Diffraction Notes

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MEASUREMENT OF RESIDUAL STRESSES USING RING-CORE TECHNIQUE

INTRODUCTION

Various methods exist to determine residual stresses in metallic engineered components. Some methods are more practical than others, depending upon the material, geometry and the desired locations and depths of measurement.

X-ray diffraction (XRD) provides an accurate and well established(1,2) method of determining the residual stress distributions produced by various types of processes. XRD methods are based upon linear elasticity, in which the residual stress in the material is calculated from the strain measured in the crystal lattice. XRD is capable of high spatial resolution, on the order of millimeters, and depth resolution, on the order of microns. The macroscopic residual stress and information related to the degree of cold working can be obtained simultaneously by XRD(3). XRD is applicable to most polycrystalline materials, metallic or ceramic, and is nondestructive at the sample surface. However, XRD is limited in characterizing the residual stresses in coarse grain materials such as castings and weldments.

Mechanical techniques, which involve removing material and monitoring strain relaxation, can often provide the only means of determining deep stresses in coarse grain components. Mechanical methods of measuring residual stress are often a more cost effective and efficient means of determining deep residual stresses in large castings or forgings. They also allow determination of the principal residual stresses as a function of depth.

The ring-core method is a mechanical technique used to quantify the principal residual stresses within a specified depth of material(4). The technique is based upon linear elastic theory and consists of dissecting a circular plug containing a strain gage. During the sectioning operation the residual strain in the part is relieved. The change in strain is monitored by an on-line computer as a function of cut depth. The principal residual stresses are determined using the derivative of the strain vs. depth data. The ring-core technique can be used on metals,

ANNOUNCEMENTS

New Name and Website

Lambda Research has consolidated our various divisions under the Lambda Technologies umbrella, as in the past 27 years we are still offering the experience, integrity, and innovation you have come to expect from Lambda. For a glimpse of our new look please visit our website at www.lambdatechs.com.

Lambda Receives Phase I Navy SBIR

Lambda was recently awarded a Navy Phase I Small Business Innovative Research (SBIR) contract for the development of a design tool to predict fatigue life in the presence of compressive residual stress.

Up Coming Articles

An article on "The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced IN718" will appear in the May issue of *Metal Finishing News (MFN)*. This article focuses on various surface enhancement methods and provides data showing LSP and LPB produce minimal cold work and also provide the greatest resistance to thermal relaxation.

Keep an eye out for the July issue of *MFN* which will feature an article detailing the successful fatigue strength improvement gained by low plasticity burnishing of Ti-6Al-4V orthopaedic implants.

Lambda's new Corporate Facility

Lambda is proud to announce the acquisition of the new 30,000 sq. ft. production facility located at 3929 Virginia Avenue in Fairfax, Ohio. We expect to be moved in and fully operational by the end of April 2005. Our corporate office and Surface Enhancement will be located at this facility. Laboratory Services will remain at our Fair Lane facility.

ceramics, and polymers, where linear elastic theory can be assumed.

The ring-core method offers the following advantages over the hole-drilling method.

1. The strain signal produced in the ring-core method is nominally an order of magnitude greater than in hole-drilling because the strains are more fully relaxed under the strain gage rosettes.

2. Hole-drilling can only be used to quantify the residual stresses that are less than nominally half of the yield strength of the material(5). This is due to the stress intensity factor around the hole that is introduced inside the monitoring strain gage grids. Using the ring-core method, material around the strain gage grid is removed, which does not produce a stress intensity factor under the active strain gage grid. Stress can be measured accurately up to the yield strength.

3. The high-speed bit used to introduce the hole in the hole-drilling technique can often cause significant residual stresses in work-hardening materials such as the nickel based superalloys and austenitic stainless steels. Machining stresses have no significant effect in the ring-core method.

4. The ring-core method is less sensitive to errors involved in placement of the cutting tool relative to the strain gage since the strain relaxation in uniform in the center of the relieved post under the monitoring strain gage.

GENERAL DESCRIPTION OF RING CORE METHOD

Residual stresses are computed from the derivative of the relaxed strains. Mathematical functions known as relaxation functions that relate the subsurface relaxed strains to those measured at the surface are also required to compute the residual stresses. The relaxation functions are unique for a specific strain gage rosette and ring core diameter. Relaxation functions can be determined empirically by coring a tensile specimen under applied uniaxial stress or with finite element techniques.

Lambda has automated the ring core method by interfacing a personal computer to a plunge-type electrical discharge machine (EDM). The ring core process is controlled with a data collection software package developed and written at Lambda. Both the depth of cut and the strains are continuously monitored and recorded. The software allows the technician to enter the ring coring parameters specifically chosen for each application. A close up photo of a completed ring core measurement is shown in Figure 1.

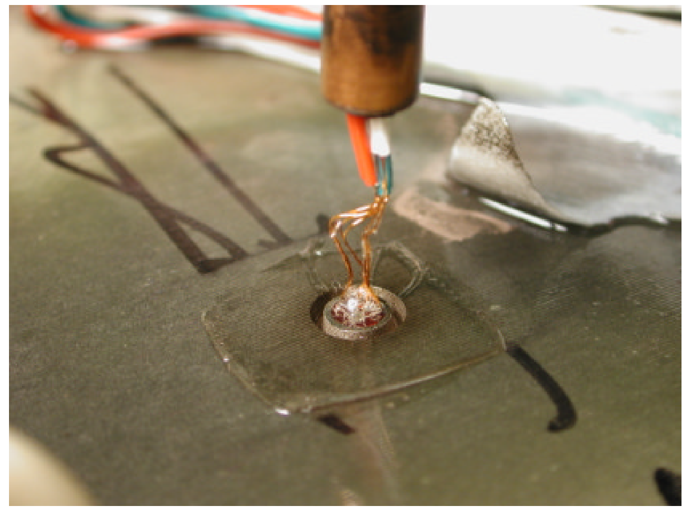

Figure 1 – Close up of ring core test location showing strain gage rosette, lead wires and EDM electrode.

Data reduction software, also written at Lambda, is used to compute the principal residual stresses as a function of depth. The maximum depth to which the residual stresses can be determined is a function of the inside diameter of the electrode. Larger diameter electrodes allow the residual stresses to be measured to deeper levels. However, the depth resolution is reduced for larger diameter electrodes.

EXAMPLES

Press Fit Pin in Sleeve:

A press fit pin and sleeve assembly was used to validate the ring core technique. The assembly consisted of a steel sleeve with nominal dimensions of 2.5 in. (63.5 mm) ID by 0.25 in. (6.4 mm) wall thickness shrunk fit around a steel pin. Both the pin and sleeve were made from a medium carbon steel. An interference fit was chosen to produce hoop tensile residual stresses of reasonable magnitude in the sleeve.

Residual stresses were first measured by x-ray diffraction (XRD) on the outside diameter to establish the benchmark. XRD residual stress measurements were made employing a $\sin^2\psi$ technique and the diffraction of chromium Ka radiation from the (211) planes of the steel. The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (211) planes of the steel were determined in accordance with the ASTM E1426-91. XRD measurements were made as a function of depth on the outside diameter of the sleeve. Subsurface measurements were made by electropolishing away layers of material.

Ring core residual stress measurements were made on the outside diameter of the sleeve. Strains were recorded in the hoop, 45 deg. and axial directions at nominal depth increments of 0.003 in. (76 µm). The residual stresses were reduced from the strain results.

Hoop and axial residual stresses measured by x-ray and ring core are shown as a function of depth in Figure 2. X-ray measurements indicate high surface compression from the finish grinding operation on the outer diameter of the sleeve. X-ray results indicate hoop and axial tensile residual stresses from the shrink fit are present below a depth of about 0.02 in. The hoop tension approaches a magnitude of nominally +25 ksi (+170 MPa). Tensile stresses also exist in the axial direction and are nominally 10 ksi less tensile than the hoop direction. Ring core results, shown in the open symbols, accurately characterize the near surface compression from machining and the tension from the press fit.

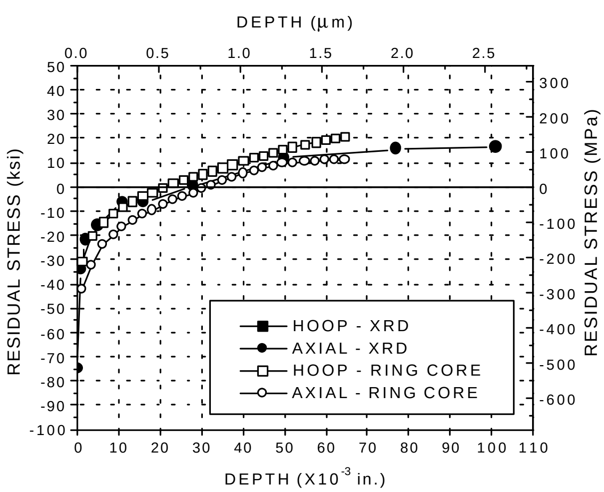

Figure 2 – Comparison of ring core to x-ray diffraction showing ring core showing good agreement of ring core compared to x-ray

<u>Inconel 718 Disk Forging:</u>

Distortion of nickel base alloy turbine disk forgings can occur during machining. Distortion, if severe enough, can result in scrapped forgings and significant costs.

Distortion occurs as stressed material is machined from a forging. Heat treatment of nickel superalloy forgings generally requires a quenching operation to obtain the desired mechanical properties. Quenching produces residual stress through a significant portion of a forging. As layers of material are machined away the forging will re-equilibrate and distort. The direction and magnitude of distortion is a function of the level of residual stresses in the material being removed.

The ring core method is an efficient means of quantifying the residual stresses in the envelope of forging material that will be removed. Principal residual stresses can be determined by ring core and used to estimate the amount of distortion using finite element techniques.

The principal residual stress data obtained by the ring-core method on an Inconel 718 disk forging are shown in Figure 3. Both the maximum and minimum principal stresses are in compressive ranging from -50 to -400 MPa. The results demonstrate that quenching can result in a deep compressive zone. Distortion of the forging will occur if the near surface layer containing the compressive residual stresses is removed by machining. Forging distortion can be predicted using finite element methods if the residual stresses are known(6).

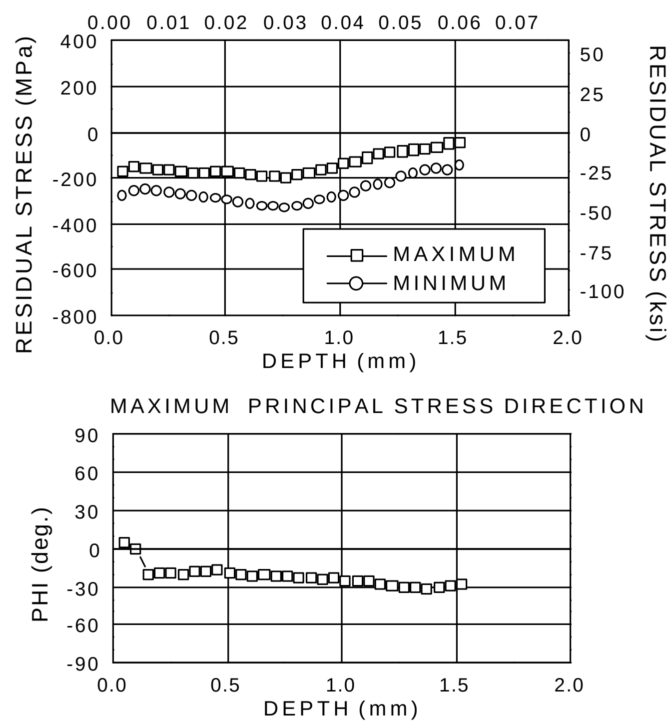

Figure 3 – Principal residual stress in Inconel 718 forging showing compressive stresses to at least 1.5 mm from quenching.

304 Stainless Steel Weldment:

Stress corrosion cracking (SCC) has been observed for decades in austenitic alloy weldments such as type 304 stainless steel. Immediately following weld deposition the weld deposit cools and contracts producing yield strength tensile residual stresses in the weld metal and in the heat affected zone. High tensile residual stresses combined with the appropriate corrosive environment will lead to SCC, component failure and significant repair costs

Diffraction techniques often times cannot be used to measure residual stresses in weldments due to coarse grain size. A statistically significant amount of diffracting grains is required in order to make a residual stress measurement by diffraction. The ring core method is not limited by coarse grain size and can be used to measure the residual stress in coarse grain weldments.

Ring core residual stresses were measured in a single pass 304 stainless steel fusion weld. The sample contained two plates with a nominal thickness of 0.25 in. welded together down the centerline with a single-pass fusion weld. Measurements were made at mid-width of the weld, adjacent to the weld in the heat-affected zone and at distances of 0.25, 0.5, 1.0 and 2.0 in. from the fusion line.

The longitudinal and transverse residual stresses measured by ring core at a nominal depth of 0.03 in. below the surface are shown in Figure 4. The residual stresses are plotted as a function of distance from the centerline of the weld. Longitudinal stresses are those parallel to the weld-line. Results indicate longitudinal tensile residual stresses in the weld and adjacent to the weld in the HAZ. The tensile residual stresses are slightly higher in the HAZ, on the order of +45 ksi (+310 MPa) because the material was not fully annealed from the weld heat input. Longitudinal residual stresses cross into compression at nominally 0.6 in. (15 mm) from the weld centerline. The transverse residual stress is compressive in, and adjacent to, the weld and tensile from 0.6 in. (15 mm) and beyond.

CONCLUSIONS

- Ring core offers a practical technique for determining the residual stress field in coarse grained weldments and forgings.
- Ring core results showed good agreement with x-ray.
- Ring core provides principal residual stress determination in the envelope of material to be machined away in the manufacture of forging components.
- Tensile residual stresses produced in weldments can be measured using ring core.

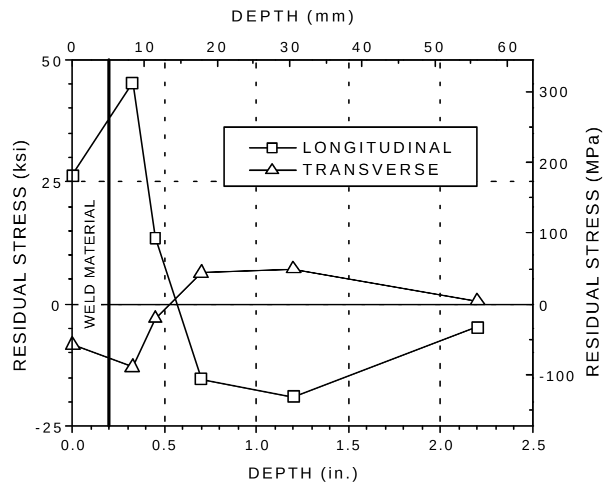

Figure 4 – Residual stresses in weldment showing high tensile stress in and near the weld.

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