

# **X-RAY DIFFRACTION CHARACTERIZATION OF THE RESIDUAL STRESS AND HARDNESS DISTRIBUTIONS IN INDUCTION HARDENED GEARS**

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## **ABSTRACT**

Accurate knowledge of the subsurface residual stress and hardness distributions is required for failure analysis, fatigue life prediction and process control of induction hardened components. X-ray diffraction (XRD) provides a powerful tool for the simultaneous determination of both the macroscopic residual stress and hardness distributions through the case and into the core of induction hardened parts. A procedure for developing the empirical relationship between diffraction peak width and mechanical hardness is described.

Subsurface XRD residual stress measurement requires layer removal and correction for the resulting stress relaxation. The corrections may dominate the results obtained at depths near the case/core interface. Traditional closed-form corrections may be inadequate when applied to gear teeth. A novel finite element analysis (FEA) correction technique applicable to arbitrary geometries and stress distributions is presented and described. Examples of the determination of the residual stress and hardness distributions through the case of induction hardened gears are presented.

## **INTRODUCTION**

Hardening of steel requires heating the steel to a temperature above its austenitic transformation point followed by quenching at a rate faster than the critical cooling rate. The critical rate depends upon the chemistry of the alloy. Following the quenching operation the steel should contain a hard martensitic phase which will form only in the thin case of carburized or induction hardened parts. The swelling that occurs during the martensitic phase transformation

will generally produce a compressive residual stress distribution in the case. Compressive residual stresses at the surface can increase fatigue life and decrease the likelihood of failure under high applied stresses. However, residual stresses produced by hardening depend upon the component geometry, and can vary greatly in magnitude or even become tensile under certain combinations of hardening parameters and geometry, degrading component life.

In the induction hardening process a surface layer is heated using a high frequency power supply and shaped coil. The temperature distribution and depth of the heated layer can be controlled by varying the frequency, time, and coil geometry. Following heating, the component is quenched in either air or liquid medium. Because the heating coils can be shaped to vary the area heated, induction hardening lends itself to components which require localized hardening or irregular geometries. Efficient use of material can be achieved by hardening localized areas of a component. A precise case depth can also be achieved with the induction hardening process, and induction heating offers higher energy fluxes than furnace carburizing.

Gears are frequently induction hardened. Because induction hardening produces minimal distortion, the gears can generally be completely machined in the soft state and then hardened in the final stages of manufacture. Wear of gear cutting tools and the time needed for machining the gears are therefore reduced. Induction hardenable carbon steels can often be used in place of more expensive higher alloy steels.

The induction hardening process must be optimized and controlled in order to achieve favorable hardness and residual stress distributions and the desired case depths. Once the residual stresses, hardness and case

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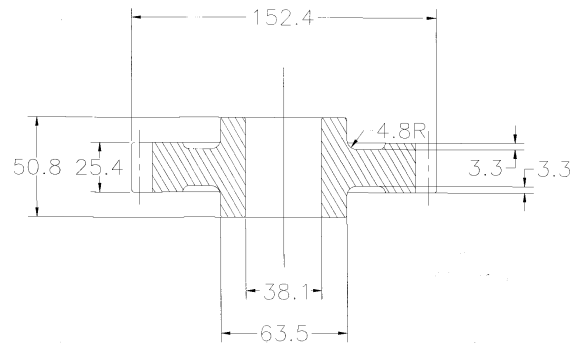
depths produced by variations of the hardening parameters are quantified, the optimal induction hardening parameters can be achieved for a given material and component geometry.

X-ray diffraction techniques can be used to quantify the residual stresses<sup>(1-4)</sup> and hardness in cold worked or heat treated<sup>(5)</sup> materials. The residual stress and hardness can be measured simultaneously at the surface and at any predetermined depths below the surface by electropolishing material for subsurface measurement. Measurements can be made at depth increments as small as 2.5µm (0.0001 in.) using continuously variable irradiated areas as small as 0.5 mm, providing depth and spatial resolution exceeding all other methods of residual stress measurement. A hardness profile can be determined at fine increments through the case/core interface or in any region or depths of interest employing high resolution x-ray diffraction techniques and an appropriate combination of electropolishing and precise sample positioning.

The objective of this study was to quantify the residual stresses and hardness in the case and core of induction hardened gears through the use of x-ray diffraction techniques. The x-ray diffraction residual stress data were corrected for stress relaxation caused by material removal in the complex geometry of a gear tooth using finite element techniques. The subsurface hardness distributions through the case were derived from the width of the diffraction peak used for residual stress measurement.

**SPECIMEN DESCRIPTION**

Three induction hardened SAE six-pitch 1552 steel test gears were supplied by Contour Hardening. The geometry of the gear, developed under sponsorship of the Gear Research Institute, is shown in Figure 1. The gears were identified by serial numbers 61, 63, and 65. The gears had an outside diameter of nominally 152.4 mm (6.0 in.), an inside diameter of 38.1 mm (1.5 in.), a maximum bore width of 50.8 mm (2.0 in.), and a tooth length of nominally 25.4 mm (1.0 in.).



**Fig. 1** SAE Six-Pitch test gear dimensions (in mm). 143.9 mm pitch diameter is indicated.

The induction hardening parameters, varied for the three samples, were the time of preheat and the dwell time before the final heat. The values of the varied parameters are listed in the table below.

Gear Serial Number	Time of Preheat (sec.)	Dwell Before Final (sec.)
61	7.0	10.00
63	4.85	1.35
65	6.50	5.00

The Time of Preheat and Dwell Before Final columns indicate the amount of time, in seconds, during which the power supply was on during preheat and off prior to the final heating, respectively. The parameters which were held constant for all three gears are listed below:

Preheat Parameters	Final Heat Parameters	Time of Final Heat (sec.)	Time of Quench (sec.)
150 kW, 10 kHz	300 kW, 300 kHz	0.5	8.0

**MEASUREMENT PROCEDURE**

**X-RAY DIFFRACTION RESIDUAL STRESS MEASUREMENT**

X-ray diffraction was used to measure the residual stresses and the hardness due to the induction hardening process of the gear specimens S/N 61, 63 and 65. The XRD measurements were taken at mid-length of an arbitrary gear tooth at a distance of nominally 0.5 mm (0.020 in.) from the edge of the root radius, nominally 7.1 mm (0.279 in.) from the crown of













