News Release

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Residual Stress Contour Mapping

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Introduction

Traditional residual stress measurement by x-ray diffraction provides a single value of the residual stress in one direction at each point of measurement, similar to the results obtained from a single electrical resistance strain gage grid. In many failure analysis or process development applications, the direction and location of the maximum residual stress may be known. In these cases, traditional residual stress measurements, generally performed as a function of depth, are adequate.

Often, however, the nature of the residual stress distribution and the locations of maximum stress are not known. For example, stresses developed by quenching, welding, or forming of complex shapes may produce stress fields which defy prediction. Mapping of entire stress fields would be the ideal solution to this class of problems but until now has been prohibitively expensive for most applications using traditional means.

Lambda Research has developed a novel apparatus to allow the mapping of residual stress distributions parallel to the surface of the sample. The apparatus has three translational degrees of freedom to allow stress distributions to be mapped on either flat or moderately curved surfaces in planes parallel to the original surface. Through the use of finite element methods, also developed at Lambda, to correct for stress relaxation in arbitrary stress fields and geometries[1], maps of the stress distributions on parallel surfaces can be generated at a series of depths into the surface by alternately electropolishing and mapping the exposed surface.

The apparatus operates on standard Huber Bragg-Brentano diffractometers instrumented with lithium drifted silicon detectors for maximum precision and the freedom to use any radiation regardless of the fluorescence of the material. The samples, which may be up to 200 mm x 200 mm, are mounted on the computer-controlled X-Y-Z stage with precision positioning of ±25 μm.

Welding Applications

The residual stress distributions developed in weldments are notoriously difficult to analyze and predict because of the complex dependence of the residual stress field upon the details of heat input during welding, phase transformations, alloy property changes with temperature, weld shrinkage, etc. Until now,

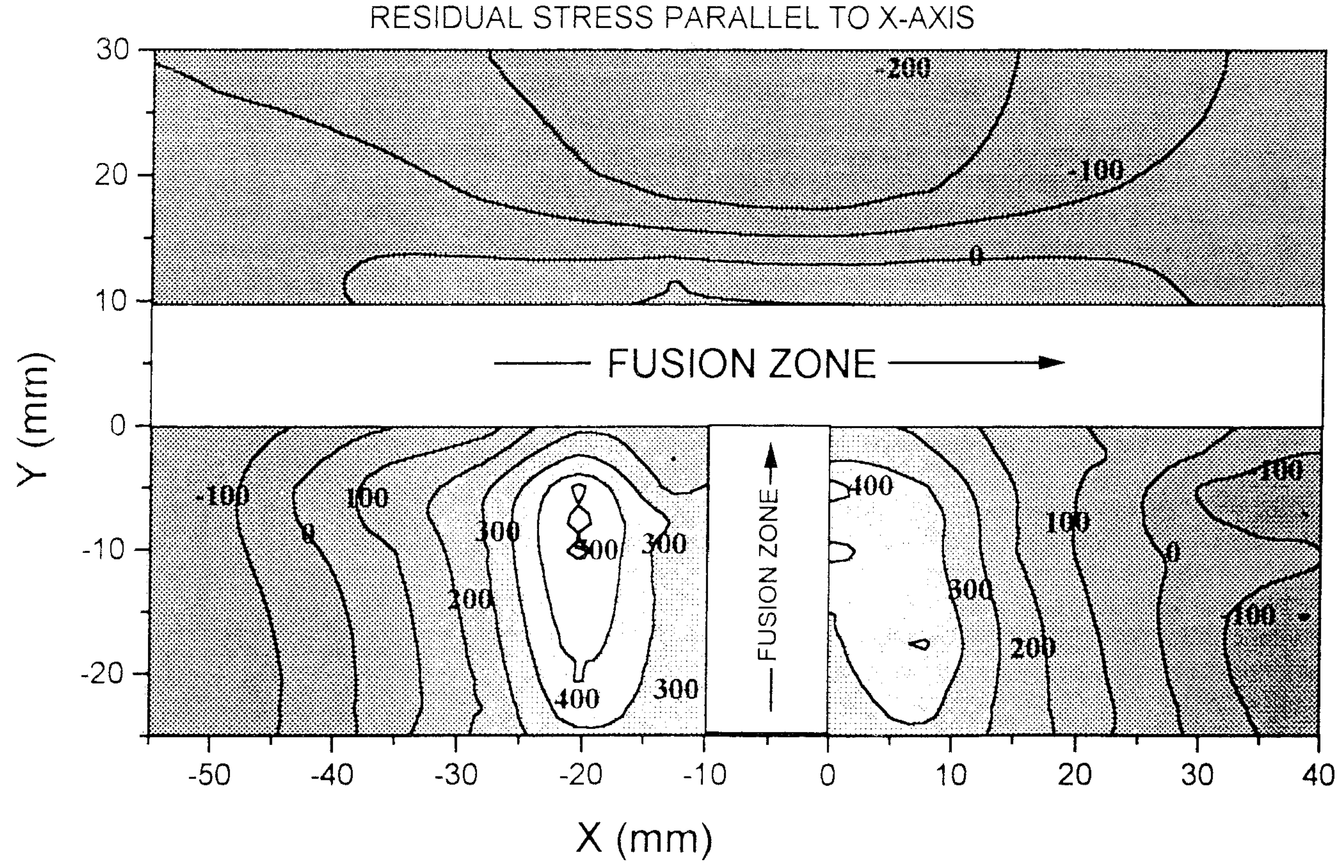

Fig.1. Residual stress distributions in "T" weld intersection of 304 stainless steel. Measurement in the parent metal and the HAZ parallel to the X-axis is indicated in the fusion zones.

experimental determination of residual stress fields in weldments has relied upon the presumption of the areas of maximum stress and limited measurements usually performed as a function of distance from the weld fusion line at a few selected locations. The conventional approach risks missing important features of the stress distribution entirely. Lambda's new mapping capability makes it practical to map the entire surface of the weldment.

Fig. 1 shows an example of the complex residual stress distributions developed in 304 stainless steel plate butt-welded to form a "T" intersection. The two smaller plates were first joined to the larger plate with the weld parallel to the X-axis of Fig. 1. The "T" weld intersection was completed by welding from the bottom edge of the plates inward to deliberately develop high stresses in the plate. The entire weldment was electropolished to remove any surface stresses from prior grit blasting and handling. Fig. 1 was then generated from approximately 110 residual stress measurements made parallel to the X-axis. Measurements were made only in the parent metal and heat affected zones (HAZ), not in the fusion zones.

Although the sample geometry process is nominally symmetrical, the stress distribution developed depends upon the direction of the welding. Significant differences are observed in the stress distributions on both sides of the "T" joint, with stresses exceeding +500 MPa occurring in an isolated region only to the left of the "T" weld.

Nonlinear finite element prediction of the residual stresses developed by welding offers a powerful tool for optimizing the manufacturing process and minimizing detrimental tensile stresses in fatigue-prone applications. The stress mapping capability developed at Lambda Research provides for the first time a means of accurately quantifying stress fields developed in weldments in a manner which can be compared directly to finite element-generated stress contours. The use of stress contours measured on coupons with high precision in the laboratory to refine finite element models of the complex welding process is one of the most promising potential applications of the stress mapping technology.

Localized Deformation Applications

A second example of stress mapping in a plane parallel to the surface is shown for four overlapping laser shock peened (LSP) spots in Fig. 2. Repetitive local deformation can create complex stress distributions. The four shaded circles indicate the position and sizes of the four LSP zones used to generate the stress field. The stress contours show the stress parallel to the X-axis. The stresses were developed on the surface of a stress-relieved and electropolished Ti-6Al-4V coupon by multiple shocks at each of the four zones indicated in rotation. The stress contour mapping reveals isolated regions of relatively high compression, in excess of -520 MPa, as well as variation exceeding 200 MPa throughout the LSP impact zones. The zones of maximum compression appear to be associated with the overlapped regions of the 1-2 and 3-4 shock zones.

Cylindrical Coordinate Applications

Lambda's new stress mapping capability also allows stress distributions to be mapped in cylindrical coordinates plotting the stress on the surface of the specimen as a function of azimuthal position. A recent study on expanded Alloy 600 steam generator tubing has been completed.[2]

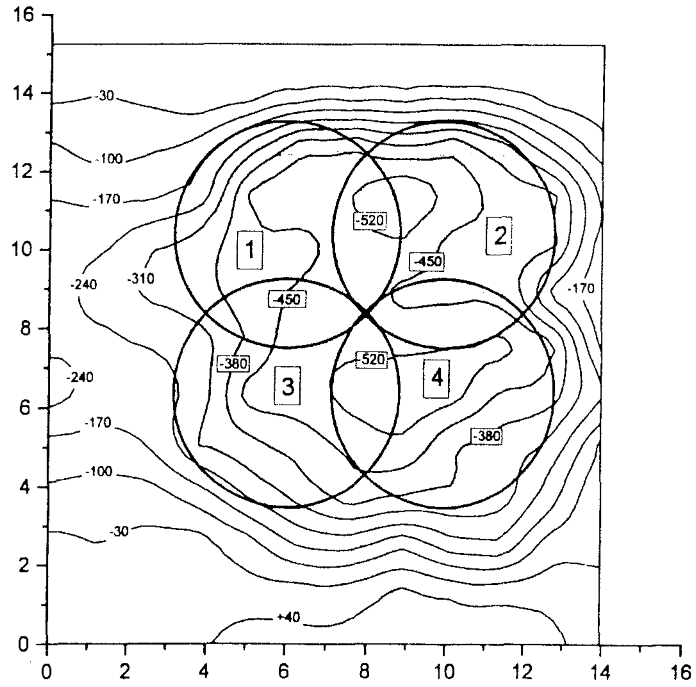

Fig.2. Stress distributions developed by laser shock peening.

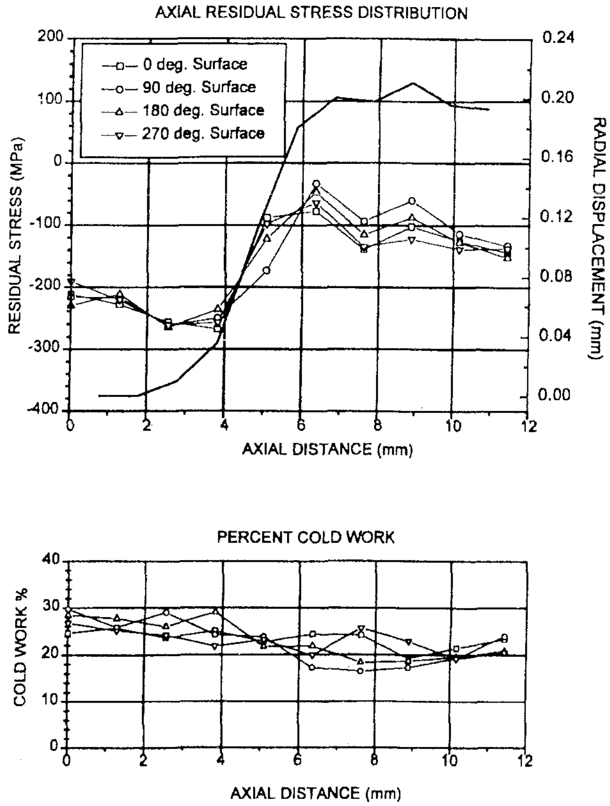

Fig.3. Residual stress distributions and percent cold work in Alloy 600 steam generator tubing.[2]

Steam generators are fabricated by expanding nickel alloy tubing into a steel plate to form a tube sheet. Susceptibility to stress corrosion failure depends upon the residual stresses developed. The expansion process may result in regions of local tensile stress at the surface in the transition region from the original diameter to full expansion.

Fig. 3 shows the axial surface residual stress at four azimuthal positions spaced 90 deg. around the circumference of an expanded tube as a function of axial position through the transition region into the expanded portion of the tube. Because data were obtained only in 90 deg. increments, the results are plotted conventionally rather than as stress contours on a Z-θ plane. The radial displacement of the tube surface revealing the transition region is plotted at the right of Fig. 3. The stress map shows that the axial residual stress distribution developed by the particular expansion process employed is quite uniform around the circumference of the tube, and no tensile regions are produced.

The cold work distributions calculated from line broadening are obtained simultaneously with the residual stress measurements[3] and are shown on the bottom of Fig. 3. Contour maps of cold work and the associated yield strength distributions can also be generated[4].

Summary

Stress mapping can now be performed on virtually any specimen of metallic or ceramic material amenable to x-ray diffraction residual stress measurement. The automated process runs unattended, which allows a great deal of data to be obtained economically. If you have a potential application that you would like to discuss, please contact Paul Prevéy, Lambda Research, at (513)561-0883.

References

1. "Finite Element Correction for Stress Relaxation in Complex Geometries," Diffraction Notes, #17, Fall, 1996.
2. Sherburne, P.A., D.J. Hornbach, R.A. Ackerman, A.R. McIlree, "Residual Stresses in OTSG Tube Expansion Transitions," to be presented at the Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, Amelia Island, 1997.
3. Prevéy, P.S. "The Measurement of Subsurface Residual Stress and Cold Work Distributions in Nickel Base Alloys," Residual Stress in Design, Process and Materials Selection, ed. W.B. Young, Metals Park, OH: American Society of Metals, 1987. pp. 11-19.
4. "Effects of Prior Machining on Residual Stress in Welds," Diffraction Notes", #15, Spring, 1995

> I have six locks on my door all in a row.
> When I go out, I lock every other one.
> I figure no matter how long somebody
> stands there picking the locks, they are
> always locking three.
>
> —Elayne Boosler