RESIDUAL STRESS EVALUATION OF A MIG BUTT WELDED ALUMINIUM ALLOY PLATE

P.M.G.P. Moreira, V. Richter-Trummer, R.A.M. da Silva, M.A.V. de Figueiredo, P.M.S.T. de Castro

Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ABSTRACT

Residual stresses are locked-in stresses which exist in a structural part without the application of any service or other external loads. The effects of residual stress may be either beneficial or detrimental, depending upon the magnitude, sign (tensile or compressive), and distribution of the stress with respect to the in service applied loads. In most cases, residual stresses arise from the production process. In this work residual stress in an aluminium alloy 6082-T6 MIG butt welded thin plate was evaluated using the sectioning and the hole drilling methods and a comparison between both methods was made.

Keywords: AA6082-T6, incremental hole drilling technique, MIG, sectioning technique, welding residual stress

1. RESIDUAL STRESS EVALUATION

Residual stresses are created due to mechanically induced plasticity or by thermal effects (Withers and Bhadeshia, 2001). In most cases, residual stresses arise from the production process. Virtually all manufacturing and fabricating processes (casting, welding, machining, molding, heat treatment, etc.) introduce residual stresses and alter the damage tolerance of those mechanical components. Quantitative estimation of residual stress is therefore important for a safe performance of structural components, (Venkitakrishnan *et al.*, 2007).

The strong thermal cycle during the arc welding process introduces microstructural modifications and heterogeneous plastic deformations, which in their turn lead to high tensile residual stresses that can be in the order of the material, yield stress. Contrary to this, some surface treatment techniques introduce compressive superficial residual stresses, which retard crack initiation.

Residual stress may be divided into three categories: acting over several grains (type I); acting over one grain (type II); or acting within one grain (type III). Residual stresses of type II and III, microscopic stresses, were not evaluated in this study. Only type I residual stresses have been evaluated in this work.

In order to measure residual stress mechanically, usually the locked-in stress must be relieved so that a sensor can register the change in strain caused by the relaxation of the stress. This is usually done destructively or semi-destructively by cutting, sectioning or by removal of successive surface layers.

Destructive methods are mechanical methods based on the relaxation of residual stresses when portions of the analyzed specimen are removed by some kind of machining or other material removing procedure. This may include the sectioning method, the contour method, and even in certain cases the X-ray measurement with which, following adequate material removal procedures, through the thickness results can be obtained. Normally this diffraction-based technique is considered as being non-destructive, when only superficial measurements are required.

In some structures, if a small hole is drilled to measure the strain relief (hole-drilling method) it can be considered almost non-destructive. The structure may stay usable as long as the created holes do not introduce significant stress concentration points, detrimental to its strength. Therefore this method is known as semi-destructive.

Diffraction techniques are the most efficient non-destructive techniques available. X-ray and neutron diffraction strain measurement techniques do not require stress relaxation and offer a non-destructive alternative, but also have limitations. They allow studying and separating all three kinds of residual stress. Unfortunately they need complex and expensive equipment, which can limit field application. Additionally, in the case of X-ray, they are limited to strain measurements in a limited depth, and normally Neutron diffraction based measurements do not accurately measure near the surface, although deep penetration can be achieved. Also, these techniques are usually not suitable to measure residual stresses in welded aluminium alloys due to the appearance of large grains and complicated textures during the thermal cycles in the welding process. According to (Fitzpatrick, et al., 2005), the X-ray method works well for grain sizes between 10 and 100μm. The present aluminium specimen has grain sizes between 50 and 100μm, and also its texture makes measurements more difficult. This is especially true in the welding zone, as can be seen in (Moreira, 2008) where this plates were measured by the X-ray method.

Welding is one of the most significant causes of residual stresses and typically produces large tensile stresses whose maximum value can be approximately equal to the yield strength of the materials being joined, balanced by lower compressive residual stresses elsewhere in the component. These large tensile stresses are often responsible for premature component failure. In the affected areas, due to the elastic superposition principle, high tensile stresses may appear which can easily exceed the yield strength of the material during service life.

During the welding process, a localized expansion occurs in the heat affected zone. While the metal is still in its fusion state, this space may be taken up either by molten filler material or by repositioned base material. Due to the high thermal gradients observed in an arc welding process, the cooling process may not occur in a homogeneous way throughout the whole plate. Some parts of the material may cool and therefore contract faster than others, leading to the creation of deformations and residual stresses, (Allen *et al.*, 1981). The high residual stress level at some locations (for example near the welding joint) strongly influences the fatigue life of components. As the stresses induced by welding may be as high as the yield strength of the material, when external loads of some kind are applied to the structure, yielding can occur.

In this work, residual stresses in an aluminium alloy 6082-T6 (with a yield stress of $276MPa$ and a rupture stress of $323MPa$) MIG butt welded thin plate were evaluated using the sectioning and the hole drilling methods.

1.1 Sectioning method

Residual stress was first estimated using the destructive sectioning method, which is based on cutting the specimen previously instrumented with strain gages, along a line perpendicular to the weldment. This technique relaxes the residual stresses essentially in the longitudinal direction and gives a reasonable estimation of the stress profile; care should be taken to avoid introducing plastic deformations during the cut. This procedure was previously applied with success as reported by other authors, *e.g.* (Walker *et al.* 1997 and Galatolo and Lanciotti 1997).

The sectioning method, a somehow expensive and time-consuming method, consists in making a cut on an instrumented plate in order to release the residual stresses that were present on the cutting line and measure the resulting strains. The cutting process used shall not introduce plasticity or heat, so that the original residual stress state can be measured without the influence of plasticity effects on the cutting planes' surface. Strain gages have to be applied to the section that should be measured, and afterwards a cut is made near this section. The maximum possible resolution of this method depends on the number of strain gages used. The main relaxation of residual stresses due to the cut can be related to the residual stresses using the following equation $\sigma = -\varepsilon \cdot E$.

Since the stresses to be determined are the residual stresses that were present before the cut was made, signs of the measured strains have to be inverted. The cut was performed using a band saw.

1.2 Hole drilling method

The introduction of a hole into a body with residual stresses relaxes the stresses at that location. The hole drilling method for residual stress measurements was first proposed by Mathar, 1934. Presently, this method is a widely accepted technique for measuring residual stresses. It is a semi-destructive technique where a tolerable small volume of material is removed. The basic hole drilling procedure, standardized in ASTM E837-08, 2008, involves drilling a small hole into the surface of a component at the centre of a special strain gage rosette and measuring the relieved strains.

The method is very versatile and can be performed either in the laboratory or the field, on different materials, and on components in a wide range of sizes and shapes. The hole is typically 0,8*mm* to 4,8*mm* in both diameter and depth. Nevertheless, achieving accurate results is not trivial; a meticulous measurement practice and the adequate choice of data analysis method are crucial for obtaining good results.

The theoretical background for the hole drilling method was first developed on the basis of a small hole drilled completely through a thin, wide, flat plate subjected to uniform plane stress. Such a configuration is far from typical applications since ordinary components requiring residual stress analysis may be of any size or shape, and are rarely thin or flat.

The aim of the hole drilling method is the evaluation of the in-plane residual stresses that can be assumed uniform with depth either from the surface of a thick specimen, or through the thickness of a thin specimen. The ASTM standard E837 refers to these cases. However, in many practical cases, the residual stresses are not uniform with depth. In such cases, the assumption of uniform stress with depth may give a misleading solution.

A blind hole produces a very complex local stress state which implies the use of empirical techniques for calculation of the residual stresses from the measured strains. The incremental hole drilling technique, which involves carrying out the drilling in a series of small steps, improves the versatility of the method and enables stress profiles and gradients to be measured.

The data-reduction relationships, equation (1), are applicable to the blind-hole when appropriate blind-hole coefficients are known. Compared to the through-hole procedure, blind-hole analysis involves one additional independent variable; namely, the dimensionless hole depth.

$$\sigma_{max,min} = \frac{\varepsilon_1 + \varepsilon_3}{4\bar{A}} \mp \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{4\bar{B}} \qquad (1)$$

$$tan(2\alpha) = \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}$$

Thus, in a generalized functional form, the coefficients can be expressed as:

$$\overline{A} = f_A\left(E, \nu, r, Z/D\right)$$
$$\overline{B} = f_B\left(E, \nu, r, Z/D\right)$$

where r is the ratio between the hole diameter and an arbitrary radius from hole centre. For any given initial state of residual stress and a fixed hole diameter the relieved strains generally increase (at a decreasing rate) as the hole depth increases. Therefore, in order to maximize the strain signals, the hole is normally drilled to a depth corresponding to at least Z/D=0,4 (ratio of the hole depth to the mean diameter of the strain gage circle). For any given set of material properties, elastic modulus E and Poisson's ratio ν, the coefficients $\overline{A}$ and $\overline{B}$ are simple geometric functions, and thus constant for all geometrically similar cases.

Whether the residual stress analysis application involves through hole or blind-hole drilling, the coefficients $\overline{A}$ and $\overline{B}$ must be determined to calculate the stresses from the relieved strains. In the case of the through hole, the coefficients $\overline{A}$ and $\overline{B}$ can be accurate values obtained by analytical calculation. Nevertheless, the needed coefficients for either through-hole or blind-hole analysis can always be determined by experimental calibration. As an example the $\overline{A}$ and $\overline{B}$ coefficients for the rosettes used in this study are provided graphically in (V.M. Group, 1993) for the blind holes and through holes assuming, in both cases, that the initial residual stress is uniform with depth.

A fundamental test should be made to check whether the residual stresses are uniform through the whole depth. This test indicates which type of analysis should be performed, for uniform stress data or for non-uniform stress data. As recommended in ASTM E837, it is always preferable to drill the hole in small increments of depth, recording the observed strains and measured hole depth at each increment. This procedure allows the judgment whether the residual stress is essentially uniform with depth, thus validating the use of the standard full-depth coefficients and for calculating the stress magnitudes.

The incremental data, consisting of relieved strain versus hole depth, can be used to detect if a non-uniform stress distribution is present. The Standard outlines the graphical procedure, for determining stress uniformity based on combination strains. The sums and differences of the measured strain data $\varepsilon_3+\varepsilon_1$ and $\varepsilon_3-\varepsilon_1$ or $\varepsilon_3+\varepsilon_1-2\varepsilon_2$ should be calculated for each depth increment (ASTM E837-08, 2008). The data should be expressed as fractions of their values when the hole depth equals 0,4 times the mean diameter of the strain gage circle. The data points indicate the percentage values of the specified strains and the curves show the limits of the two largest computed combination strains. The graph should yield data points very close to the curves presented in (ASTM E837-08, 2008). Data points that deviate by more than 3% from the curves presented in the standard indicate either substantial stress non-uniformity through the material thickness, or strain measurement errors.

At least five techniques for analysing residual strain data are available in the literature: Uniform Stress, Equivalent Uniform Stress, Power Series, incremental strain method and the Integral method. According to (Grant and Lord, 2000), developments of the integral method were introduced by Niku-Lari *et al.*, 1985 among others, where finite element calculations were used for calibration. In the integral method, the contributions of the total measured strain relaxations of the stresses at all depths are considered simultaneously (Schajer, 1988). This provides a separate evaluation of residual stress within each depth increment.

Previous studies have shown that the Integral method usually leads to the best results for non-uniform stress fields, in particular those where the stress varies rapidly with depth, *e.g.* (Grant and Lord, 2000).

According to (Grant, 2002) the integral method is able to decode relaxed strains that relate to highly non-uniform residual stress distributions. The same author states that for residual stresses near the yield stress, the integral method overestimates the true residual stresses within the calculated increment, but in the following increment, the calculated stress is an underestimation. Oscillations of this nature should be easily detected and such residual stress results have to be treated with extreme caution.

The ASTM standard E837 (ASTM E837-08, 2008) for the application of the hole drilling technique to uniform and non-uniform stress along the thickness also recommends this data reduction technique for similar cases.

2 RESULTS

A weld bead was deposited on aluminium alloy AA6082-T6 plates with the dimensions 450x500x3*mm*. The welding parameters used for all tests were: An Argon gas flow rate of 20*l/min*, 70*cm/min* weld travel speed, a current of 128*A* and a voltage drop of 17,1*V*. The stick-out was 15*mm*.

2.1 Sectioning method

For the acquisition of the longitudinal stress relieved during the cut twenty strain gages were applied, ten on each side of the plate (back and top side), see Fig. 1.

Strain gages were distributed on both sides of the weld bead to confirm symmetry, and they were concentrated in sites where a higher stress gradient was expected.

The gages were connected to three 8-channel Spider8 data acquisition systems manufactured by HBM and one 4-channel "P3 indicator and recorder" from Vishay.

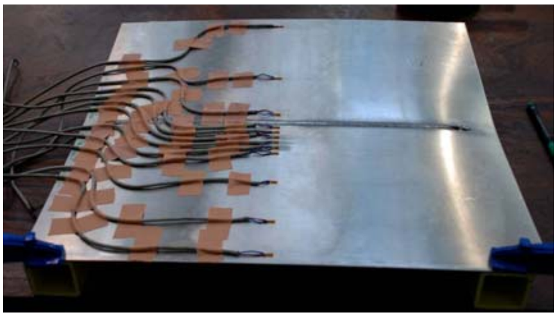

Fig. 1 – Instrumented plate before the sectioning method.

A personal computer was used to store the measured data from the data acquisition systems. Strain gages with the reference Vishay CEA-13-125UN-120 were used; their resistance was 120Ω±0,3% with a gage factor of 2,110±5%.

Two cuts at different distances from the strain gages were performed. The first cut was made at a distance of 10*mm* from the strain gage line in order to protect the strain gauges from the saw in a first attempt, see Fig. 2. The second cut was made to verify that the distance used in the previous one was able to describe the real stress state, leading only to a marginal difference in the strain result due to additional relaxation.

The residual stress profile measured is presented in Fig. 3. A symmetric profile was verified which enabled the representation of the profile for the complete plate width. The residual stress is always higher on the plate top surface (side of the weldment). It was

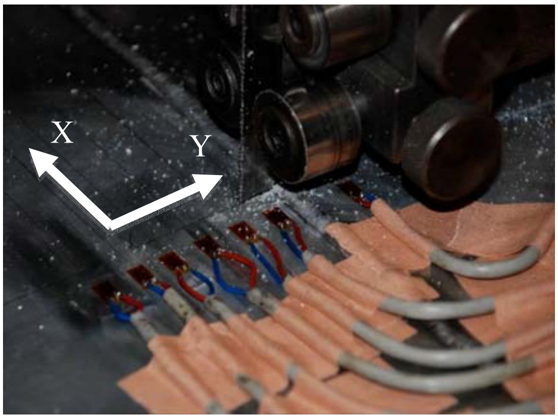

Fig. 2 - Sectioning method, band saw sectioning procedures.

verified that for distances higher than 25*mm* from the weld centre, the residual stresses in the back surface are compressive. On the top surface, between 35*mm* and 90*mm*, the residual stress is also compressive, but for distances higher than 90*mm* these become positive. For distances lower than 25*mm*, the residual stresses are of tensile nature, increasing towards the weld bead limit.

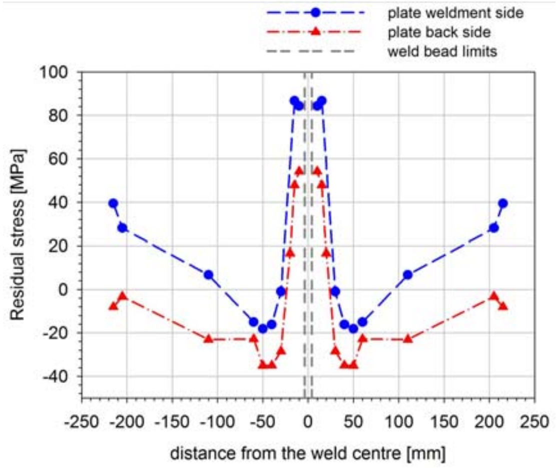

Fig. 3 - Stresses in the longitudinal direction obtained by the sectioning method.

2.2 Hole drilling method

Special three-element strain gage rosettes were installed on the test plate at the point where residual stresses were to be determined. Seven rosettes with a nominal resistance of 120Ω were used for the measurement: five rosettes of the type CEA-13-062UM-120 and two rosettes of the type CEA-13-062UL-120 from Vishay. The UL design has a gage-circle diameter equal to 3,25 times the active gage length. The UM rosette configuration has the same ratio of gage circle to grid length, but the grids are narrower in order to allow their close grouping on one side of the hole. The rosettes' main characteristics are presented in Table 1. Before application, the surface was degreased and abraded according to the Vishay Application Note B-129 keeping in mind that surface alteration should be kept to a minimum.

A precision milling guide was attached to the test part and accurately centred over a drilling target on the rosette. A detail of the milling equipment used is presented in Fig. 4. The hole has to be shallow and aligned with the centre of the rosette.

Table 1- Rosettes characteristics [*mm*]

	CEA-13-062UL-120	CEA-13-062UM-120
Gage length (per section)	1,57	1,57
Grid centreline diameter	5,13	5,13
Hole diameter	1,5 to 2,0	1,5 to 2,0
Matrix length	12,7	9,6
Matrix width	15,7	12,2

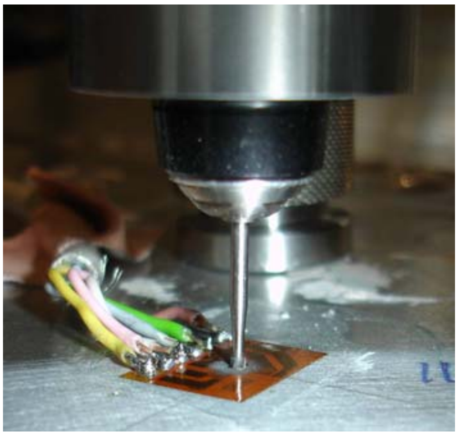

Fig. 4 - Hole drilling process.

The holes were drilled with a carbide-tipped cutter with a diameter of 1,6*mm*. The seven holes were positioned perpendicularly to the welding line at distances of 7,4*mm*, 15*mm*, 20*mm*, 30,4*mm*, 45*mm* 115*mm* and 150*mm* relatively to the centre of the weldment. 7.4 mm was the minimum distance from the weldment centre where it was possible to place a rosette. As an example, a picture of the hole drilled nearest to the weldment (7,4*mm*) is presented in Fig. 5. Because of the irregular geometry and surface of the weldment bead it was not possible to place any rosettes at the top of the weld bead.

Measured strain data was analyzed using the commercial software H-Drill (Schajer H-Drill). Using special data-reduction relationships the principal residual stresses

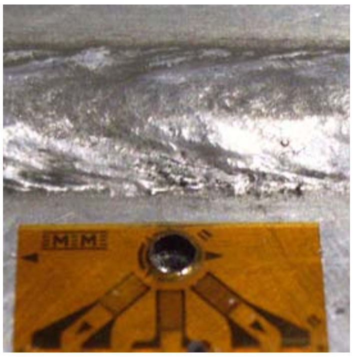

Fig. 5 - Hole closer to the weldment.

and their angular orientations are calculated from the measured strains.

The choice of which stress calculation method to use depends on which one gives the most satisfactory balance between a realistic result and a stable solution. Since the nature of the residual stresses being measured is generally not known in advance, the strategy was to try three methods (Integral, Power Series, and Uniform Stress). Engineering judgment combined with knowledge of the expected stresses and measured strains lead to the conclusion that the integral method had to be applied, since it had the most satisfactory balance between a realistic result and a stable solution. The strain misfit as described in (Schajer, 2006) was low enough to be valid in all measured cases.

In all seven sets of measured strain data, the uniform method could not be applied due to the variation of the residual stress through the thickness.

In this analysis the X stress is the stress in the weldment longitudinal direction and Y stress is aligned perpendicular to the weldment.

2.2.1 Hole drilled at 7,4mm from the weldment

Analyzing the data for the hole drilled at 7,4*mm* from the centre of the weldment it was observed that the integral method gave the best result, see Fig. 6. Nevertheless results were only valid until a depth of approximately 0,25*mm*. After that, the stresses reach a level of approximately 65% of the yield stress, which should be accepted as the limit, since according to (Lin, 1995) higher stresses may lead to errors between 32 and 47% (at 95% of the yield stress for example). At the surface a compressive residual stress field occurs and as the depth increases the stress value becomes positive.

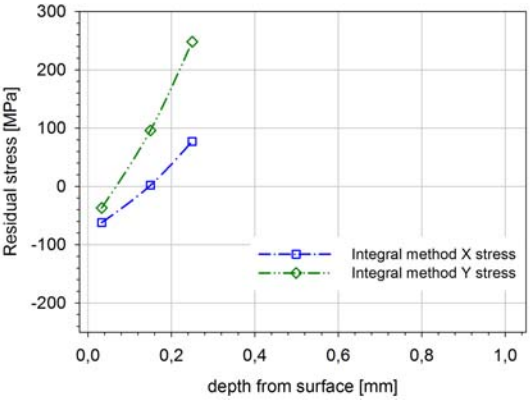

Fig. 6 - X and Y stress for the integral method, 7,4*mm* distance.

2.2.2 Hole drilled at 15mm from the weldment

Analyzing the data for the hole drilled at 15*mm* from the centre of the weldment it was observed that the integral method also gives the best approximation, see Fig. 7. The longitudinal stress has strong compressive values near the surface but from 0,2*mm* to 0,5*mm depth* it acquires tensile values. It should be noticed that in the range from 0,3*mm* to 0,7*mm* the calculated principal stress is higher than the material yield stress. Since the theory of elasticity is used to correlate the measured strain relaxation with the residual stresses existing prior to the drilled hole, local yielding caused by the stress concentration around the hole can affect the measured residual stress as soon as approximately 60% of the yield strength are reached. This effect normally leads to an overestimation of the real residual stresses by this technique, and the error can reach more than 50% (Nobre, 2000).

So, for this depth interval the values should be taken with great care. Nevertheless it may be concluded that a strong tensile stress field is present.

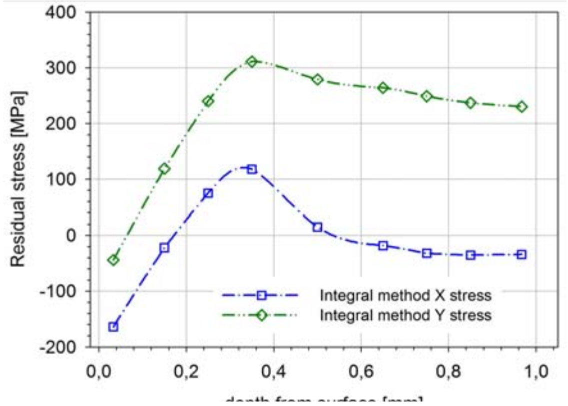

Fig. 7 - X and Y stress for the integral method, 15*mm* distance.

2.2.3 Hole drilled at 20mm from the weldment

For the hole drilled at 20*mm* from the centre of the weldment the integral method gave the best result, see Fig. 8. In this case results were valid until a depth of approximately 0,9*mm*. At the surface the longitudinal stresses are compressive and turn tensile that with depth at about 0,35*mm* to 0,55*mm*.

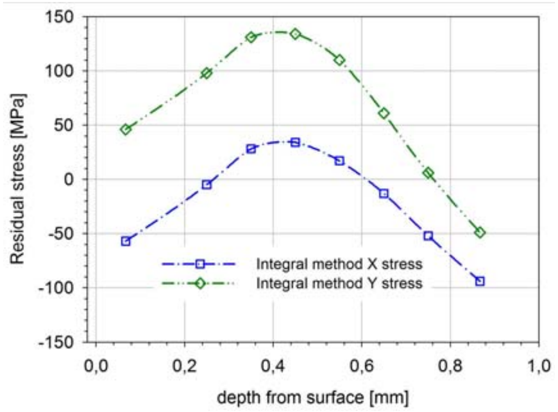

Fig. 8 - X and Y stress for the integral method, 20*mm* distance.

2.2.4 Hole drilled at 30mm from the weldment

For the hole drilled at 30*mm* from the centre of the weldment both the power series method and the integral method gave similar results, although the integral method describes the stress profile better, see Fig. 9. In this case results were valid until a depth of almost 1,0*mm*. The longitudinal stress is almost zero near the surface, getting compressive through the depth and stabilizing near 0,8*mm*.

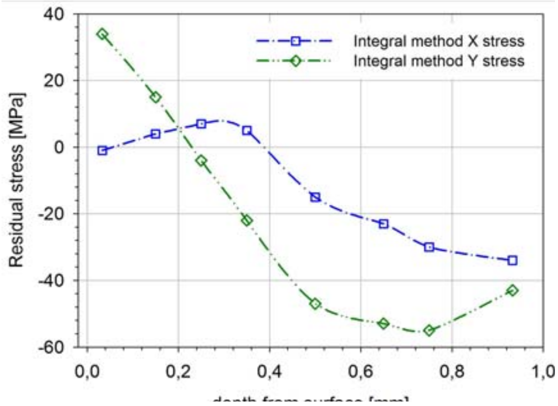

Fig. 9 - X and Y stress for the integral method, 30*mm* distance.

2.2.5 Hole drilled at 45mm from the weldment

For the hole drilled at 45*mm* from the centre of the weldment the integral method gives the best approximation of the real stress profile, see Fig. 10. In this case results are valid until a depth of almost 1,0*mm*. The longitudinal stresses are near zero up to a depth of 0,6*mm and turn* tensile afterwards.

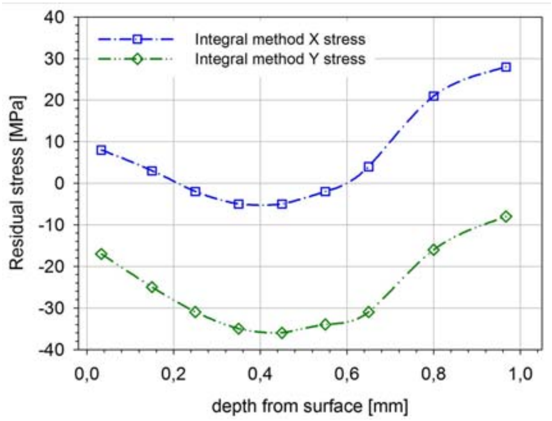

Fig. 10 - X and Y stress for the integral method, 45*mm* distance.

2.2.6 Hole drilled at 115mm from the weldment

The integral method also leads to the best approximation for the hole drilled at 115*mm* from the centre of the, see Fig. 11. Nevertheless, for the longitudinal stress (X stress) since the result is almost constant trough the dept (around 10*MPa*) the power method also gives a good approximation.

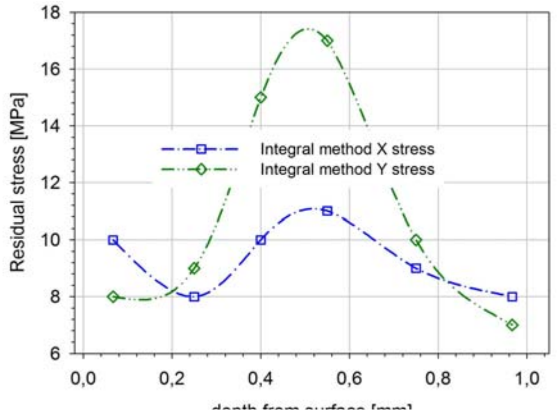

Fig. 11 - X and Y stress for the integral method, 115*mm* distance.

2.2.7 Hole drilled at 150mm from the weldment

Analyzing the data for the hole drilled at 150*mm* from the centre of the weldment it was observed that power method gives the best approximation to the stress profile as can be seen in Fig. 12. The longitudinal stress has tensile values through the valid measured depth up to approximately 1*mm*.

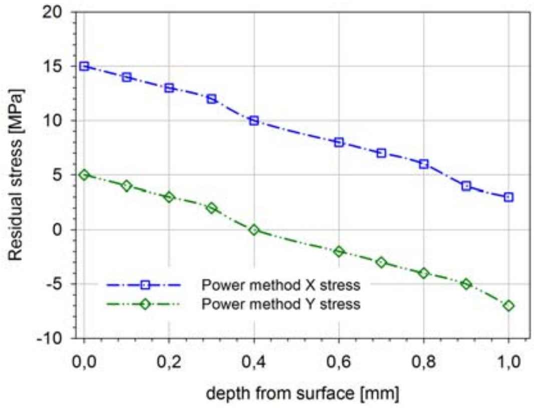

Fig. 12 - X and Y stress for the power method, 150*mm* distance.

3. RESULT DISCUSSION

The residual stress profile across the welding line for different depths is plotted in Fig. 13. For a distance from the weld centre of 30*mm* measurements at different depths present values between -10*MPa* and 10*MPa*. After this distance, the residual stress profile for all depths presents a linear variation with a positive slope. After 90*mm* the residual stress at all depths has similar values, which increase towards 20*MPa* at a distance of 150*mm* from the weld centre.

Near the weldment, measurements for depths lower than 0,1*mm* present high compressive stresses. As the depth of measurement increases, the residual stress becomes positive, and for a depth of 0,3*mm* they are in agreement with the results obtained with the sectioning method, Fig. 13.

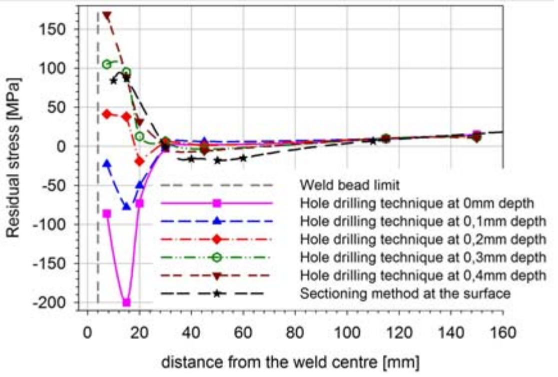

Fig. 13 - Hole drilling, longitudinal residual stress profile for different depths.

With the data collected from the hole drilling procedure a contour plot analysis of the longitudinal residual stresses through the thickness as a function of the distance from the weld centre was performed. This analysis resulted in two contour plots at the locations schematically represented in Fig. 14.

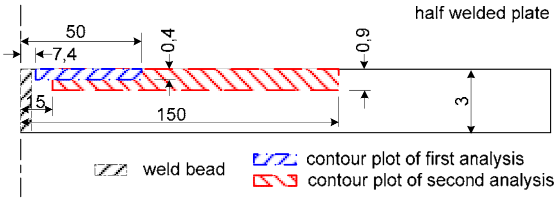

Fig. 14 - Schematic representation of the contour plots location.

Fig. 15 shows the longitudinal residual stress field up to a depth of 0,4*mm* and at distances from the weld centre between 7,4*mm* and 50*mm* The whole seven sets of were used.

In a second analysis, the longitudinal residual stress profile was analyzed up to a depth of 0,9*mm* and at distances from the weld centre between 15*mm* and 150*mm*, see

Fig. 16. For this analysis the rosette nearest to the weldment could not be considered because the data was only considered valid up to a depth of 0.25*mm*.

Near the weldment, at the surface and at a depth of about 0,9*mm* compressive stress fields can be seen. Between these areas, at a depth of around 0,4*mm*, the longitudinal residual stress becomes positive. As the distance from the weld centre increases, at all depths, the residual stress field has low tensile stress values.

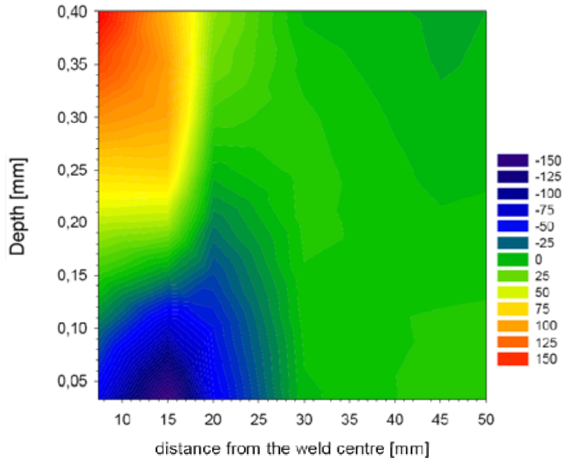

Fig. 15 - Longitudinal residual stress field for depths lower than 0,4*mm (residual stress is represented in MPa).*

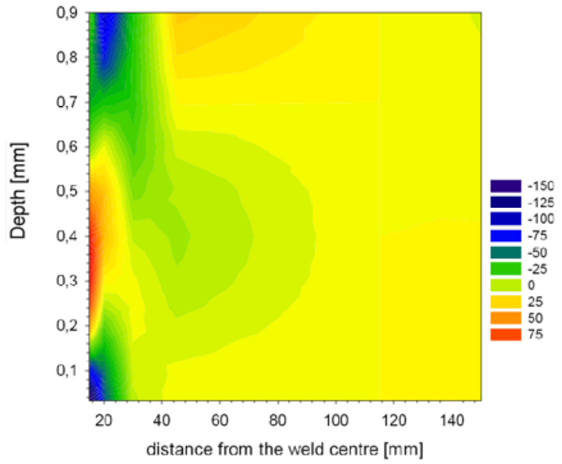

Fig. 16 - Longitudinal residual stress field for depths lower than 0,9*mm (residual stress is represented in MPa).*

4. CONCLUSIONS

The longitudinal residual stress values acquired with the hole drilling method at 0,3*mm* depth are similar to the values measured with the sectioning method. It was verified that the sectioning method also does not give the residual stress values directly at the surface. Considering this, the sectioning method and the hole drilling method are in good agreement.

The hole drilling procedure, a semi-destructive technique, proved to be a valid method when analysing residual stresses trough the plate initial depth. Nevertheless, the sectioning method, despite being more expensive and destructive, was capable of giving an average residual stress plot of the welded plate in a shorter time.

ACKNOWLEDGMENTS

The work was partially supported by PhD scholarship FCT SFRH/BD/19281/2004, FP6 project AST3-CT-2004–516053 and FCT PTDC/EME-TME/66362/2006. The collaboration of Albino C. Dias and José R. Almeida is gratefully acknowledged. The hole drilling hardware of I. P. Bragança was kindly made available by Dr. João Ribeiro.

REFERENCES

Withers P. and Bhadeshia H., Overview - Residual stress part 2 - Nature and origins. Materials Science and Technology, 2001. 17(4): p. 366-375.

Venkitakrishnan P., Philip J., and Krishnamurthy R., An assessment of stresses in thin walled welded tubes through hole drilling and sectioning methods. Journal of Materials Processing Technology, 2007. 185(1-3): p. 228-232.

Fitzpatrick M. E., Fry A. T., Holdway P.,

Kandil F. A., Shackleton J. and Suominen L., Determination of Residual Stresses by X-ray Diffraction – Issue 2. A National Measurement good practice guide, NPL, 2005, 52

Moreira P. M. G. P., Lightweight stiffened panels: Mechanical characterization of emerging fabrication technologies. PhD Thesis, 2008. Universidade do Porto

Allen J., Bailey N., Harrison J., Leggatt R., Parlane A., Procter E, and Saunders G., Residual stresses and their effects, ed. TWI. 1981.

Walker C., McKelvie, and Hyzer J., An analysis of residual stress patterns resulting from hole expansion in an infinite plate, a thick cylinder, and an asymmetric lug. Optics and Lasers in Engineering, 1997. 27(1): p. 75-87.

Galatolo R. and Lanciotti A., Fatigue crack propagation in residual stress fields of welded plates. International Journal of Fatigue, 1997. 19(1): p. 43-49.

Mathar J., Determination of Initial Stresses by Measuring the Deformation Around Drilled Holes. ASME Transactions, 1934. 56(4): p. 249-254.

Grant P.V., Lord J.D. and Whitehead P.S., The Measurement of Residual Stresses by the Incremental Hole Drilling Technique. A National Measurement good practice guide, NPL, 2002, 53

ASTM E837-08, Standard Test Method for Determining Residual Stresses by the Hole drilling Strain-Gauge Method. 2008.

V.M. Group, Measurement of residual stresses by the hole-drilling strain gage method, in Technical Note TN-503-5. 1993.

Grant P. and Lord J., An Evaluation of Four Hole Drilling Analysis Techniques with respect to Non-Uniform Residual Stress Fields. Measurement Note MATC(MN), 2000. 31.

Schajer G., Applications of Finite Element Calculations to Residual Stress Measurements. Journal of Engineering Materials and Technology, 1981. 103: p. 157-163.

Nikulari A., Lu J., and Flavenot J. , Measurement of Residual-Stress Distribution by the Incremental Hole-Drilling Method. Experimental Mechanics, 1985. 25(2): p. 175-185.

Schajer G. S., Measurement of Non-Uniform Residual Stresses Using the Hole Drilling Method. Journal of Engineering Materials and Technology, 1988. 110(4): p. Part I: pp.338-343, Part II: pp.3445-349.

Schajer G. S., H-Drill software. V 3.01, ed. V.M. Group.

Schajer G. S., H-Drill User Guide. 2006

Lin Y.C. and Chou C.P., Error induced by local yielding around hole in hole drilling method for measuring residual stress of materials. Mat. Sci. Tech. , 1995, 11: pp. 600-604

Nobre J. P., Kornmeier M., Dias A.M. and Scholtes B., Use of the Hole-drilling Method for Measuring Residual Stresses in Highly Stressed Shot-peened Surfaces. Exp. Mech., 2000. 40(3): pp. 289-297