Nondestructive Residual Stress Distribution Measurement in Nanostructured Ultrahigh-Strength Gear Steels

Y. Qian[1], J. Almer[2], U. Lienert[2], B. Tiemens[1], G.B. Olson[1]

[1]Northwestern University, Evanston, IL U.S.A.; [2] Argonne National Laboratory, Argonne, IL, U.S.A

Introduction

The well-established enhanced fatigue performance associated with beneficial compressive residual stresses has been broadly applied in the development of new engineering materials, particularly gear and bearing steels. Residual stress enhancement processes, such as shot/laser peening, have also been investigated to maximize their benefits on fatigue strength [1]. However, the measurement of residual stress distributions still heavily relies on the conventional X-ray technique, involving destructive material removal, tedious data correction and time-consuming data collection, which slows new material design and process optimization. To overcome this problem, we employ novel, non-destructive synchrotron techniques with high-energy x-rays to measure the distribution of residual strain/stress in a laser-peened, ultrahigh-strength gear steel [2-3]. This study will assist in process optimization, to achieve the desired residual stresses for selected applications.

Methods and Materials

X-ray measurements were performed at the 1-ID beamline at the Advanced Photon Source (APS), Argonne National Laboratory. An x-ray energy of 76 keV and conical slit were used to create a diffraction volume of ~$20\times20\times150\mu m^3$. An area detector was placed after the conical slit to collect diffraction over a plane encompassing (nearly) the axial and normal strain directions. Cylindrical specimens (76 mm long, 9.525 mm diameter) were rotated during the measurement to ensure a sufficiently large number of grains were irradiated. The steel, FerriumC67®, was designed utilizing thermodynamics-based strengthening models to achieve a new level of case hardness (67 HRc) and good core toughness, employing a 3nm M_2C carbide dispersion [4]. After heat treatment, C67 was laser peened and subject to rolling contact fatigue (RCF) screening tests under the extreme Hertzian contact stress of 5.4 GPa. Both regions away from ('untested') and under wear tracks were studied for comparison.

Results

Four BCC reflections from martensite [(200), (211), (220) and (222)] were recorded and (211) was used for residual strain analysis. Strain components (ε_{11}, ε_{12} and ε_{22}) were obtained and the axial (ε_{11}) is plotted in Fig. 1 for unpeened and laser peened C67 samples. Large compressive axial strains were observed near-surface after peening. After cyclic loading the surface strain relaxed but a sub-surface maximum was formed, attributed to yielded material from the extreme cyclic loading [5]. These strains were converted to stresses (not shown) via elastic constants and assuming equibiaxial strain ($\varepsilon_{33}=\varepsilon_{11}$).

Discussion

Residual strains for a shot peened steel similar to C67 were also measured. Comparison between ε_{11} profiles indicates both shot and laser peening can induce large compressive strains (-3~4×10^{-3}) at the material surface but the effective depth from laser peening (~300 μm) is twice as deep as from shot peening (150 μm). Thus laser peening is more favorable for subsurface fatigue resistance. Substantial surface strain relaxation was also observed in the shot peened steel. These results show that the extreme loading conditions of the RCF screening test are significantly altering the material and therefore not a useful indicator of material performance under normal service conditions. Residual stress profiles show that -1.5 GPa has been achieved at the depth of 25 μm for laser peened C67. However, even higher compressive stresses are expected by further optimizing the peening process.

The nondestructive synchrotron technique makes it possible to keep specimens intact for subsequent evaluations such as fatigue tests. Accuracy was also improved by avoiding material removal and data correction. Moreover, the nondestructive character enables the unique strain/stress analysis on wear tracks. The use of a conical slit significantly accelerates the measurement by defining a 3D probe size while allowing for simultaneous strain measurement in two directions, compared to using conventional linear slits and point detection. Therefore the technique employed here can greatly benefit process optimization for desired residual stresses.

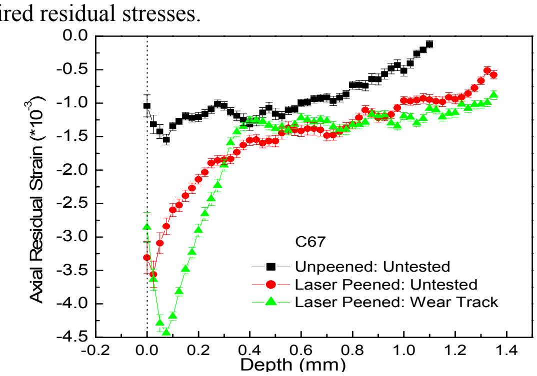

Fig. 1 Residual strain profiles for C67

Acknowledgments

The authors would like to thank Marcus Young for assistance inthe experiment, and QuesTek Innovations Inc. for providing samples. This work is supported by the DOE, Office of Industrial Technologies. Use of the APS was supported by the DOE, Office of Science, Office of Basic Energy Sciences, under contract no. W-31-109-Eng-38.

[1] B. A. Shaw, C. Aylott, et al., Int. J. Fatigue **25**, 1279 (2003)
[2] S. F. Nielsen, A. Wolf, et al., J. Synchrotron Rad. **7**, 103 (2000)
[3] R. V. Martins, U. Lienert, et al., J. Neutron Res. **9**, 249 (2001)
[4] C. J. Kuehmann, G. B. Olson, Adv. Mater. Process. **5**, 40 (1998)
[5] A. P. Voskamp, R. Osterlund, et al., Metals Technol. **Jan.**, 14 (1980)