Measuring Residual Stress in Gears

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QUESTION #2

I have heard that X-ray diffraction does not tell the whole story and that I should really run a fatigue test. I understand this may be the best way, but is there another method that gives a high degree of confidence in the residual stress measurement?

Expert response provided by Robert Errichello:

X-ray diffraction (XRD) analysis is the accepted quantitative method for determining residual stresses. Other methods such as dissection, hole drilling, ultrasonic, and Barkhausen noise analysis are either not quantitative or do not have sufficient spatial or volumeric resolution to adequately characterize residual stress distributions.

XRD measures the lattice spacing (d-spacing) between atoms; you can think of XRD as a strain gage. Tensile stress increases d-spacing and compressive stress decreases d-spacing. Hence, XRD actually measures strain and the residual stresses producing the strain are calculated assuming a linear, elastic deformation of the crystal lattice. The elastic constants (modulus of elasticity, E, and Poisson's ratio, ν) must be known or determined empirically (Ref. 1) to calculate residual stresses from measured strains.

Additionally, XRD analysis has the capability to detect the FCC phase of austenite, the BCC phase of ferrite, and the BCT phase of martensite, because each phase has different d-spacing. Therefore XRD is a quantitative method that is considered to be the most accurate method to determine the amount of retained austenite. Fatigue life, fracture toughness, and machinability are all strongly influenced by the percent-retained austenite. So if you are concerned with these properties, you need to know the amount of retained austenite.

Generally, tensile residual stresses are detrimental, and compressive residual stresses are beneficial to fatigue strength. Classic bending fatigue cracks originate at the surface of the root fillet in gear teeth. XRD analysis can measure the surface residual stresses non-destructively at the surface of the root fillet and allow you to determine whether the residual stresses are sufficiently compressive. If not, shot peening can be used to increase the compressive residual stresses.

If Hertzian fatigue life is important, you need to know the subsurface residual stress profile — in addition to the surface residual stresses — because the controlling stresses are subsurface. Unfortunately, XRD analysis can only measure subsurface residual stresses destructively by successively removing layers of the surface by electrolytic polishing, which tends to be slow and costly. Nevertheless, the subsurface profile of residual stresses strongly influences the Hertzian fatigue strength and you need to assess their values if you wish to determine the resistance to Hertzian fatigue. Furthermore, if you are interested in the crack propagation phase of bending fatigue, the subsurface residual stresses are important.

XRD is an indispensible tool for failure analysis. For example, it is used to investigate changes in residual stress profiles in Hertzian contacts in gears and rolling element bearings that are caused by Hertzian stresses that exceed the yield strength in local areas beneath the surface. Generally, residual compressive stresses increase with rising Hertzian stress, and are displaced to greater depths. By comparing the residual stresses in failed components to those of unused components, one can draw conclusions about the actual Hertzian stress that acted on the failed component.

XRD is also very helpful in understanding why different materials and heat treatments lead to different fatigue strengths. For example, Reference 2 showed that carburized bearings are more durable than through-hardened bearings in wind turbine gearboxes because carburized bearings have higher compressive, residual stresses and greater amounts of retained austenite.

Applications for XRD analysis include:

- ***Materials research.*** For example, characterizing surface and subsurface residual stresses and retained austenite profiles in through hardened, surface hardened, and case hardened gear teeth and rolling element bearing raceways.
- ***Process quality control.*** For example, determining surface compressive stresses produced by shot peening, tensile residual stresses produced by abusive grinding, or alterations of residual stresses caused by stress-relieving heat treatment. In general, surface and subsurface residual stress profiles are required to fully characterize effects of heat treatment, machining, grinding, shot peening, and other manufacturing processes.
- ***Failure analysis***. For example, investigating whether residual stresses and retained austenite meet quality specifications and whether residual stresses were altered due to loading, plastic deformation, or thermal stressing.
- ***Fracture mechanics damage tolerance***. Near surface and subsurface residual stresses control the growth of fatigue cracks and need to be considered when estimating damage tolerance.

X-ray residual stress measurements being made on a pinion by the Xstress Robot by Stresstech Group.

Limitations of XRD analysis include:

- Line of sight is required for the X-ray beam.
- Only a shallow layer (< 10 μm deep) is measured.
- Subsurface surveys are destructive (require electrolytic polishing).
- The sample must have reasonably fine grains that are not severely textured.
- The elastic constants of the material must be known.

References

1. ASTM E1426. "Standard Test Method for Determining the X-Ray Elastic Constants for Use in the Measurement of Residual Stress Using X-Ray Diffraction Techniques."
2. Errichello, R., R. Budny and R. Eckert. "Investigations of Bearing Failures Associated with White Etching Areas (WEAs) in Wind Turbine Gearboxes," *Tribology Transactions,* Vol. 56, No.6, 2013, pp. 1069-1076; (also published in *Power Transmission Engineering,* March 2014, pp. 38-44).

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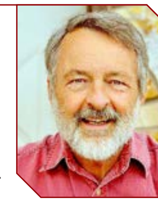

Robert Errichello heads his own gear consulting firm, GEARTECH, and is founder of GEARTECH Software, Inc. He has over 50 years of industrial experience. He has been a consultant to the gear industry for the past 37 years and to over 50 wind turbine manufacturers, purchasers, operators, and researchers. He has taught courses in material science, fracture mechanics, vibration, and machine design at San Francisco State University and the University of California at Berkeley. He has presented numerous seminars on design, analysis, lubrication, and failure analysis of gears and bearings to professional societies, technical schools, and the gear, bearing, and lubrication industries. A graduate of the University of California at Berkeley, Errichello holds BS and MS degrees in mechanical engineering and a Master of Engineering degree in structural dynamics. He is a member of several AGMA Committees, including the AGMA Gear Rating Committee, AGMA/AWEA Wind Turbine Committee, ASM International, ASME Power Transmission and Gearing Committee, STLE, NREL GRC, and the Montana Society of Engineers. Bob has published over 80 articles on design, analysis, and application of gears, and is the author of three widely used computer programs for design and analysis of gears. He is technical editor for GEAR TECHNOLOGY and STLE Tribology Transactions. Errichello is recipient of the AGMA TDEC Award, the AGMA E.P. Connell Award, the AGMA Lifetime Achievement Award, the STLE Wilbur Deutch Memorial Award, the 2015 STLE Edmond E. Bisson Award, and the AWEA Technical Achievement Award.