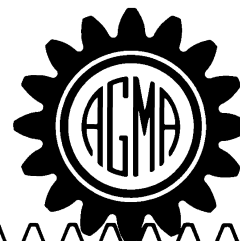


Grinding Induced Changes in Residual Stresses of Carburized Gears

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American Gear Manufacturers Association



TECHNICAL PAPER

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Robert LeMaster, Bryan Boggs and Jeffrey Bunn, University of Tennessee and Camden Hubbard and Thomas Watkins, Oak Ridge National Laboratory

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Carburizing is a commonly used method for increasing the strength and wear resistance of gearing. A significant benefit of the carburization process is that compressive residual stresses are developed near the surface due to phase transformations that occur during the post carburization heat treatment steps. After carburization and heat treatment it is necessary to finish the gear by processes such as grinding or skiving. These finishing processes develop the precise geometric form required while improving the surface finish. Finishing processes change the residual stress imparted by carburization and subsequent heat treatment. Residual stresses change during the finishing process due to the removal of material and stresses induced from the machining operation.

This paper presents the results of a study performed to measure the change in residual stress that results from the finish grinding of carburized gears. Residual stresses were measured in five gears using the x-ray diffraction equipment in the Large Specimen Residual Stress Facility at Oak Ridge National Laboratory. Two of the gears were hobbled, carburized, quenched and tempered, but not finished. The remaining three gears were processed similarly, but were finish ground. The residual stresses were measured at 64 different locations on a tooth from each gear. Residual stresses were also measured at fewer points on other teeth to determine the tooth-to-tooth variation. Tooth profile measurements were also made of the finished and unfinished gear samples.

The results show a fairly uniform and constant compressive residual field in the nonfinished gears. There was a significant reduction in the average residual stress measured in the finished gears. Additionally, there was a significant increase in the variability of the residual stress that was introduced by the grinding process. Large variations were observed in both the lateral and longitudinal directions on a tooth surface. Analysis of the data suggests a linear relationship between the change in average residual stress and the amount of material removed by the grinding process.

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Introduction

Carburizing is a commonly used method for increasing the strength and wear resistance of gearing. A significant benefit of the carburization process is that compressive residual stresses are developed near the surface due to phase transformations that occur during the post carburization heat treatment steps. After carburization it is necessary to finish the gear by processes such as grinding or skiving. These finishing processes develop the precise geometric form required while improving the surface finish. Finishing processes change the residual stress imparted by carburization and subsequent heat treatment processes. These changes are due to the removal of material and the associated rebalancing of the residual stresses and the introduction of near surface residual stresses by the machining operations.

A grinding allowance is used to specify the amount of material to be left on a machined gear prior to heat treatment. This excess material and any material associated with a geometry change during heat treatment are removed by the finishing process. The magnitude of this grinding allowance will affect the strength, fatigue life, and wear resistance of the finished gear because of its relationship to changes in the residual stresses. Removal of the excess material will also remove any retained Austenite located in the layer removed.

This paper presents the results of a study performed to measure and quantify the change in residual stress that results from the finish grinding of carburized gears. Residual stresses were measured in five gears using x-ray diffraction equipment in the Residual Stress User Center at Oak Ridge National Laboratory. Two of the gears were hobbled, carburized, quenched and tempered, but not finished. The remaining three gears were processed similarly, but were finish ground. The residual stresses were measured at sixty-four locations on a randomly selected tooth from each gear. Residual stresses were also measured at fewer

points on other teeth to determine the tooth-to-tooth variation. Tooth profile measurements were also made of the finished and unfinished gear samples.

Test gears

The three finish ground samples were designated as Finished 1, 2, and 3. The two remaining unfinished samples were designated as Unfinished 1 and 2. Each gear had twenty-five teeth, a diametral pitch of 4 teeth/inch, a pressure angle of twenty degrees, full radius fillets, no addendum modification, and a face width of 0.75 inch. The gears were flat with no ribs, rims, or other weight reduction features (Figure 1).



Figure 1. A typical finished gear. This gear is designated Finished 1.

The measurement of residual stresses in gear teeth using x-ray diffraction is complicated by the curvature of the involute and trochoid geometries and the potential for interference of the incident or diffracted beam by adjacent teeth. The size of the gears used in this study was chosen so that the residual

stresses could be measured over most of the tooth surface.

Most of the residual stresses measured were in the longitudinal direction of the gear tooth (Figure 2). A few residual stress measurements were also made in the lateral direction. The sixty-four locations on a tooth from each sample where residual stresses were measured are shown in Figure 3. There are eight lateral locations associated with each radius. The lateral locations are spaced 0.079 inch apart. Residual stress measurements were not made at the critical bending stress location in the fillet. This was due to the high curvature in the fillet area and interference with the incident or refracted beam path from adjacent teeth.

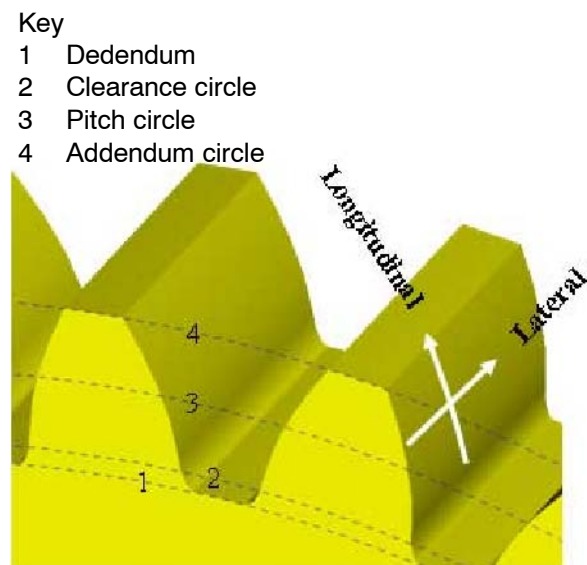


Figure 2. Longitudinal and lateral tooth directions on tooth.

The gear blanks for each sample were taken from the same length of 8620H bar stock. The steps used in the fabrication of the samples are listed in Table 1. The time at temperature for the normalize, stress relief, and defuse steps was based on 1 hour per inch of thickness. The carburization step was done using an 80–90% natural gas derived endothermic gas atmosphere. Test slugs were pulled during the carburization step to verify an effective case depth of 0.030 inch. The final surface hardness was determined to be within the range of 58–62 HRC. The finish grinding was done using a vitrified alumina grinding wheel on a CNC grinder.

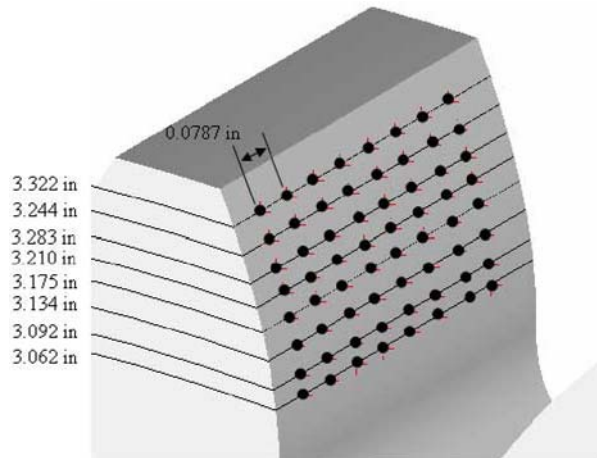


Figure 3. Radial and lateral locations where the residual stress measurements were made.

Table 1. Fabrication steps.

1. Rough machine	
2. Normalize	(1740 °F)
3. Stress relief	(1250 °F)
4. Finish machine	
5. Carburize	(1650 °F)
6. Defuse	(1550 °F)
7. Oil quench	(135 °F)
8. Temper	(450 °F)
9. Finish grind	

The profiles of each sample were measured using a Coordinate Measuring Machine (CMM) at Oak Ridge National Laboratory. The profiles were measured at three lateral locations on each sample. There was no discernable difference between the three lateral measurements for each sample when the measurements were superimposed. The profiles measured at the first lateral location on the five samples are compared in Figure 4. There was virtually no discernable difference between the measured profiles of the samples designated Unfinished 1 and Unfinished 2. There was also little noticeable difference between the samples designated Finished 1 and Finished 2. However, the gear designated Finished 3 had noticeably more material removed at the tip than did gears Finished 1 and Finished 2. At the pitch circle all of the finished samples were virtually the same.

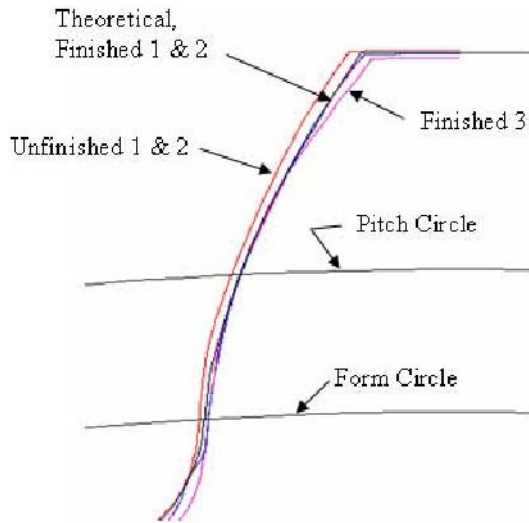


Figure 4. Comparison of the measurement profiles of the finished and unfinished gears.

Figure 5 shows the grind depth versus radius for each of the finished samples. The grind depth reported is the perpendicular distance from the unfinished profile to the finished profile (Figure 6). The increased tip relief observed in the sample designated Finished 3 is quite noticeable. With the exception of the tip relief found in Finished 3, the grind depth is similar for all radii greater than the form radius. The material removed at the pitch circle by grinding ranged from 0.0082 to 0.0085 inch (0.208 to 0.216 mm).

X-ray diffraction measurements

Residual stress measurements were made using the Model 1600 TEC diffractometer in the Residual Stress User Center at Oak Ridge National Laboratory. The residual stress measurements involved measuring the inter-atomic spacing (d-space) between atoms for the (211) crystal plane at different x-ray beam incident angles (ψ) [1]. The measured d-space is the average value for a group of properly oriented grains near the irradiated surface. The residual stress was determined using the $\sin^2 \psi$ technique [2]. In this method d-space is plotted as a function of $\sin^2 \psi$. The y-intercept of the plot was taken as the unstrained d-space (d_0) with the slope being proportional to the residual stress. A 2 mm (0.079 inch) diameter collimator, vanadium filter, and $K\alpha$ radiation from a chromium x-ray target were used. Figure 7 shows a picture of a portion of the diffractometer and one of the samples mounted in

the diffractometer. On average, ten ψ -angles with a two-degree oscillation were used at each radial location. As seen in Figure 7, black electrical tape was used to cover neighboring teeth to eliminate any radiation scattered from them. Figure 8 provides an example of a typical d-space versus $\sin^2 \psi$ plot.

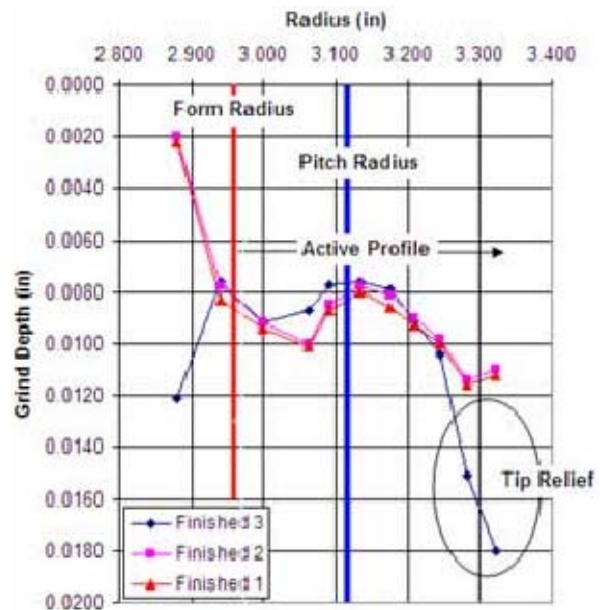


Figure 5. A comparison of the grind depth versus measurement radii for the three finished gears.

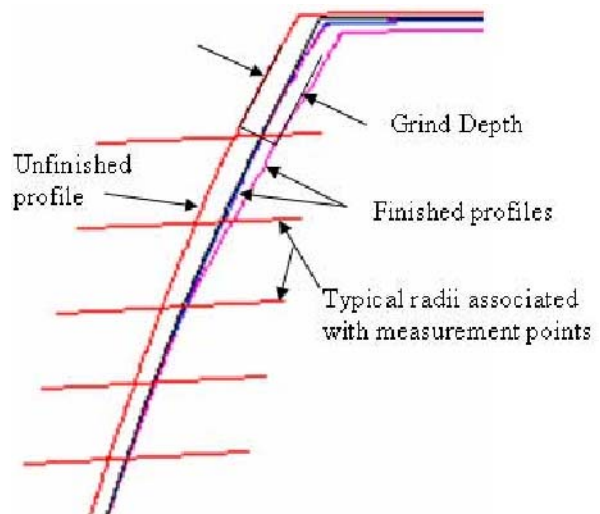


Figure 6. Grind depth is the difference between the unfinished and finished tooth surfaces measured normal to the finished gear tooth surface.