RESIDUAL STRESS DEPTH PROFILES OF AUSROLLED 9310 GEAR STEEL

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ABSTRACT

Residual Stress analysis utilizing x-ray diffraction in conjunction with material removal by chemical polishing provides a very effective method of analyzing the near surface residual stress profile of steels. In this experiment, residual stress profiling has been used to analyze the effects of surface ausrolling during the marquenching of a 9310 gear steel which has been carburized to 1% carbon. The ausrolling process is an advanced thermomechanical processing technique used to ausform only the critical surface layer of gears and produce a hard, tough, fine-grained martensitic product. This study compares the residual stress profile of a marquenched specimen with a moderately deformed ausrolled specimen and with a heavily deformed ausrolled specimen, in order to correlate the effects of residual stress with the improved fatigue properties of the gear steel. While no significant variation was observed between the residual stress profile of the marquenched specimens (no deformation) and the line contact ausrolled specimens (moderate deformation), significant increases in the amount of compressive residual stress was noted in the residual stress profile of the point contact ausrolled (heavily deformed) samples. The maximum increase in compressive residual stress due to point contact ausrolling was approximately 500 MPa, when compared to the marquenched sample. This increased residual compressive stress will lower the effective shear stresses during rolling contact fatigue and would therefore explain some of the increase the rolling contact fatigue endurance of the point contact ausrolled specimens.

Keywords: ausforming, ausrolling, gears, marquenching, x-ray diffraction, residual stress, retained austenite

INTRODUCTION

It has been well established that ausforming produces improved material responses in certain steels. Under proper conditions, the ausforming process transforms the high carbon steel into a very fine grained martensitic structure, with inherited dislocation networks and ultrafine carbide precipitates, that exhibits high strength and toughness[1,2]. However, the bulk ausforming is cost prohibitive for many applications, since extensive bulk deformation at elevated temperatures of anything except a very small simple part would require enormous and costly machines, substantial energy requirements to run the machines, and continual die maintenance. By eliminating the need for deformation of the entire bulk of the gear, ausrolling brings ausforming to a feasible and cost effective option for gears. The superior martensitic product formed by ausrolling has been shown to

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improve the rolling contact fatigue resistance of 9310 gear steel carburized to 1% carbon, and is also expected to improve the bending fatigue resistance of the gear steel[3]. By improving the rolling contact and bending fatigue resistance (both significant causes of gear failure), industrial and defense gear applications could benefit from: improved gear life, smaller and/or lighter gears, and improved gear performance. This study examines the residual stress and retained austenite profiles of three specimen groups (marquenched, point contact ausrolled, line contact ausrolled), so that the effects of residual stress and retained austenite can be incorporated into fatigue endurance analysis.

EXPERIMENT

Three sets of specimens were prepared as part of a larger study on the effects of ausrolling on the fatigue response of UNS G93106 steel carburized to 1% carbon: point contact ausrolled specimens, line contact ausrolled specimens, and marquenched specimens. Unless otherwise noted, the specimen preparation steps below apply to all specimens; the only difference between the three final sets of specimens is the degree of deformation that was induced in each set of specimens during the ausrolling stage.

All specimens were machined from pieces of 35 mm UNS G93106 bar stock obtained from a single melt. Specimens were machined to produce a cylindrical test section 25 mm long and 25 mm in diameter along with extra material which would be used to grip the test section in the subsequent thermomechanical processing and fatigue testing. After machining, the specimens were vacuum carburized to a surface carbon content of 1% C, a surface hardness after final quench and temper of 60-62 HRC, an effective case depth of 2.0 mm to 2.3 mm to 50 HRC, and a total case depth of 3.1 mm to 3.4 mm to 0.4% C. The specimens were then divided into three groups for the ausrolling stage: one group to be marquenched, one group to be line contact ausrolled, and one group to be point contact ausrolled. The specimens were processed individually using the single die ausrolling machine at the National Center for Advanced Drivetrain Technology at Penn State's Applied Research Laboratory. Each specimen was surface induction heated in a nitrogen flooded atmosphere to 885 °C to austenitize the specimen. Next, each specimen was quenched into a 232 °C oil bath, so that the austenitized material could be maintained as metastable austenite during the subsequent processing (Figure 1). For the line contact ausrolled specimens, a cylindrical die rotating at 380 rad/min was fed radially into the freely rotating specimen until an infeeding force 22 kN was achieved (Figure 2a). For the point contact ausrolled specimens, a crowned cylindrical die rotating at 380 rad/min was fed radially into the freely rotating specimen until an infeeding force of 22 kN was achieved; the die was then through-fed along the axis of the specimen while maintaining the 380 rad/min rotational velocity and the 22 kN infeeding force (Figure 2b). Since the same loads were used during both line contact ausrolling and point contact ausrolling, the line contact ausrolled specimens received only a moderate amount of deformation (the force was spread over the entire line of contact), while the point contact ausrolled specimens received a relatively heavy amount of deformation (the force was concentrated at the point of contact). For the marquenched specimens, no deformation was induced during the ausrolling stage, but to ensure the same thermal history for all specimens the marquenched specimens were held in the 232 °C oil tank for 5 minutes (the amount of time it takes to ausroll the specimens). Following the ausrolling process, the specimens were removed from the 232 °C oil tank and quenched in room temperature water. The specimens were then sent out to be tempered at 150 °C for one hour followed by a liquid nitrogen quench, and another one hour temper at 150 °C.

Figure 1 Thermomechanical processing history of 9310 steel carburized to 1.0% carbon and its relation to isothermal transformation structures

Figure 2 Ausrolling die configurations for: a. cylindrical die, line contact mode, and; b. crowned cylindrical die, point contact mode.

All x-ray diffraction measurements were carried out at Oak Ridge National Laboratories' (ORNL) High Temperature Materials Laboratory (HTML) using a Scintag PTS 4-axis goniometer with a chromium x-ray tube (operating at 45 kV and 40 mA) and a solid state detector. A cylindrical collimator with a diameter of 2 mm and a divergence of 0.1° was used. For the residual stress measurements, each specimen was scanned over the angular range: 2θ from 148° to 164° $\{(211+112)$ martensite reflection at approximately $2\theta = 155.3^\circ\}$ with a step of 0.1° and a hold time of 10 seconds, and seven sample tilts in the range χ from -45 to 45 (equal steps in $\sin^2 \chi$) were used

in two perpendicular directions on the sample surface (hoop and axial directions). The resulting peaks were analyzed using a Pearson VII fit with Scintag's peak fit software to determine the 2θ position and the calculated deviation. The 2θ positions were then entered into a spreadsheet which calculated the residual stresses using the Dölle and Hauk solution (assuming a biaxial stress state) [4]. Since all specimens were identical in composition and identical in carburization profile, an averaged value of the d_0 (d_0 is the unstressed lattice spacing) results at each depth was used to calculate the residual stress at that depth. The variation in d_0 is caused by the variation in carbon content with depth due to carburization of the surface. Estimation of the standard deviation was carried out using a residual stress least squares analysis program developed at the HTML. Material removal was accomplished using chemical etching in a stirred room temperature solution (170 ml water, 20 ml Hydrofluoric Acid, and 30 ml Hydrogen Peroxide). Residual stress data was not corrected for the layer removed.

Retained austenite was measured using Cu K α radiation. For the analysis, the (200) austenite peak at approximately $2\theta = 75^\circ$ and the martensite doublet (211)(112) at $2\theta = 82^\circ$ were used. A range of $10^\circ 2\theta$ around each peak was scanned, with a step of 0.6° and a data collection time of 10 sec/step. The analysis of the retained austenite content was carried out using the algorithm described by Cullity [5].

RESULTS

The stress results of the x-ray diffraction depth analysis are shown in Figures 3 and 4. The figures show that the hoop stresses and axial stresses are similar: the results are nearly identical when the calculated error for each point is taken into account. The marquenched specimens showed little variation from the moderately deformed line contact ausrolled specimens in either the hoop stress or axial stress calculations. However, the heavily deformed point contact ausrolled specimens exhibited consistently higher compressive stresses than either the marquenched or line contact

Figure 3 Residual Hoop Stress Profiles

Figure 4 Residual Axial Stress Profiles

ausrolled specimens up to a depth of approximately 1600 microns. At the surface of the specimen, the point contact specimen showed approximately five times the residual compressive stress of the marquenched specimen, with a 400 MPa difference between the two specimens. At the point of maximum difference between the point contact ausrolled and the marquenched specimens, the point contact specimens had almost 500 MPa more residual compressive stress than the marquenched specimens. The 500 MPa difference translates to approximately 3.5 times more residual compressive stress in the point contact specimen than in the marquenched specimen at the 375 micron depth. The results indicate that the residual stress state is similar for the marquenched and the moderately deformed line contact ausrolled specimens, while the heavily deformed point contact specimen contains significantly higher compressive residual stresses.

The retained austenite analysis for the specimens is shown in Figure 5. The error in calculating the amount of retained austenite was estimated from measurements on NIST standards and is $\pm 3\%$

Figure 5 Retained Austenite Profiles

retained austenite. The heavily deformed point contact ausrolled specimen has the lowest percentage of retained austenite on the surface of the specimen, followed by the marquenched and line contact ausrolled specimens, respectively. Also of note, the percentage of retained austenite for the point contact ausrolled specimen decreases toward the surface, while the percentage of retained austenite increases toward the surface for the marquenched and line contact ausrolled specimens.

DISCUSSION

An initial set of x-ray diffraction experiments showed that there were no significant variations in the surface residual stress within each group of specimens, nor were there any significant variations in the surface residual stress around the circumference of each specimen. The lack of variation was expected since the specimens within each group were processed identically and the circular symmetry of the specimens should produce uniform deformation around the circumference of the specimens. Once it was established that there was little variation between specimens within a group and little difference between points on each specimen, it was decided that a residual stress profile from a representative specimen from each group would be sufficient to represent the overall trends for this preliminary study. Furthermore, full triaxial stress analysis of the surface of each of the three sample groups indicated that a biaxial approximation of the surface stress state would be sufficient.

As expected, the results show an increase in the compressive residual stress with increased deformation: the heavily deformed point contact ausrolled specimen showed significantly greater near surface compressive stress than either the moderately deformed line contact ausrolled specimen or the undeformed marquenched specimen. However, greater difference was expected to exist between the marquenched and the line contact specimen: the residual stress profile for the line contact ausrolled specimen did not show any significant or consistent variation from the residual stress profile of the marquenched specimen.

While the residual stress profile for the line contact ausrolled specimens did not vary significantly from the residual stress profile of the marquenched specimens, a previous study by Lange [3] did show that line contact ausrolled specimens exhibited an improved rolling contact fatigue endurance when compared to marquenched specimens. The lack of differentiation between the residual stress profiles of the marquenched specimen and line contact ausrolled specimen may be due to the fact that the line contact specimen receives only a moderate degree of surface deformation during the ausrolling process; the moderate deformation may not significantly alter the residual stress state. Since the data from the current study indicates that the residual stress state in the line contact ausrolled specimens is not significantly different than the residual stress states in the marquenched specimens, the improved rolling contact fatigue endurance observed by Lange in the line contact specimens is likely to be caused by the microstructural changes induced by the ausrolling process (a detailed description of these changes is provided in the introduction). It appears that significant changes in the residual stress state require the significant amounts of ausrolling (deformation) induced into the point contact ausrolled specimens.

Significant differences were noted in the residual stress profile of the point contact ausrolled specimen relative to the baseline marquenched specimen. Therefore, unlike the line contact ausrolled specimens, the notably higher residual compressive stress levels found in the point contact ausrolled specimens can be used to account for some of the measured increase in the rolling contact fatigue endurance of the point contact ausrolled specimen when compared to the marquenched specimens. The significantly greater residual compressive stresses in the point contact ausrolled specimen

would reduce the magnitude of the effective shear stresses in the specimens during rolling contact fatigue. By lowering the effective shear stresses, the increased residual compressive stresses retard crack initiation and slow crack propagation. The exact amount of increase in rolling contact fatigue life caused by the residual stress will depend on the yield strength of the material and the loading conditions of the specimen, neither of which are available at the present time. Further work in the study of these specimens is being carried out to determine the yield strength of the three specimen groups (point contact ausrolled, line contact ausrolled, and marquenched) and the optimal loading conditions for rolling contact fatigue testing. At this point, however, it can be noted that the influence of the residual stress will have a greater impact at lower RCF loadings: the residual stress would be more significant relative to the maximum stress. Also of note, previous residual stress evolution studies using another gear steel indicate that there are minimal changes in the residual stress state as the material is cycled to failure [6].

The amount of retained austenite on the surface is the lowest for the point contact specimen and the amount of retained austenite appears to decrease toward the surface for the point contact specimen. This may mean that the amount of retained austenite is reduced by the heavy deformation occurring during point contact ausrolling, producing a strain induced transformation.

CONCLUSION

While no significant variation was observed between the residual stress profile of the marquenched specimens (no deformation) and the line contact ausrolled specimens (moderate deformation), significant increases in the amount of compressive residual stress was noted in the residual stress profile of the point contact ausrolled (heavily deformed) samples. The maximum increase in compressive residual stress due to point contact ausrolling was approximately 500 MPa, when compared to the marquenched sample. This increased residual compressive stress will lower the effective shear stresses during rolling contact fatigue and would therefore explain some of the increase the rolling contact fatigue endurance of the point contact ausrolled specimens studied by Lange[3]. The precise impact of the residual stress will be determined once additional mechanical analysis of the specimens is completed.

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