Increased Surface Fatigue Lives of Spur Gears by Application of a Coating

Timothy L. Krantz
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Clark V. Cooper
United Technologies Research Center, East Hartford, Connecticut

Dennis P. Townsend
Townsend Engineering, Westlake, Ohio

Bruce D. Hansen
Sikorsky Aircraft, Stratford, Connecticut

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Timothy L. Krantz
Army Research Laboratory
Cleveland, Ohio USA
Timothy.L.Krantz@grc.nasa.gov 216-433-3580

Clark V. Cooper
United Technologies Research Center
East Hartford, Connecticut USA

Dennis P. Townsend
Townsend Engineering
Westlake, Ohio USA

Bruce D. Hansen
Sikorsky Aircraft
Stratford, Connecticut USA

ABSTRACT
Hard coatings have potential for increasing gear surface fatigue lives. Experiments were conducted using gears both with and without a metal-containing, carbon-based coating. The gears were case-carburized AISI 9310 steel spur gears. Some gears were provided with the coating by magnetron sputtering. Lives were evaluated by accelerated life tests. For uncoated gears, all of fifteen tests resulted in fatigue failure before completing 275 million revolutions. For coated gears, eleven of the fourteen tests were suspended with no fatigue failure after 275 million revolutions. The improved life owing to the coating, approximately a six-fold increase, was a statistically significant result.
Keywords: Gear, life, fatigue, pitting, coatings.

INTRODUCTION
The power density of a gearbox is an important consideration for many applications and is especially important for gearboxes used on aircraft. One factor that limits gearbox power density is the need to transmit power for the required number of cycles while avoiding gear surface fatigue failure (micropitting, pitting or spalling). Effective and economical methods for improving surface fatigue lives of gears are therefore highly desirable. Thin hard coatings have potential for improving gear performance. In fact, coatings are reported to have some successful applications [1-3] where product durability improvements have been achieved by the application of thin hard coatings to gears.

Diamond-like carbon and related materials have the potential for a wide variety of applications that require wear protection and/or low-friction properties. Because of the widely recognized potential, the deposition methods and resulting properties of the films have been studied extensively [4-6]. Today’s deposition technology allows for the production of a great diversity of coatings, but the ability to tailor the tribological behavior of a coating for a particular application has been elusive.

Aerospace gearing requirements are demanding, calling for high power density, long life, and excellent reliability. The low friction properties and high hardness of diamond-like and related coatings offer the possibility to improve the performance of aerospace gearing. Naik, et al [7] tested the adherence and toughness of two coatings using both disk-on-rod rolling-contact and gear tests, and they reported promising results. Alanou, et al [8] found that coatings could increase the scuffing load capacity of rolling and sliding disks used to simulate aerospace gearing contacts, but they also reported poor adherence for one particular substrate and coating combination. Joachim, Kurz and Glatthaar [3] reported promising results of evaluations of tungsten carbon carbide and amorphous boron carbide coatings using laboratory tests, but they also report mixed results when applying such coatings to commercial applications.

The purpose of the present investigation was to compare the surface fatigue lives of coated and uncoated gears using accelerated life tests. The testing is considered as accelerated in that the contact stresses used for testing exceeds the stresses used for design of the target application (helicopter gearing). The metal-containing, carbon-based diamond-like (Me-DLC) coating selected for this study was designed specifically for the aerospace gearing applications.
DESCRIPTION OF THE TEST GEARS, LUBRICANT, AND COATING

The test gears used for this work were manufactured in one lot from a single heat of consumable-electrode vacuum-melted (CVM) AISI 9310 steel. The nominal chemical composition of the AISI 9310 material is given in Table 1. The gears were case carburized and heat treated according to Table 2. Figure 1 is a photomicrograph of an etched and polished gear tooth showing the case and core microstructure of the test gears. The nominal properties of the carburized gears were a case hardness of Rockwell C60, a case depth of 0.97 mm (0.038 in.), and a core hardness of Rockwell C38. The test gears were a subset of a larger lot of gears that were used by Townsend and Shimski [9] to study the influence of elastohydrodynamic film thickness and extreme pressure additives on gear surface fatigue life.

### Table 1 — Nominal Chemical Composition of AISI 9310 Gear Material

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.22</td>
</tr>
<tr>
<td>Chromium</td>
<td>1.21</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.12</td>
</tr>
<tr>
<td>Copper</td>
<td>0.13</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.63</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.27</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.005</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.005</td>
</tr>
<tr>
<td>Iron</td>
<td>balance</td>
</tr>
</tbody>
</table>

### Table 2 — Heat treatment for AISI 9310 Gears.

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
<th>Temperature</th>
<th>Time, hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>°F</td>
</tr>
<tr>
<td>1</td>
<td>Preheat in air</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Carburize</td>
<td>1,172</td>
<td>1,650</td>
</tr>
<tr>
<td>3</td>
<td>Air cool to room</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Copper plate all over</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>Reheat</td>
<td>922</td>
<td>1,200</td>
</tr>
<tr>
<td>6</td>
<td>Air cool to room</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Austenitze</td>
<td>1,117</td>
<td>1,550</td>
</tr>
<tr>
<td>8</td>
<td>Oil quench</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>Subzero cool</td>
<td>180</td>
<td>-120</td>
</tr>
<tr>
<td>10</td>
<td>Double temper</td>
<td>450</td>
<td>350</td>
</tr>
<tr>
<td>11</td>
<td>Finish grind</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>Stress relieve</td>
<td>450</td>
<td>350</td>
</tr>
</tbody>
</table>

The lubricant used for testing was from a single batch of synthetic paraffinic oil. Physical properties of this lubricant are summarized in Table 4. Five percent of extreme pressure additive with partial contents including phosphorus and sulfur was added to the lubricant. This lubricant and additive combination has been used extensively for gear fatigue testing in the NASA Glenn spur gear fatigue rigs. For example, Krantz [10] reported 146 tests using this same oil (termed “NASA standard” in the referenced article) to evaluate the surface fatigue lives of AISI 9310 steel gears. The oil and additive mixture used in this work is similar to 5-centistoke oils used for helicopter main gearboxes. The film thickness at the pitch point for the operating conditions of the surface fatigue testing was calculated using the computer program EXTERN. This program, developed at the NASA Glenn Research Center, is based on the methods of Anderson, Lowenthal, and Black [11,12]. For the purposes of the calculation, the gear surface temperature was assumed to be equal to the average oil outlet temperature. This gave a calculated pitch-line film thickness of 0.54 μm (21 μin.).
Figure 1.—Photomicrograph of an etched and polished test gear tooth (from Townsend and Shimski, ref. [9]). (a) Core microstructure. (b) Case microstructure.

**TABLE 4. — Lubricant Properties.**

<table>
<thead>
<tr>
<th>Additive</th>
<th>Lubrizol 5002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity, cSt</td>
<td>311 K (100 °F)</td>
</tr>
<tr>
<td></td>
<td>372 K (210 °F)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.83</td>
</tr>
<tr>
<td>Flash point, K (°F)</td>
<td>544 (520)</td>
</tr>
<tr>
<td>Pour point, K (°F)</td>
<td>211 (–80)</td>
</tr>
</tbody>
</table>

* Partial content of additive: phosphorus, 0.6 wt%; sulfur, 18.5 wt%.

W(tungsten)-DLC coatings were deposited onto carburized spur gears after final grinding, by using an unbalanced magnetron sputter deposition process, at a deposition temperature of approximately 200°C [13]. Prior to coating deposition, the spur gears were “vapor honed” using pressurized water-based media containing ~10 μm diameter Al₂O₃ particles. The coating/gear system consisted of an elemental Cr (chromium) adhesion layer adjacent to the steel substrate, followed by an intermediate, transition region, featuring alternating lamellae composed of Cr and WC, and an outermost W-containing hydrocarbon (W-C:H) layer. The composition of the outermost W-C:H layer, in atomic percent, has been determined via secondary ion mass spectrometry (SIMS) to be approximately 12% W, 70% C, 15% H, and 3% Ni, which forms the binder element for the WC sputter targets [14].

Measurements of the properties of Me-DLC coating materials are sparse, primarily on W-DLC coatings [15–18]. The Young’s modulus of the DLC coating is in the range 100-120 GPa as measured using beam-curvature [15, 16] and instrumented indentation [7, 18] methods. W-DLC deposited on steel is in residual compression. Measurements performed by beam curvature indicate a stress, σ_R ≈ 900 MPa [15]; the amorphous nature of the Me-DLC coating [19, 20] precludes stress measurement through the application of x-ray diffraction methods. The fracture toughness of the W-DLC has been determined from the critical strain for channel cracking [15] as: Γ_{DLC} = 35 Jm⁻². The toughness of the interface between the W-DLC coating and the steel substrate in the presence of a Cr adhesion layer has been shown to be well in excess of that for the Me-DLC coating, itself [15]. This high toughness eliminates the interface as a weak link and distinguishes the present systems from those with weak interfaces.

**TEST APPARATUS AND PROCEDURE**

The gear fatigue tests were performed in the NASA Glenn Research Center’s gear test apparatus. The test rig is shown in Fig. 2(a) and described in reference [21]. The rig uses the four-square principle of applying test loads, and thus the input drive only needs to overcome the frictional losses in the system. The test rig is belt driven and operated at a fixed speed of 10 000 r.p.m. for the duration of a particular test.

A schematic of the apparatus is shown in Fig. 2(b). Oil pressure and leakage replacement flow is supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes located inside one of the slave gears, torque is applied to its shaft. This torque is transmitted through the test gears and back to the slave gears. In this way power is circulated, and the desired load and corresponding stress level on the test gear teeth may be obtained by adjusting the hydraulic pressure. The two identical test gears may be started under no load, and the load can then be applied gradually. This arrangement also has the advantage that changes in load do not affect the width or position of the running track on the gear teeth. To enable testing at the desired contact stress, the gears are tested with the faces offset as shown in Fig. 2. By utilizing the offset arrangement for both faces of the gear teeth, a total of four surface fatigue tests can be run for each pair of gears.

Separate lubrication systems are provided for the test and slave gears. The two lubrication systems are separated at the gearbox shafts by pressurized labyrinth seals, with nitrogen as the seal gas. The test gear lubricant is filtered through a 5-μm (200-μin.) nominal fiberglass filter.

A vibration transducer mounted on the gearbox is used to automatically stop the test rig when the broadband r.m.s. vibration magnitude increases beyond a threshold, indicating that gear surface fatigue damage has occurred. The gearbox is also automatically stopped if there is a loss of oil flow to either the slave gearbox or the test gears, if the test gear oil overheats, or if there is a loss of seal gas pressurization.

The test gears were run with the tooth faces offset by a nominal 3.3 mm (0.130 in.) to give a surface load width.
on the gear face of 3.0 mm (0.120 in). The actual tooth face offset for each test is based on the measured face width of the test specimen, and the offset is verified upon installation using a depth gage. The nominal 0.13-mm- (0.005-in.-) radius edge break is accounted for to calculate load intensity. All tests were run-in at a load (normal to the pitch circle) per unit width of 123 N/mm (700 lb/in.) for 1 hour. The load was then increased to the desired test load. For the uncoated gears, all tests were conducted using a test load of 580 N/mm (3300 lb/in.), which resulted in a 1.7-GPa (250-ksi) pitch-line maximum Hertz stress. For the coated gears, six tests were conducted at the same test load as was used for the uncoated gears while eight tests were conducted using a test load of 720 N/mm (4100 lb/in.) which resulted in a 1.9-GPa (280-ksi) pitch-line maximum Hertz stress. The Hertz stress just stated is an idealized stress index assuming static equilibrium, perfectly smooth surfaces, and an even pressure distribution across a 2.79 mm (0.110 in.) line contact (the line length is less than the face width allowing for the face offset and the radius edge break).

Figure 2.—NASA Glenn Research Center gear fatigue test apparatus. (a) Cutaway view. (b) Schematic view.

Figure 3.—Measured dynamic tooth force at nominal test conditions (from Krantz, ref. [10]). The solid line is the measured data, and the dashed lines are replicates of the measured data spaced along the ordinate at the equivalent of one tooth pitch. The zones of double tooth contact (DTC) and single tooth contact (STC) are illustrated.

**TEST RESULTS AND DISCUSSION**

Results of the gear surface fatigue testing are summarized in Table 5. A total of 29 tests were completed, 15 tests using the uncoated gears and 14
tests using the coated gears. All of the baseline tests were conducted at a Hertzian stress index of 1.7 GPa (250 ksi), with all tests resulting in failures. The range of duration for the tests using uncoated baseline gears was 25—272 million revolutions. The coated gears were tested at two loads. Six of the coated gears were tested at a Hertzian stress index of 1.7 GPa (250 ksi), and eight of the coated gears were tested at a stress index of 1.9 GPa (280 ksi). The range of duration for the tests using coated gears was 63—311 million revolutions, and 11 of the 14 tests were completed with no failure after at least 275 million revolutions.

The measured fatigue lives of the uncoated-baseline gears had life distributions with equal Weibull slope parameters. A likelihood ratio statistical test (Meeker and Escobar, [24]) was used to verify that the assumption of equal slopes was indeed a reasonable assumption. Software employing the maximum likelihood method (Krantz, [25]) was used to estimate the Weibull parameter values from the test data. Figure 4 is a Weibull plot displaying the test data and the lines representing the maximum likelihood fit Weibull distributions. Data points are plotted at the positions of exact median ranks (Jaquelin, [26]) with adjustments to the order numbers to account for suspended tests (Johnson, [27]). The results of the statistical analysis are summarized in Table 6. The ten-percent lives of the uncoated and coated gear populations were estimated to be 28×10⁶ and 180×10⁶ cycles, respectively.

From the data plot and the statistical analysis, it is clear that the lives of the coated gears were longer than the lives of the uncoated gears by a factor of approximately six. To test that the measured life difference was a statistically significant one, the null hypothesis was set forth that the coated and uncoated gears represented a single fatigue life population. If the null hypothesis were true, the observed life difference would have come about from random sampling effects. The null hypothesis was tested using the likelihood ratio method (Meeker and Escobar, [24]), and it was found that the null hypothesis can be rejected with greater than 99.5 percent confidence, a statistically significant difference.

The preceding text provides a quantitative assessment of the influence of the coating on gear surface fatigue life. One can also make a qualitative comparison to other gear fatigue studies that have been conducted using the same test rigs, the same test procedure, the same gear material, and the same lubricant. Table 7 provides a compilation of gear fatigue test data gathered from references [28–32]. The table is sorted by the measured 10-percent life, except the gears of the present study occupy the last two rows of the table. The measured fatigue lives of the uncoated-baseline gears of the present study are consistent with the historical database for the AISI 9310 gear steel. The coating used for the present study provided for significantly longer surface fatigue lives of the gear tooth surfaces. The coating performance is especially impressive keeping in mind that for the coated gears, eight of the fourteen tests were conducted at a higher Hertzian stress (1.9 GPa) than was the stress (1.7 GPa) for the other tests reported in Table 7.

Figure 5 provides images of the tested gears showing tested surfaces with fatigue failures. The figure shows

### TABLE 5. — Summary of test results

<table>
<thead>
<tr>
<th>Gear type</th>
<th>Hertz stress index (GPa)</th>
<th>Number of tests</th>
<th>Number of failures</th>
<th>Number without failure (after 275×10⁶ revolutions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncoated</td>
<td>1.7</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>coated</td>
<td>1.7</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>8</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

The distributions of the fatigue lives were modeled as 2-parameter Weibull distributions (Weibull, [22] and Hallinan, [23]). The fatigue lives are system lives, the system consisting of two identical gears. Tests that were suspended after pre-specified times showed no signs of impending failure, and so such tests were treated as right-censored life tests for the purpose of statistical analysis. It was decided not to estimate the slope of the coated gear population with only 3 failure data points. Instead, it was assumed that the coated and uncoated gears had life distributions with equal Weibull slope parameters. A likelihood ratio statistical test (Meeker and Escobar, [24]) was used to verify that the assumption of equal slopes was indeed a reasonable assumption. Software employing the maximum likelihood method (Krantz, [25]) was used to estimate the Weibull parameter values from the test data.
typical features of the failed surfaces, and regardless if
the gear was coated or uncoated the pitted teeth had
similar features. For both the uncoated and coated
surfaces, the surface topography changes with running.
The surfaces take on a smoother appearance, and there
is evidence of wear. By subjective evaluation, it appears
that the total amount of wear on the coated surfaces is
less than that of the uncoated surfaces. Because of the
face-offset testing method, there remains in the middle of
a tested gear a thin track of tooth surface that was not in
contact. Tracing across a tested tooth surface using a
soft stylus, one can feel a clear wear step on the
uncoated gears. Such a step could not be detected on
the coated and tested gears. One could speculate that
the longer fatigue lives of the coated gears were a result
of the wear protection offered by the coating. Such a
mechanism has been stated as an explanation for an
increase of fatigue lives for bearings due to providing a
coating to rolling elements of bearings (Olofsson, et al,
Ref. [33]). It has been speculated in the literature that
improved durability of coated surfaces can in some cases
be attributed to a polishing mechanism (Polonsky, et al,
Refs. [34,35]). That is, one can consider that the
surfaces polish one another during initial running. Some
guidance concerning the abrasive and polishing
characteristics of hard coatings can be found in the
literature (Refs. [36-39]). Based on data from these
studies, it is likely that the running-in and polishing of
micro-scale features of the coated surface occurred
during a fraction of the total running times of the gears.

The increased surface fatigue lives due to polishing
(or superfinishing) of uncoated, high quality, ground gears
has been clearly established (Refs. [10, 40, 41]). It has
been speculated that the increase of surface fatigue lives
for superfinished gears might be due to reductions of
asperity interactions (Refs. [10, 42]). It is considered
likely that for coated gears, the changes to the
topography of the tooth surface during running plays an
important role concerning the surface fatigue.

To help characterize the running-in characteristics of
the coated and tested gears, a tested gear was inspected
using a scanning-electron microscope. Figure 6 shows
typical features at three levels of resolution. At low
resolution (Fig. 6[a]), one can see traces of the grinding
marks, indicating that the coating thickness was uniform
enough such that application of the coating did not
significantly change the surface topography. Figure 6(a)
also shows the contact pattern, with the run-in portion of
the surface appearing as slightly darker than the un-run
portion of the surface. Figure 6(b) shows a portion of the
surface of Fig. 6(a) at a somewhat higher resolution. It
appears that the coating has been smoothed and/or
removed (darker areas) along certain grinding-mark
features. Figure 6(c) shows the same portion of the
tooth at a still higher resolution. The spherical shape of
the coating micro-structure is evident, and a portion of
the surface has been smoothed. By using backscatter
electron micrographs and energy dispersive x-ray
spectrums, it was found that in localized areas the coating
had been removed from the surface.

**SUMMARY**

The purpose of the present investigation was to
compare the surface fatigue lives of coated and uncoated
gears using accelerated life tests. The test gears used
were manufactured in one lot from a single heat of
consumable-electrode vacuum-melted (CVM) AISI 9310
steel. The gears were case-carburized and ground to
aerospace quality. A subset of the ground gears was
provided with a thin, hard, low-friction coating by
magnetron sputtering, a physical vapor deposition (PVD)
process. The coating that was applied to the gears was a
metal-containing, carbon-based (Me-DLC) coating. Tests
were conducted using a four-square type gear fatigue rig.
Tests were run until either of surface fatigue failure of any
one gear tooth or until a predetermined number of cycles
had occurred with no failure. The following specific
results were obtained.

1. Fifteen tests were completed using the uncoated
gears using a load intensity corresponding to a
Hertzian stress index of 1.7 GPa (250 ksi).
2. Fourteen tests were completed using the coated
gears. Two load intensities were used for the
coated gears, with six tests conducted at a
Hertzian stress index of 1.7 GPa (250 ksi) and
eight tests conducted at a stress index of 1.9
GPa (280 ksi).
3. For the uncoated gears, all tests resulted in
failure with test durations ranging from 25—272
million revolutions.
4. For the coated gears, three of the tests resulted
in failure while eleven tests were suspended
without failure. The testing durations ranged from
63—311 million revolutions.
5. The distributions of the fatigue lives were
modeled as 2-parameter Weibull distributions.
From the Weibull analysis, the ten-percent lives
of the uncoated and coated gear populations
were estimated to be 28×10^6 and 180×10^6 cycles,
respectively.
6. The measured life difference is a statistically
significant difference to a greater than 99.5
percent statistical confidence.

Figure 5— Typical appearance of failed gear tooth
surfaces. (a) Uncoated gear. (b) Coated gear.
Table 7.—Surface fatigue lives of case-carburized AISI 9310 gear pairs tested in the NASA Glenn Research Center gear fatigue test apparatus. All tests conducted using gears of the same geometry, same heat treat specification, same lubricant, same testing speed of 10 000 r.p.m., and same testing methods.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year published</th>
<th>Material(^a)</th>
<th>10-Percent life, cycles(^b)</th>
<th>50-Percent life, cycles(^b)</th>
<th>Weibull slope</th>
<th>Failure index(^c)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>1982</td>
<td>CVM AISI 9310</td>
<td>19×10^6</td>
<td>46×10^6</td>
<td>2.1</td>
<td>18/18</td>
<td>Ground</td>
</tr>
<tr>
<td>29</td>
<td>1995</td>
<td>CVM AISI 9310</td>
<td>21×10^6</td>
<td>45×10^6</td>
<td>2.4</td>
<td>19/20</td>
<td>Ground</td>
</tr>
<tr>
<td>30</td>
<td>1980</td>
<td>CVM AISI 9310</td>
<td>23×10^6</td>
<td>52×10^6</td>
<td>2.3</td>
<td>30/30</td>
<td>Ground</td>
</tr>
<tr>
<td>28</td>
<td>1982</td>
<td>CVM AISI 9310</td>
<td>30×10^6</td>
<td>68×10^6</td>
<td>2.3</td>
<td>24/24</td>
<td>Ground, shot peened.</td>
</tr>
<tr>
<td>31</td>
<td>1992</td>
<td>VIM-VAR AISI 9310</td>
<td>42×10^6</td>
<td>140×10^6</td>
<td>1.6</td>
<td>14/20</td>
<td>Ground, medium-intensity shot peened</td>
</tr>
<tr>
<td>32</td>
<td>1989</td>
<td>VIM-VAR AISI 9310</td>
<td>48×10^6</td>
<td>200×10^6</td>
<td>1.3</td>
<td>24/33</td>
<td>Ground</td>
</tr>
<tr>
<td>31</td>
<td>1992</td>
<td>VIM-VAR AISI 9310</td>
<td>89×10^6</td>
<td>250×10^6</td>
<td>1.9</td>
<td>13/20</td>
<td>Ground, high-intensity shot peened</td>
</tr>
<tr>
<td>N/A</td>
<td>2003</td>
<td>CVM AISI 9310</td>
<td>28×10^6</td>
<td>83×10^6</td>
<td>1.7</td>
<td>15/15</td>
<td>Ground (present study, baseline)</td>
</tr>
<tr>
<td>N/A</td>
<td>2003</td>
<td>CVM AISI 9310</td>
<td>180×10^6</td>
<td>530×10^6</td>
<td>1.7</td>
<td>3/14</td>
<td>Ground and coated (present study)</td>
</tr>
</tbody>
</table>

\(^a\)CVM indicates consumable-electrode vacuum-melted; VIM-VAR indicates vacuum-induction-melted + vacuum-arc-remelted

\(^b\)The 10-percent and 50-percent lives are those obtained by fitting the test data to two-parameter Weibull distributions. The lives are system lives, the system being a pair of gears.

\(^c\)Indicates the number of failures out of the number of tests. The durations of tests suspended without failure were in the range 275–330×10^6 cycles.

Figure 6 – Scanning electron images of a coated and tested gear. (a) Low resolution image showing the contact pattern (slightly darker area) and grinding patterns. The left portion of the image is the fillet and root region, and the tip of the gear is out of the field-of-view toward the right. (b) Medium resolution image of the region near the low-point of contact on the tooth. (c) High resolution image from an area of figure 6(b) showing the spherical micro-topography of the coating and smoothing of an asperity ridge.
REFERENCES


Increased Surface Fatigue Lives of Spur Gears by Application of a Coating

Timothy L. Krantz, Clark V. Cooper, Dennis P. Townsend, and Bruce D. Hansen

Hard coatings have potential for increasing gear surface fatigue lives. Experiments were conducted using gears both with and without a metal-containing, carbon-based coating. The gears were case-carburized AISI 9310 steel spur gears. Some gears were provided with the coating by magnetron sputtering. Lives were evaluated by accelerated life tests. For uncoated gears, all of fifteen tests resulted in fatigue failure before completing 275 million revolutions. For coated gears, eleven of the fourteen tests were suspended with no fatigue failure after 275 million revolutions. The improved life owing to the coating, approximately a six-fold increase, was a statistically significant result.