

Residual Stress Characterization of Welds

Using X-Ray Diffraction Techniques

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ABSTRACT

Neglect of residual stresses created during welding processes can lead to stress corrosion cracking, distortion, fatigue cracking, premature failures in components, and instances of over design. Automated residual stress mapping and truly portable equipment have now made the characterization of residual stresses using x-ray diffraction (XRD) practical. The nondestructive nature of the x-ray diffraction technique has made the residual stress characterization of welds a useful tool for process optimization and failure analysis, particularly since components can be measured before and after welding and post welding processes.

This paper illustrates the importance of residual stress characterization in welds and presents examples where x-ray diffraction techniques were applied in the characterization of various kinds of welds including arc welds, TIG welds, resistance welds, laser welds and electron beam welds.

Numerous techniques are available to help manage potentially harmful residual stresses created during the welding process thus, the effects of a few example post weld processes such as grinding, heat treating and shot peening are also addressed.

INTRODUCTION

The advantages of XRD and three areas of concern regarding residual stress and weld quality, stress corrosion cracking, fatigue, and stress concentrations, will be briefly discussed.

Fatigue and Stress Concentrations

Tensile residual stress fields created during the welding process often contribute to decreases in the fatigue life of welded components, especially when they exist in the HAZ. The residual stress state existing in certain weld toes and undercuts can also be critical when stress concentration geometries exist

which can magnify the effects of applied loads. When issues of fatigue cracking are considered, potentially harmful tensile residual stresses alone or in combination with stress concentrations can lead to fatigue crack initiation and propagation. This means that accurate residual stress characterization must be performed in key areas such as the toe and the HAZ of welds to understand fatigue failures, help in the experimental verification of stress concentration factors predicted by finite element models and to reduce instances of over-design and unneeded increases in weight.

Environmentally Assisted Weld Cracking

Also known as Stress Corrosion Cracking or SCC, environmentally assisted cracking is a major source of potential failures in the process industries, in pulp mills, in storage vessels, and even in aircraft. Most often, SCC occurs in the heat affected zone (HAZ) immediately adjacent to a weld simply because the HAZ is left in a state of very high residual tensile stress as a result of the shrinkage and differential cooling occurring in most welds. Tensile stresses (residual or applied) are the main component of the stress corrosion cracking triangle: the other two are a susceptible metal and an environment that often needs to be only slightly corrosive to that metal. For instance, grade 316 stainless steel is essentially inert to the corrosive effect of common salt *unless* tensile stresses are present, when it becomes very sensitive to chloride induced SCC. There are a number of possible solutions. The obvious one is to change the environment, but that is rarely possible. The next is to change the metal, but usually that is expensive and if the equipment is already built, impractical. Thermal stress relieving is a partial solution at best because, to relieve all the tensile stresses in the HAZ, it is necessary for the heating to

reach the annealing temperature and the material properties will be lost.

Corrosion engineers have long recognized that an effective solution for the retardation or even prevention of SCC is the introduction of compressive stresses in the HAZ. This can be done using controlled shot peening. Surface residual tensile stresses in the HAZ may approach or even exceed the yield strength of the material but if the surface is shot peened, the dimpling action of the shot bombardment can reduce the tensile stresses and even replace them with residual stresses that are in compression if properly done.

Hence, there is a clear need for accurate nondestructive residual stress characterization of welds to verify the residual stress state of weld HAZs in components that may be susceptible to SCC. This type of weld characterization can be performed nondestructively on components that are already in service and ideally, on welded components *before* they go into service.

Advances in XRD Technology

Accurate characterization of residual stresses in welds has been difficult and often impractical since most residual stress measurement techniques are destructive and lack the resolution to accurately characterize the steep stress gradients that exist in weld HAZs. Recently, the measurement of residual stresses using x-ray diffraction techniques has become both practical and efficient. In addition, the introduction of stress mapping techniques has allowed the quick and precise characterization of entire welds, including areas of interest such as steep stress gradients and their associated tensile residual stress maxima. The stress map display has given engineers a complete and accurate visual analysis of the magnitude and distribution of residual stresses in their welded components.

Since surface stress measurements using x-ray diffraction techniques are non-contact and nondestructive, measurements can be performed at the same point before and after a process such as post weld heat treating or shot peening, so that residual stresses can be characterized at all steps of the manufacturing process. This can help in the optimization of these manufacturing processes and the management of their associated residual stresses.

MEASUREMENT APPARATUS

The residual stress measurements were performed at the Proto Mfg. Ltd. x-ray diffraction laboratory and in the field using a dual solid state detector diffractometer with automated stress mapping hardware and software.

BASICS OF THE X-RAY DIFFRACTION STRESS MEASUREMENT TECHNIQUE

The x-ray method does not measure stress directly but measures strain from which stress values are calculated. The

x-ray method rather elegantly takes advantage of the crystalline structure of the material itself, by using the atomic lattice spacing as a strain gage. As a result, thousands of "built in strain gages" within the crystals which compose the material are available for strain measurement by the x-ray diffraction method. To phrase it more exactly, the surface strain present can be determined by the measurement of the elastic atomic lattice spacing or "d-spacing" as it is commonly called. This lattice spacing, the distance between the planes of atoms, is dependent upon the material and the stresses present in the material. The x-ray diffraction angle θ for a given x-ray wavelength λ can be used to determine the material "d" spacing by means of Bragg's law:

$$n\lambda = 2d \sin \theta \dots\dots\dots(1)$$

For x-ray diffraction to occur, i.e. constructive wave interference, the path difference traveled by the diffracted beam through the material, as compared to a non-diffracted beam, must be equal to $n\lambda$ (Noyan and Cohen, 1987). The presence of residual stresses in the material produces a shift in the x-ray diffraction peak angular position (Cullity, 1978) which is directly measured by the detector.

Once the lattice d-spacings are measured for the unstressed (d_o) and stressed (d_i) material conditions, the atomic lattice strain can then be calculated by the following relationship (Hilley et. al., 1971):

$$\text{strain} = (d_i - d_o) / d_o \dots\dots\dots(2)$$

For isotropic materials, strains can be converted to stress values using the equation shown below.

$$\text{stress } (\sigma) = \frac{d_\psi - d_o}{d_o} \left(\frac{E}{1+\nu} \right) \frac{1}{\sin^2 \psi} \dots\dots\dots(3)$$

where: $\frac{E}{(1+\nu)}$ is the x-ray elastic constant, ψ is the angle subtended by the bisector of the incident and diffracted beam and the surface normal, d_ψ is the lattice spacing at a given ψ tilt and d_o is the unstressed lattice spacing.

Residual stresses are measured using either of two techniques. The first is the single exposure technique (SET), whereby a stress measurement is performed using only one tilt angle. This technique gives the user a very quick and efficient method to perform a stress measurement and is particularly suited to cases where many measurements are needed quickly. The second is the multiple exposure technique (MET), whereby multiple beta tilts are used in the analysis.

The MET method is more revealing for material conditions for which the d vs. $\sin^2 \psi$ relationship is not linear, as assumed in equation (3), but takes much longer than the SET (Klug and Alexander, 1974).

Techniques are also available that deal with phase changes that may exist through the weld, the HAZ and the parent material (Noyan and Cohen, 1987).

RESULTS AND DISCUSSION

The following examples illustrate various applications of x-ray diffraction based residual stress characterization of welds.

Arc Welded Monorail Box Girder

An area of concern in the installation of monorail girders is the residual stresses due to welds. These are of particular interest because high stress gradients can be created by the large amounts of differential heating and cooling inherent in the welding process. A stress gradient profile was performed across a weld splice where two monorail girders were welded together.

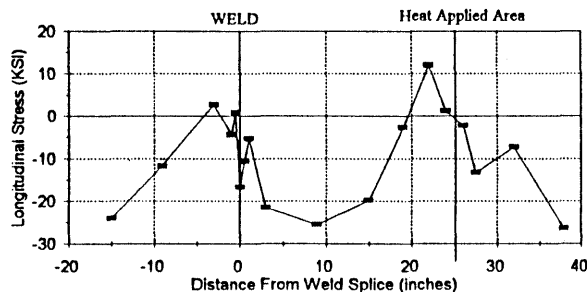


Figure 1 - Welded and heat straightened box girder

This particular section of the box girder was also heat straightened. Looking at figure 1 reveals the tensile stresses in the weld and in the heat straightened area and how they are different from the baseline compressive residual stresses in the parent material. These areas of tensile residual stress will be susceptible to SCC and fatigue cracking. The effect of the tensile residual stresses will be increased since the rolling stock passing over these locations will add an additional tensile load to the already tensile residual stress state at these locations.

Laser Welded Stainless Steel Pipe

The residual stresses in a 316 stainless steel pipe that was laser welded were mapped through the weld and parent material. The concern was that the laser weld had created tensile residual stress levels near yield which could decrease the burst strength of the pipe while in service.

The residual stress map in figure 2 reveals a slightly tensile residual stress field in the center of the laser weld. If this section of pipe were placed in service, the tensile residual stress maxima already existing in the center of the weld would be increased even more so due to the applied stress of the working pressure on the pipe thus making this area highly susceptible to SCC. Should SCC be a concern, some post weld residual stress management process would be recommended to introduce compressive surface stresses in the weld and HAZ.

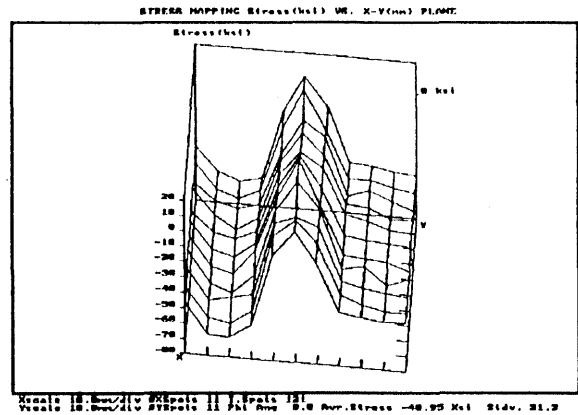


Figure 2 - Laser welded 316 stainless steel pipe

Electron Beam Welded Inconel

Residual stress profiles were measured at the surface and at depth in the weld metal, in the heat affected zone and on the parent material of an Inconel sample that was electron beam welded. Because the surface of the weld and the adjacent parent material were machined, surface measurements were affected significantly by the cold working of the material (see figure 3).

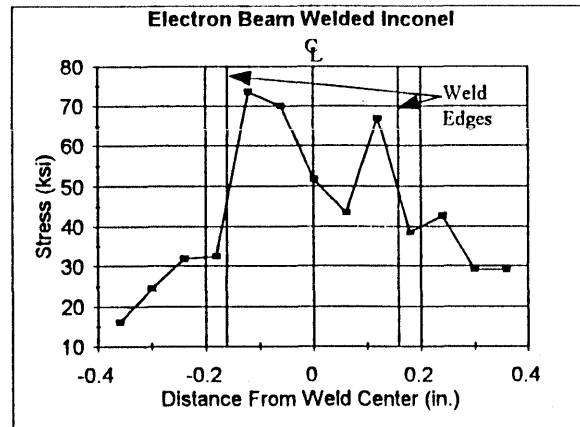


Figure 3 - Electron beam welded Inconel specimen

Here tensile residual stress maxima exist in the center of the weld. These stresses should also be managed to increase the service life of this weld.

Resistance Welded Stainless Steel Saw Blades

Stainless steel band saw blades, resistance welded, "annealed" and ground were failing prematurely under normal service. It was suspected that residual stresses created during the welding, post welding heat treatment and grinding processes were causing the failure.

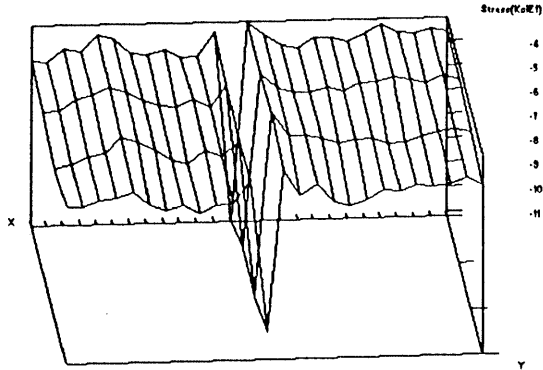


Figure 4 - As welded saw blade.

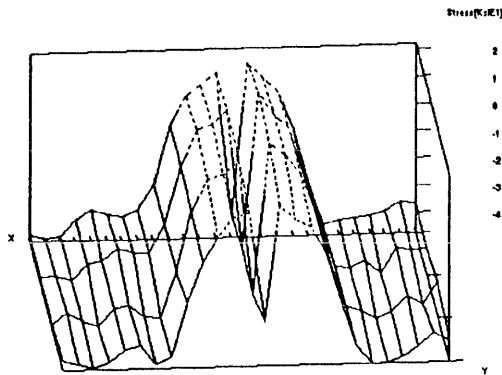


Figure 5 - Post weld heat treated saw blade.

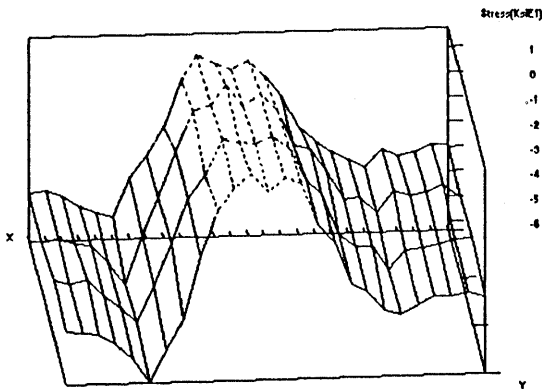


Figure 6 - Welded, heat treated and ground saw blade

Residual stress mapping techniques were used to identify at which stage in the process harmful residual stresses were introduced. Figures 4, 5 and 6 show blades in the welded, welded and heat treated, and welded, heat treated and ground conditions respectively.

It can be seen in figure 4 that no significant tensile residual stresses are present in the weld or HAZ. After heat treat (see figure 5), the low compressive stresses in the HAZ are pushed into residual tension. When the entire area is ground, slightly lower tensile residual stresses are present in the HAZ (see figure 6).

This information can be used to adjust the post weld heat treat and grinding to optimize the process parameters and thus will help make the blades less susceptible to fatigue failure in service.

Arc Welded and Ground T-Butt Weldment

T-butt weldments in marine structures are an important issue in the service life of the structure. With high service loads on failure critical components, it is essential to understand the stress levels in welds, particularly at the toe of welds where stress concentrations exist.

An HY-80 T-butt weldment was incrementally loaded and the residual or total stress (residual + applied stress) was measured at the weld toe at each of the known applied loads.

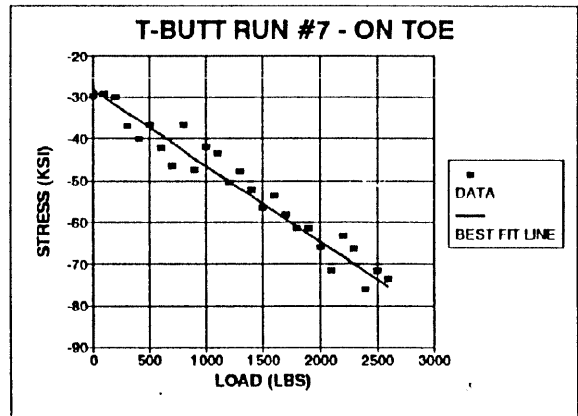


Figure 7 - Stress vs. Load plot on toe of t-butt weld fillet

The plot in figure 7 shows the results of these measurements. From the slope of this plot the experimentally measured stress concentration factor was derived for this particular geometry. This kind of information is invaluable in fine tuning finite element models which have difficulty with the complexity found at material discontinuities such as weld toes.

Shot Peened Stainless Steel TIG Weld

Two stainless steel plates were butt welded together. A stress map was collected from the toe of the weld out into the HAZ and parent material (see figure 8). This sample had a much larger HAZ than the other samples that were analyzed.

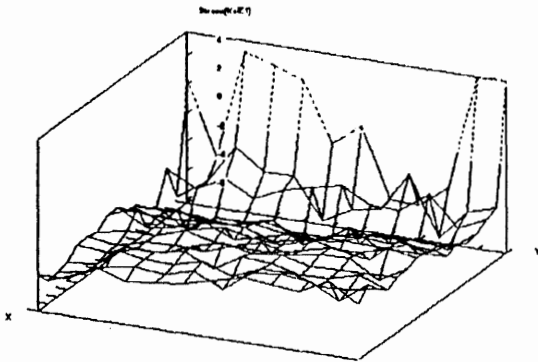


Figure 8 - Stainless steel butt weld

The origin of this map was set at the toe of the weld to concentrate on the weld toe and HAZ. Because the small band of tensile residual stress in the HAZ follows the contour of the weld toe, the plot exhibits residual stress maxima varying from tension to compression. No post weld stress management processes were applied to this weld leaving tensile residual stresses in the HAZ and in the weld toe

Shot Peened Stainless Steel TIG Butt Weld

A similar sample was prepared with two 316L stainless steel plates butt welded with Hastelloy C-22 filler. In this case however, the welded coupon was shot peened with CW-22 shot at 8-10 A intensity and 100% coverage. A portion was masked off prior to peening so that only part of the weld was shot peened and the remainder was left in the as welded condition. The plot of this stress map can be seen in figure 9.

In this case, the peening parameters used were sufficient to put the weld's surface stresses into compression. This can be seen by looking at the left hand side of the map shown in figure 9 where the tensile residual stress level peaks. This region of tension is in the area where the weld was masked from peening. All other areas that were not masked and hence peened were found to be in compression.

This is an example where residual stresses due to welding and the effects of a post weld stress management process can be characterized simultaneously.

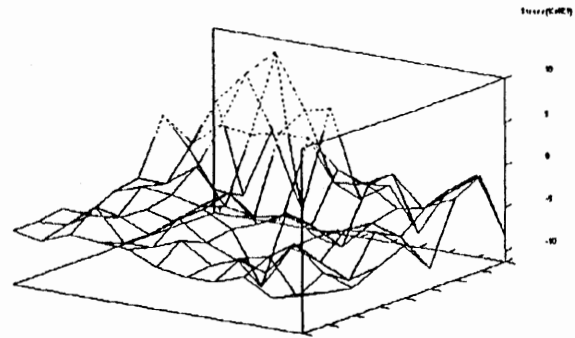


Figure 9 - Shot peened 316L stainless steel butt weld

Shot Peened Inconel TIG Butt Weld

A heavy L plate was fabricated by TIG welding two pieces of Inconel 825 plate with Inconel 625 filler. Since tensile residual stresses were expected in the weld and the HAZ, shot peening was introduced to manage the potentially problematic tensile residual stresses. The weld and parent material were shot peened with CW-28 shot at 16-18A intensity and 125% coverage. To verify the effectiveness of the peening, a section of the weld was masked off and not peened so that the peened and as welded conditions could be compared. A residual stress map was performed on an area encompassing both peened and unpeened portions of the weld.

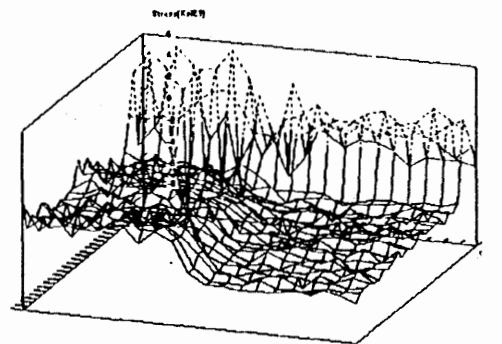


Figure 10 - Shot peened Inconel 825 L plate weld

It can be seen in figure 10 that the shot peening technique used had a significant effect on the stress state of the weld and parent material as seen by the "step" or drop in residual stress near the center of the map. On the left hand side, a typical weld stress map is observed with tensile residual stresses in the weld and in the HAZ and then dropping off in the parent material. The right side of this map was the peened portion. Here the characteristic profile is much more compressive (or less tensile) and smooth however, tensile residual stresses still exist. This indicates that the peening process had the effect of reducing the tensile residual stress field in the weld and HAZ and introducing a much more uniform compressive residual stress level in the parent material. However, it was not sufficient to make the surface stresses in the HAZ entirely compressive. This would suggest that the peening parameters could be changed to increase the compressive residual stress imparted upon the weld and HAZ. This kind of information cannot be obtained using the standard Almen strip test.

CONCLUSIONS

It has been known for some time that tensile residual stresses in welds that undergo tensile cyclic loading suffer from a reduction in fatigue life. It is also known that components with tensile residual stresses will suffer from SCC under the right conditions. Managing tensile stresses properly using post weld processing techniques such as shot peening, heat treatment, grinding, rolling, etc... can increase the service life of welded components significantly or even decrease the service life if applied improperly.

As seen in the previous examples, no single post weld treatment will necessarily successfully manage residual stresses in all cases. When full residual stress characterization has been performed, it may be determined that more than one post weld process may be required for a given weld condition hence the importance of verifying the effectiveness of post weld processing at each step to ensure the desired residual stress levels have been achieved.

The applications previously described also exhibit the practicality and advantages of using the nondestructive x-ray diffraction method. It is the only method available presently

which can characterize stresses and stress gradients in welds with the resolution required to solve the problems.

Characterization of residual stresses in welds provides the information the engineer or manufacturer needs to properly manage the welding process, optimize product quality, minimize the effects of fatigue and SCC and help minimize production costs while enhancing component performance.

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Note : Regarding Stress Map Plots

Stress map displays are normally presented in a color plot with tensile stresses shown as red lines and compressive stresses shown as green lines. This of course is not possible in this black and white article, thus dotted lines indicate tensile stress and solid lines compressive stress. It should also be noted that on the z-axis or stress scale of the stress map plots that the scale is often multiplied by a power shown as (ksiE1) which indicates that the results are in ksi (1000 psi) and are multiplied by 1×10^1 .

REFERENCES

- B.D. Cullity, 1978, "Elements of X-Ray Diffraction", 2nd Edition, Addison-Wesley Publishing Co. Inc., Reading, Mass.
- M.E. Hilley et. al., 1971, "Residual Stress by X-Ray Diffraction - SAE J784a", Society of Automotive Engineers, Inc., Warrendale, PA.
- H.P. Klug, L.E. Alexander, 1974, "X-Ray Diffraction Procedures", 2nd Edition, Wiley-Interscience, U.S.A.
- I.C. Noyan, J.B. Cohen, 1987, "Residual Stress Measurement by Diffraction and Interpretation", Springer-Verlag, New York.
- J.A. Pineault, M.E. Brauss, 1993, "Measuring Residual Stress Using X-Ray Diffraction on Shot Peened Components", MAT-TEC, France.