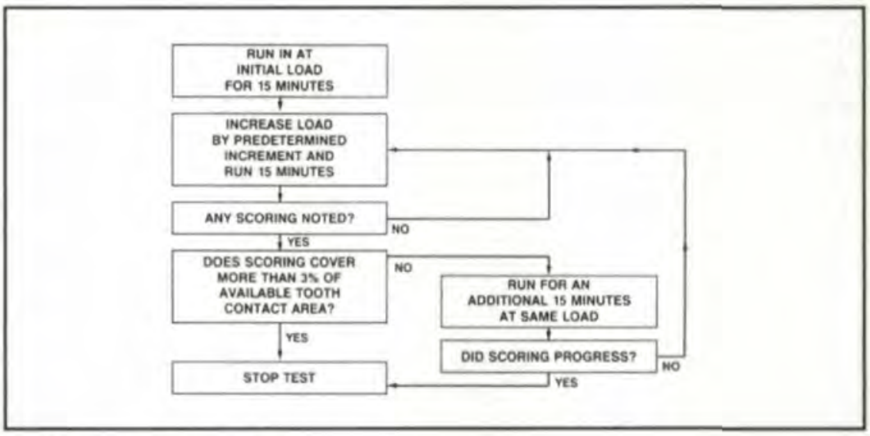

Fig. 15 – Scoring test procedure.

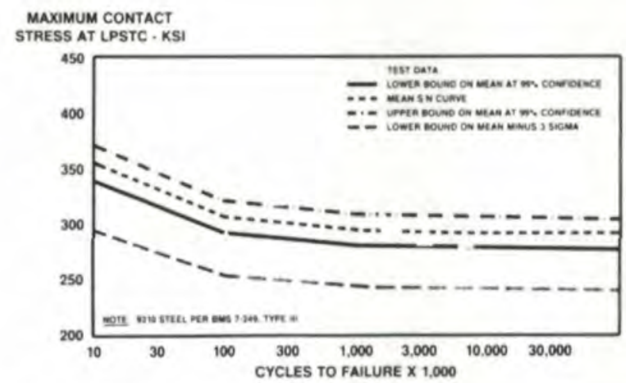

Fig. 16 – Tooth surface durability data for CBN-ground gear.

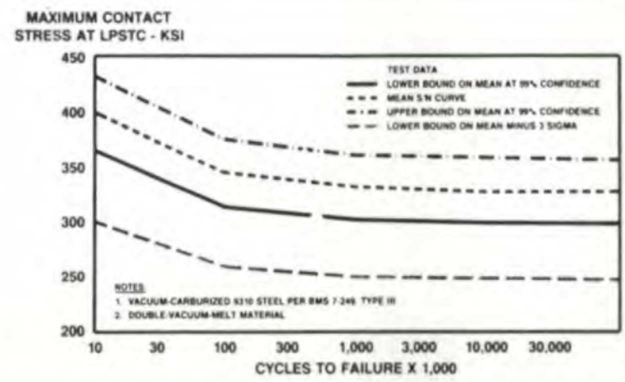

Fig. 17 – Tooth surface durability data for conventionally ground gear.

testing. The results were analyzed statistically based on a normal distribution so that the scoring probability curve shown in Fig. 18 could be developed. For reference purposes, the curve obtained from a similar test program with conventionally ground spur gears is superimposed on the same figure. The difference between the two curves is insignificantly small.

The additional line shown in Fig. 18 denote AISI 9310 gears that were carburized, hardened, and conventionally ground. The data for these other oils, presented for comparative reference only, were obtained either from similar R&D testing or by ratioing Ryder-type data to fit the format shown. The data shown are valid for reference purposes, but their use in design must be modified by appropriate safety factors to account for increased data uncertainty relative to the MIL-SPEC oils.

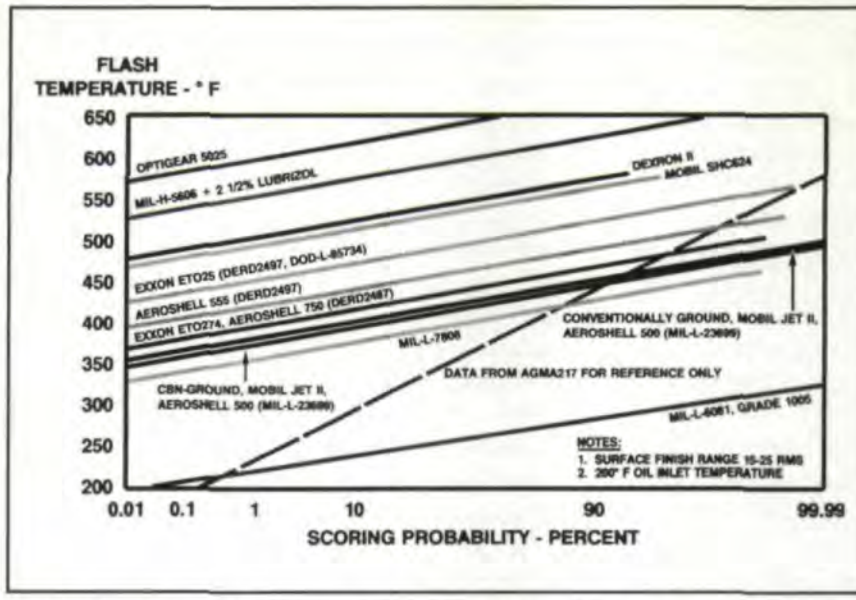

Fig. 18 – Scoring probability of conventionally and CBN-ground spur test gears.

Discussion

Based on the data presented here, it appears that there is not a significant difference in the load capacity of gears that have been finished by CBN grinding when compared to exactly identical gears that have been finished by conventional methods with aluminum oxide wheels. This observation would seem to contradict the data shown in Fig. 5 in which the CBN process is credited with a substantial improvement in the bending fatigue capability of parts that were CBN-ground when compared to conventionally ground parts. However, several factors must be considered before proceeding further.

First and foremost, the data presented in Fig. 5 are neither based on gear tooth testing nor is the material one that would be used for a gear. In addition, all of the gears that were used in the testing reported herein were shot-peened all over after final grind.

The major difference, however, may well be that these gears are all (both conventional and CBN) of typical helicopter main power train quality. This being the case, both the conventional and the CBN grinding processes are very carefully controlled and monitored so that problems related to burning and other heat-related distress do not occur in the finished parts.

If the conventional grinding process is carefully controlled, it will produce parts that are free of even minimal distress. Conversely, if it is not carefully controlled and monitored, parts with high residual tensile stresses and possibly some burns can become part of a given lot of parts, thus reducing the overall average load capacity. Since one of the main advantages of the CBN process is its relative insensitively to such problems, it stands to reason that, when compared to conventional grinding of commercial quality, it is possible that the CBN parts may show an improvement in fatigue life. This improvement is, however, plainly not evident when CBN parts are compared with very high-quality parts made by conventional techniques.

This is not to say that the use of CBN grinding is of no advantage. This testing simply indicates that, for helicopter-quality gears, no load capacity advantage is obtained through the use of CBN gears.

Considerable advantage can be obtained, even for helicopter-quality gears, through use of CBN gears due to improvements in productivity and consistency of parts. In fact, based on the favorable results of this program, CBN grinding has been approved as a production process for several current applications with good results.

Residual Stresses

One of the advantages that is frequently claimed for CBN parts[4-5] is the existence of a residual compressive layer on the ground tooth surfaces after CBN finishing. The implication is, of course, that the residual stress profile produced by conventional grinding is poor by comparison.

As noted above, based on the favorable results of this program, the CBN process was ultimately approved for use on 9310 steel production gears. Before this approval was granted, however, completed destructive metallurgical evaluations were performed on several of these production parts. Specifically, comparative evaluations were conducted on conventionally ground production parts and on the proposed CBN-ground replacement parts. In general, the two types of finishing methods produced parts of like metallurgical characteristics. As part of the metallurgical evaluation, residual stress measurements were taken by x-ray diffraction techniques on both types of parts before and after shot-peening. The results of these measurements are shown in Figs. 19 and 20 for the CBN and conventionally ground parts, respectively. These production parts are 10 diametral-pitch, 19,000-rpm helical gears transmitting about 2,000 horsepower.

While the CBN-ground gears do exhibit a very shallow compressive stress layer, the properly conventionally ground gears also show a similar shallow compressive stress layer. This compressive layer is, however, much enhanced by proper shot-peening on both the CBN and conventionally ground gears, as is evident from these plots.

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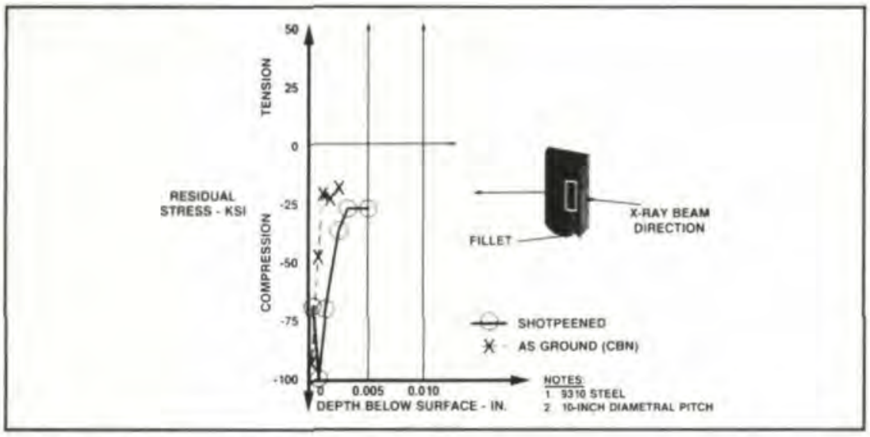

Fig. 19 – Residual stresses for CBN-ground gears.

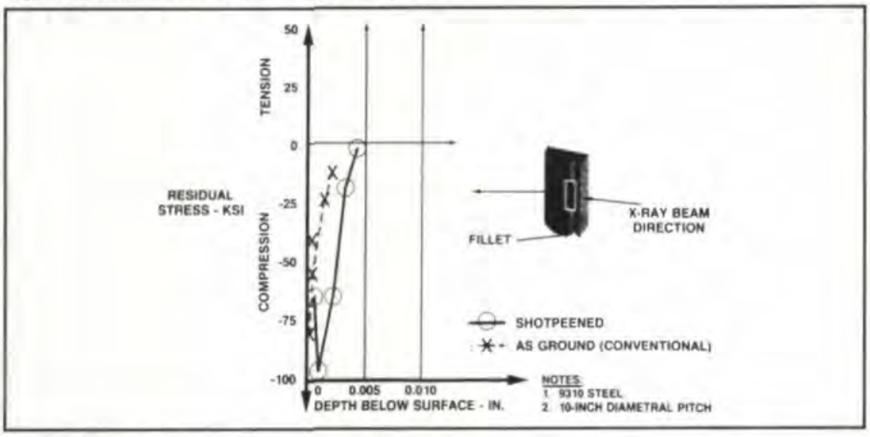

Fig. 20 – Residual stresses for conventionally ground gears.

Comment

While the data presented herein do not demonstrate any improvement in load capacity for CBN-ground gears, they do show this to be a viable process for finishing helicopter gears. The discrepancy in reported improvements in load capacity reported elsewhere in the literature may be more easily understood if a few points are kept in mind.

Many of the reports of improved load capacity are based on comparisons that are not truly "apples-to-apples". For example, Kimmet[4] cites such an improvement by noting that". . . CBN ground gears have a significantly longer fatigue life as compared with conventionally processed gears." However, the conventionally processed gears in that case were carburized and lapped, not carburized and conventionally ground; the latter would have made a more valid comparison. Other cases have been reported in which CBN gears have replaced conventionally ground gears with improved performance. This too, is probably a correct, but incomplete observation. The author can cite a very convincing example in his own experience in which a set of CBN-finished gears was used to replace a set of ground gears that were experiencing premature failure. The result was that the CBN gears did, in fact, solve the early failure problem. However, the truth of the matter was that the conventionally ground gears were abusively ground; this lack of proper grinding technique resulted in the failures observed.

It is far easier to produce properly finished CBN gears than conventionally ground gears. This is the main advantage in load capacity, not any inherent property of the processing itself. As demonstrated herein, properly processed conventionally ground gears do, in fact, have a statistically insignificant edge in terms of load capacity.

Conclusions

Based on the results of this program, we have reached the following conclusions specifically related to helicopter-quality AISI 9310 vacuum-melt gears finished by conventional and CBN grinding:

1. CBN-ground gears provide equivalent performance to conventionally ground gears of identical geometry and metallurgy.
2. CBN grinding, when compared to properly processed conventionally ground gears, provides no improvement in load capacity or fatigue life.

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