Measurement Of Residual Stresses Caused By Welding

Toby Prosin

School of Mechanical Engineering

CEED Partner: Alcoa World Alumina

Abstract

On an Alcoa alumina refinery site there are large numbers of welded carbon steel pressure vessels. It is known that welding causes residual stress fields to remain in the structure [6]. Tensile stress in conjunction with caustic conditions and elevated temperature is known to cause stress corrosion cracking (SCC) [5, 7]. Alcoa uses precautionary post weld heat treatment (PWHT) following welding to mitigate the risk of SCC [10]. This precaution is very costly to Alcoa. It is possible that some PWHT is not necessary, however a qualitative assessment of PWHT necessity is needed. Since residual stresses are a major contributor to SCC [5], measurement of residual stresses would contribute to satisfying this criteria. Analysis of known residual stress measurement techniques has been implemented on known non-destructive technologies such as X-ray Diffraction (XRD), Hole-drilling, magnetic, ultrasonic and Instrumented Indentation methods.

1 Introduction

Alcoa World Alumina (Alcoa) operates nine alumina refineries across the globe. Each alumina refinery contains multitudes of carbon steel pressure vessels, each requiring regular inspection and maintenance every 2 – 4 years. The approximate total number of pressure vessels in these refineries amounts to around 1500. Often during maintenance, weld repairs or minor modifications involving welding may be carried out [10]. Normally-specified welding on vessels located on an Alcoa site is often specified by welding procedure specification (WPS) P101. Welding is usually dictated by P101 unless there are special circumstances. This is a manual metal arc welding (MMAW) process that uses consumable E4816 electrodes to lay the weld. Multiple weld runs are deposited in a 60° single Vee joint with this electrode. The welding is typically conducted on grade AS 1548-7-430 carbon steel or similar. The majority of Alcoa pressure vessels are composed of this steel type. Standard welding practices produce residual stresses because of non-uniform morphing of the weld metal due to the heat input [6]. Typical welding stress profile in a non-PWHT specimen is shown in figure 1.1.

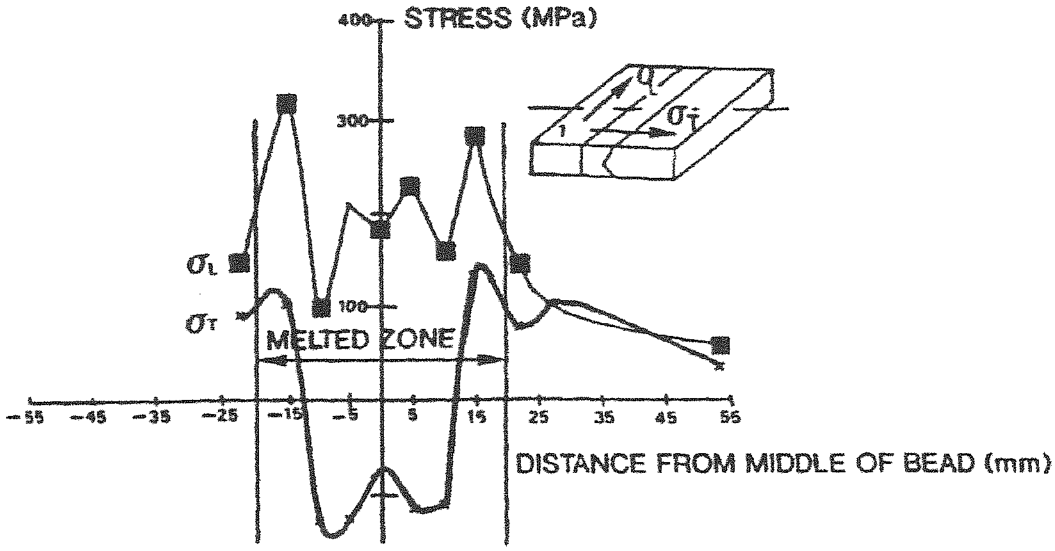

Figure 1.1 Longitudonal and Transverse surface residual stresses measured using XRD on a multipass welded steel plate (50mm thick). [1]

The surface (10_m depth) transverse stresses are compressive before about 13mm from the weld centreline, while longitudinal tensile stresses are tensile. The danger zone is from 0 to 45mm from the weld centreline. After this distance the stresses drop away rapidly to a safe level. The danger zone is the region where stresses can significantly contribute to hazards such as stress corrosion (SCC).

1.1 Stress corrosin cracking (SCC)

SCC is the brittle failure of normally ductile steel vessels by crack propagation. On an Alcoa site caustic SCC is observed in welded vessels operating at elevated temperatures in contact with caustic NaOH [9].

These cracks in carbon steel typically follow grain boundaries on the surface. In a weld, cracks tend to initiate at the weld face and run perpendicular to the direction of the tensile stress [7]. Transverse cracks are due to the high longitudinal tensile residual stresses on the surface of the weld. Below figure 1.2 has evidence of transverse SCC on an inlet steam nozzle on a caustic wash heater in one of Alcoa's refineries. The nozzle was in service for 7 years before cracking was initiated. The cracks vary in depth, some penetrating through thickness. There was no post weld heat treatment (PWHT).

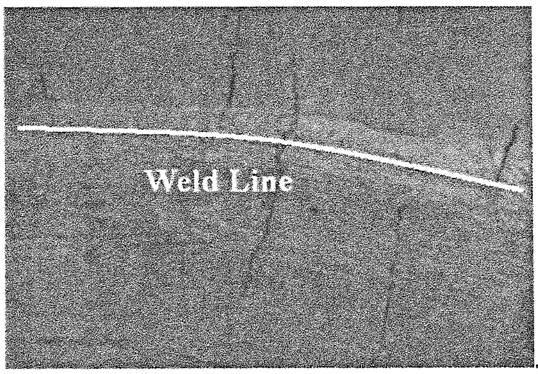

Figure 1.2 Transverse SCC on steam valve

Longitudinal tensile stresses are the main concern with SCC development. The majority of SCC will run transversely to the weld line. However SCC is known to occur parallel to the weld centreline due to transverse tensile stress in rare instances. Longitudinal SCC in one of Alcoa's carbon steel heaters is displayed in figure 1.2.

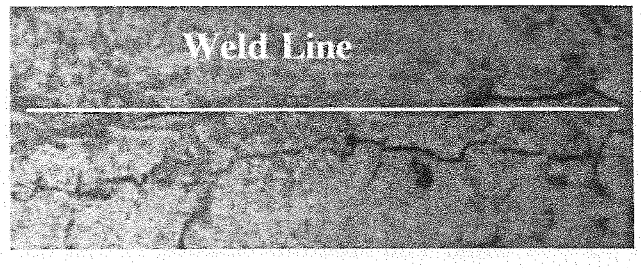

Figure 1.2 Longitudinal SCC

It can be seen that is imperative to measure both longitudinal and transverse residual stresses on the surface of a weld.

1.2 SCC prevention precautions

On Kwinana site in 2007, according to Alcoa's OC1 heater strategy meeting, 10 Heaters are specified to be overhauled and 5 heaters are to be re-tubed. 24 other vessels are also documented to require attention this year. There are around 90 vessels on site that require regular maintenance and repair. These vessels are inspected between 24 and 48 month intervals, and will require major repairs involving welding at least once a decade. Alcoa's standard practice for minimising the SCC risk is to apply PWHT following all work involving welding [10]. The heat treatment is designed to reduce sufficient residual stresses in order to prevent SCC. Unnecessary heat treatment should be minimized to reduce costs without impacting on vessel integrity. Therefore a qualitative assessment of SCC susceptibility is needed in order to determine if performing PWHT is necessary. A qualitative assessment of vessel susceptibility to SCC after welding could be acquired if residual stresses could be measured. This would allow Alcoa to improve welding processes and eliminate unnecessary PWHT to forgo the associated costs.

1.3 Costs

At Pinjarra Refinery, digestion unit downtime comes at a high production cost of many thousands of dollars for every hour that the equipment is off-line. On the other hand, downtime for a single heat exchanger in the digestion process comes at an energy cost of hundreds of dollars per hour. In any case, Alcoa must remain focussed on reducing pressure vessel downtime. The PWHT costs up to $5 000 and contributes up to 16 hours to vessel downtime each time it is used. The cost of overhaul for many vessels can lead into the hundreds of thousands of dollars using either Alcoa personnel or contactors.

2 Measurement technologies

There exist many stress measurement techniques in industry. Each has specific advantages and disadvantages. A thorough analysis of residual stress measurement techniques is needed to evaluate the usefulness of a particular device to Alcoa. Devices will be compared on the following criteria; accuracy and depth of measurement, stress type and direction measured, portability of device, and the destructive nature of testing. Known methods of residual stress measurement include the use of saw cutting, contour methods, hole-drilling, XRD, neutron scattering, Raman spectroscopy, instrumented indentation, magnetic methods and ultrasonics. Alcoa's primary concern with respect to stress measurement is the on site measurement of residual stresses caused by welding on carbon steel plant vessels. The testing must test for stresses in carbon steel, and leave the vessel operational. Therefore the testing needs to be classified as non-destructive. This leaves XRD, hole drilling, ultrasonic methods, magnetic methods and instrumented indentation techniques for deeper study into the validity of residual stress measurement on site.

2.1 Measurement Device

In order for a residual stress measurement device to be useful to Alcoa it must meet the following specifications. The accuracy should be plus or minus around 15 Mpa. Pressure vessels composed of AS 1548-7-430 has yield strength of 353 Mpa at normal Alcoa operating conditions of 145 °C. The threshold stress level for SCC to initiate is around 10 - 20 % of yield [5], thus the threshold stress is around 35 – 71 Mpa. The recommendation is that the measurement accuracy of the device should be within around 20 % of the upper limit. The spatial resolution is to be no larger than 0.5 mm^2, to keep stress maps accurate. Depth of measurement must be within 200μm of the surface in order to evaluate surface stresses. Alcoa staff must be able to operate device, non-intensive training may be allowed. The device must be of reasonable size in order to fit into confined spaces without impeding the safety of the operator. The appliance is to be no greater that 50x50x50 cm. The mass must not exceed 20kg, in order to be portable without the need for alternative transport equipment according to occupational health and safety legislation. The device must be able to measure longitudinal and transverse macro stresses on the surface of the weld. Average stresses are acceptable. The range of measurement should be in the order of magnitude equal to yield strength of the material, as we are interested in measurement to assess the susceptibility to SCC, stress needs only be known to exceed the safe stress limit. The time for a residual stress analysis including surface preparation must not exceed half an hour. Surface preparation must not disturb the surface stress levels. Device must be able to perform within temperatures experienced on site, 0-45 °C. Possible maintenance should be performed on site by Alcoa staff.

2.1.1 X-ray diffraction (XRD)

XRD relies on the elastic deformations within a polycrystalline material to measure stresses in a material. The deformations cause changes in the spacing and orientation of the lattice planes from their stress free value (d_0) to a new value that corresponds to the magnitude of the applied stress. If a tensile stress is applied, the lattice spacing will increase for planes perpendicular to the stress direction, and decrease for planes parallel. This new spacing will be the same in any similarly oriented planes, with respect to the applied stress and the crystal lattice therefore effectively acts as a very small strain gauge. [1] XRD measures an average stress level of longitudinal and transverse stresses. If stress as a function of depth is to be known, a destructive layer removal technique must be applied. The XRD measurement itself is relatively straightforward and equipment readily available. Portable diffractometers are available which can be taken out into the field for measurements of structures.

Measurement of residual stresses caused by welding is a fairly common application XRD systems. Known XRD technologies generally fulfil the criterion that Alcoa are after, however accuracy is expected to be in the range of +- 30 Mpa. The uncertainty is too high for Alcoa specifications. Additionally when price is taken into consideration (around $250K US per unit) XRD technology is not the most reasonable choice for Alcoa.

2.1.2 Hole Drilling

2.1.2 Hole Drilling

The hole drilling strain gauge method is the one of the most established mechanical techniques for measuring residual stresses and can be considered as non-destructive for large structures. It is relatively simple, cheap, quick and versatile. Equipment can be laboratory-based or portable, and the technique can be applied to a wide range of materials and components [4]. The general principle of the procedure involves drilling a small hole into a specimen containing residual stresses. A high-speed precision drill is to be accurately centred over the centre of a strain gauge rosette and zero-balanced. The hole is drilled at the point where residual stress is desired to be known. The rosette is bonded on to the surface of the specimen. The surface strains are relieved as the hole is drilled and incremental readings are made of the relaxed strains [11]. The hole drilling method does not release strains from inherent residual stresses completely. Thus, the stresses cannot be directly calculated from the measured strains. However from these strains the residual stress can be calculated using formulae and calculations derived from experimental and finite element analyses [8]. Some surface preparation is required to achieve good bonding of the strain gauges, but care must be taken not to remove too much material particularly if the residual stresses close to the surface are important.

2.1.3 Ultrasonic Methods

Ultrasonic techniques for the measurement of residual stress are based on variations of the wave speed within the material which are directly affected by the magnitude and direction of stresses present. Ultrasonic waves are launched by a transmitting transducer, propagate through a region of the material, and are detected by a receiving transducer. This will give information about stresses in the interior of the material. The velocity variation is proportional to the average stress in the region where the waves propagate [1]. This is known as the acoustoelastic effect. The underlying physics is based on atomic spacing. If we consider two atoms perfectly adjacent to each other, there is a strong repulsive force between them due to the negatively charged electrons interacting. As the interatomic distance increases, this force will decrease, until it reaches the equilibrium separation (the position of minimum energy). If we continue to increase this distance, temporary dipole forces will become present, creating increased attractive forces. These forces will increase until the distance exceeds the position of maximum attraction and will decrease due to weakening of magnetic field, proportional to distance. These distances are influenced by contraction and tension induced by strain in the material. The macroscopic response of a solid is determined by averages of these interatomic forces.

This technology has limited practical application due to errors caused by transducer coupling, preferred orientation, temperature, and grain size. The errors lead to stress tolerances being much greater than the desire 15Mpa range.

2.1.4 Magnetic testing

The ferromagnetic properties of steels and other ferromagnetic materials are sensitive to the internal stress state due to magnetostriction and the consequent magnetoelastic effect. Magnetostriction is the process whereby each magnetic domain, resembling an individual bar magnet, is aligned in the direction of magnetisation. It is a property of ferromagnetic materials that causes them to change their shape when subjected to a magnetic field. These length changes are usually extremely small, in the range of tens of parts per million. However, they do affect the domain structure of the material. At minimum energy the magnetisation will align with the 'easy' crystalline axis [3]. Using Barkhausen noise analysis residual stress levels can be found with relation to intensity of electromagnetic 'noise'. The techniques measurement is affected by many other variables, such as hardness, texture and grain size to a large extent, therefore precision cannot be trusted.

Magnetic testing is subject to many of the limitations and error sources of ultrasonic methods. Highly nonlinear response with low sensitivity to tensile stresses providing the largest drawback to the use of this technique [1].

2.1.5 Instrumented Indentation technique (IIT)

IIT is possibly the newest technique known to measure residual stresses. IIT for stress measurement works on the principal that stresses inside a material effect a material's hardness and thus indentation load. The effect is seen in differences between the stress free indentation loading curve (otherwise known as the load-depth or p-h curve) and the residual stress induced p-h curve for each material. Indentation is made to a fixed depth and the indentation force is measured. Tensile residual stresses reduce the load force needed to penetrate to a given depth compared to the stress free situation. Compressive stresses work vice-versa [2]. The greatest advantage of this technique when compared to other non-destructive residual stress measurement testing is the ability to avoid errors induced by changing microstructures in the heat affected zone (HAZ). A reference p-h curve can be created for each microstructure observed in the HAZ, with indentation load data being compared between the reference and the sample.

3 Experimentation

Welded samples, specified by Alcoa standard WPS P101 are being requisitioned to be created and send to known residual stress measurement companies for testing. The samples are to be tested using XRD, hole drilling, magnetic, ultrasonic and IIT technologies. The aim of these tests is to receive and compare residual stress profiles produced by each of the different technologies. This is the first step in determining the situation that actually exists on an Alcoa site. The results received by this testing will give a quantitative comparison between the different non-destructive techniques.

4 Acknowledgments

Thanks are extended to Alcoa personnel Art Woldan, Dr Olaf Celliers, Rob West, Metlabs personnel John Mclean, Robin Ainsworth and Tom Adam for the assistance given to the author.

5 References

[1] J. James Lu and L Mordfin 1996. *Handbook of Measurement of Residual Stresses*, Society for Experimental Mechanics, Inc., Lu, J. (Ed.), Fairmont Press, Inc., Georgia USA.

[2] Kyung-Woo Lee, Min-Jae Choi, Kwang-Ho Kim and Dongil Kwon, 2007, *Assessment of weld mechanical properties using instrumented indentation technique*, Seoul Korea.

[3] M. Bahiana and Belita Koiller, 1998, *Domain size effects in Barkhausen noise*, J. C. Denardin and R. L. Sommer, Departamento de Fı´sica, UFSM, Santa Maria Brazil.

[4] Measurements Group Inc, 1988, *Measurement of Residual Stresses by the Hole-Drilling Strain Gauge Method*, Tech. Note TN-503-3, USA.

[6] Paul Degarmo, 2003, Materials and Processes in Manufacturing, John Wiley and Sons, inc, USA.

[7] Professor Ian Henderson, 2002, *Cracking in weldments*, Technology awareness forum for Alcoa World Alumina Australia, Welding Technology institute of Australia WTIA, Australia.

[8] Professor R. Oettel Siempelkamp and Gutachter-Gesellschaft, *Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials,* The Determination of Uncertainties in Residual Stress Measurement, Dresden Germany.

[9] Russell Coade et al. 2000, *Ensuring the Integrity of a Contact Heater in the Digestion Train of an Alumina Refinery,* J ETRS Pty Ltd, VIC Australia.

[10] Standards Australia, 1997, *Pressure equipment manufacture - AS 4458,* Australian standards, Australia.

[11] The American Society for Testing of Materials ASTM, 1995, *Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method*, ASTM: E837-95, USA.