

RESIDUAL STRESS MEASUREMENT USING THE CONTOUR AND THE SECTIONING METHODS IN A MIG WELD: EFFECTS ON THE STRESS INTENSITY FACTOR

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ABSTRACT: The longitudinal residual stress distribution in a 6082-T6 aluminum alloy MIG butt welded thin plate was determined using the contour method. Although several geometries have been successfully studied with the contour method before, the authors are not aware of previous attempts to use this method in a long narrow section as in the present case. Validation was done using literature data including the CEGB-R6 procedure as well as experimental plate surface measurements obtained using the established sectioning technique. The residual stress measurement was used in fatigue crack growth simulations in order to compare the fatigue behavior of the plate with and without residual stress.

Keywords: Contour Method, Fatigue crack growth, MIG welding, Residual stress, SIF calibration

RESUMO: A distribuição longitudinal de tensões residuais de uma placa fina em alumínio 6082-T6, soldada topo-a-topo por arco eléctrico, foi determinada com o método *contour*. Mesmo tendo esta técnica sido aplicada a várias geometrias distintas, os autores desconhecem a sua aplicação a uma placa de secção fina como a apresentada no presente trabalho. A validação dos resultados foi efectuada através de resultados obtidos na literatura, incluindo o procedimento CEGB-R6, e também através do já conhecido método experimental de seccionamento. A medição de tensões residuais foi utilizada na previsão do crescimento de uma fenda de fadiga, com o intuito de comparar o comportamento ao de uma fenda a crescer na mesma placa livre de tensões residuais.

Palavras chave: Calibração do factor intensidade de tensão, crescimento de fendas de fadiga, método *contour*, soldadura MIG, tensão residual

1. INTRODUCTION

Residual Stress

Residual stresses, either tensile or compressive, are those that remain in a body when it is stationary and in equilibrium with its surrounding [1]. Residual stress effects may be either positive or negative. If applied on purpose, in most cases they are of compressive type, for example reducing the probability for crack initiation. Positive residual stresses introduce an initial stress level which reduces the maximum permissible exterior tensile stresses. These are most commonly introduced by production processes.

Residual stresses with negative effect on the fatigue life may be found for example in MIG (Metal Inert Gas) welds. In

the center of the welding pool the highest tensile residual stresses may be encountered. Along the full width of the specimen, the equilibrium has to be balanced, and therefore compressive residual stresses have to exist. In this case, the maximum expected residual stress should be limited by the weld metal's yield stress; however the weld bead is a mixture of filler wire and base material, and it is likely that local yield stress values will be in the range between filler wire and base material values.

The residual stress measuring techniques can be divided into three categories: non-destructive, semi-destructive and destructive. The techniques described within this work are both destructive methods which rely on stress relief caused by material removal.

Residual stresses may be reduced by design, using specialized production processes, or they may be removed after their creation by heat or vibration treatment for example.

MIG welding

Metal inert gas welding (MIG) is a fusion welding process with a consumable wire electrode. Developed in the 1940s, it is now widely used in industrial applications and is also well understood from the scientific point of view.

2. SPECIMEN

A MIG weld bead was deposited on a 500 mm x 500 mm and 3 mm thick plate by a FANUC Arc Mate SR robot. Clamping does not prevent distortion, because the plate was only restricted on four points. Longitudinal residual stresses should not be affected significantly by this preparation since the clamping rigidity in this direction is weak. The welding parameters are shown in Table 1.

Table 1. welding parameters

voltage drop	17.1 V
current	128 A
stick-out	20 mm
welding speed	700 mm/min

Aluminum alloy 6082, in the T6 condition achieved by artificial aging at 180°C, was used for this work. Tensile tests of the specimen base material (BM) were carried out to obtain the stress/strain curve and the major material properties (σ_y , σ_r , E and elongation ϵ), using a 250 kN servo-hydraulic MTS testing machine and a 25 mm gauge length. The ASTM E 8M [2] standard was followed. Results are given in Table 2.

Table 2. tensile strength data

yield strength [MPa]	rupture stress [MPa]	Young's Modulus [GPa]	elongation
322	376	64.9	18%

These values are in agreement with those presented in the literature for the same material [3].

3. DETERMINATION OF LONGITUDINAL RESIDUAL STRESSES

Contour method

The contour method has been developed by M B Prime at Los Alamos National Laboratory [4]. It consists of the measurement and analysis of a cut-surface in the plane where residual stress is to be determined. The stress relief because of the cut creates a deformation field which can be measured and then used to infer the residual stresses that were present at the plane of interest before the cut was made. In the present case, this plane is a very long and narrow section (500 mm x 3 mm) of the welded specimen, as mentioned before.

The procedure is divided into four main phases which are described in this section.

Cutting

Since the residual stress distribution is to be determined in the center of the welded plate, it is cut into two halves perpendicular to the welding deposition line. The cut is done by wire electric discharge machining (wEDM), because according to Prime et al. [5] this process introduces less residual stresses which could influence the result, than other cutting methods. Wire electric discharge machining removes material by spark erosion. Since this is a non-contact method, it does not create localized plastic deformations on the cut surface as it is the case in conventional machining. The surface of the cut has a very good finish, which simplifies the data treatment procedure needed to smooth the measurement data of the deformed surface.

Actually the clamping used in this work is not as complex as the clamping described by M B Prime [4], but as can be seen later on, it is sufficient to effectively eliminate plasticity induced errors and to guarantee a straight cutting plane.

Cut-surface measurement

The surface of the wEDM cut has to be digitized in a way that permits the introduction of gathered data into a finite element model. Touch-probing is chosen for this process because of its availability, and because it was already successfully used by Prime [4].

The measurement is done using a touch probe with an 1 mm diameter Renishaw ruby tip on a Brown & Sharp CMM (Coordinate Measuring Machine), model Gamma, since it meets the precision requirements.

Measurements were taken along the centerline of both plate halves.

Data preparation

In order to be able to apply the measured data to a finite element model, this data has to be prepared. The measured geometry has to be translated into nodes and elements which define the mesh used, and the noise must be filtered out of the deformation measurement. Most of the data preparation is done within the MATLAB programming environment.

Four essential points should be considered when preparing the measured data:

The mean value of each data-point is taken between both halves of the plate after interpolating them onto the same grid, in order to guarantee that every single points' error is reduced. The resulting mean displacement distribution is the one that would have been obtained on both halves, if the cut had been exactly linear throughout the whole section.

The data is smoothed, and fitted to continuous functions with continuous first derivatives, so that the interpolation of the node values to the Gauss points does not create errors and the stresses are correctly passed from one element to the next. Since a very small difference in the displacement distribution, can lead to big differences in calculated stresses, the selection of the smoothing function has to be done with great care. Because of differentiation when calculating the stresses, local variations in the displacements will be amplified in the stress results..

The data has to be aligned to a horizontal cutting plane, since there is no warranty up until now that the measured cut-surface was in an overall horizontal position while measured by CMM. This procedure guarantees the moment equilibrium of the surface residual stresses.

The mean value of the deformation has to be subtracted in order to guarantee that in the linear model the tensile and compressive stresses have similar integral values along the cut surface. This is necessary, because the plate is in equilibrium and no reaction force may result from the deformation of the cut surface.

Modelling

A linear elastic finite element model is chosen to serve as a calculation base for the expected residual stresses. As mentioned in [4], since the deformations are small, the analysis is linear and the deformation may be applied to a simple model.

The only objective of the used constraints is to prevent rigid body motion, since in reality the plate is not restrained when the displacement is measured. The calculated stresses should not be influenced, therefore only one constraint in two directions perpendicular to the displacement (x and y) is applied, and the rotation around the displacement axis is restrained as can be seen in Figure 1. This is easily understandable, since the real plate is not restrained in any manner when the measurement is done.

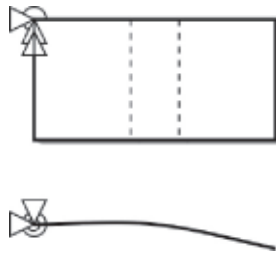


Fig. 1. Applied constraint to prevent rigid body motion

Because the plate may be considered thin, S4 elements were used, which are based on a plane stress formulation.

The smoothed displacement discussed before is applied to the finite element model, where the stresses are calculated.

The contour method calculates the residual stress distribution in the plane of the cut, and is not intended to provide the stress field for the complete body.

Sectioning method

The sectioning method is also used for residual stress determination for comparison and validation of previous results obtained.

The sectioning method has been successfully used, for example by Lanciotti *et al* at the University of Pisa [6]. This is also a destructive method, expensive and time-consuming since strain gauges have to be applied to the section that should be measured, and then a cut is made near this section.

The sectioning method consists in making a cut on an instrumented plate in order to release the residual stresses that were present on the cutting line. For this, the cutting process used should not introduce plasticity or heat, so that the original residual stress can be measured without the influence of plasticity effects on the cutting planes' surface.

Good residual stress measurement results obtained with this method are reported in the literature, *e.g.* [6] and [7] for welded stiffened aluminum structures and centre cracked tension specimens accordingly.

18 strain gauges are used on top and bottom of the left side of the plate. The right side has only 6 strain gauges on top and on bottom in order to verify the symmetry of the obtained stresses in relation to the deposited welding line. The maximum possible resolution of this method depends on the number of strain gauges used.

The strain-gauge locations, concentrated in sites of high stress gradients, were chosen taking into account preliminary results obtained by the contour method.

For acquisition of the stress relieved during the cut, 24 strain gauges are used. Those gauges are connected to three 8-channel Spider8 data acquisition systems manufactured by HBM. A three wire quarter bridge connection is used for the strain gauges so that possible perturbations can be reduced. Vishay CEA-13-125UN-120 strain gauges are used. Their resistance is $120.0\Omega \pm 0.3\%$ with a gauge factor of $2.110 \pm 5\%$.

The stresses are those necessary to create the measured deformation as soon as the cut has relaxed the specimen. Since the stresses to be determined are the residual stresses that were present before the cut is made, signs of the measured stresses have to be inverted. Young's law is used for stress determination, since no plasticity is considered in the present case. Since the residual stresses were verified to be symmetric over the welding line, the right half of the representation in Figure 2 is a symmetric copy of the left one.

Stress measurement results of both methods

Figure 2 shows a comparison between the centerline residual stress obtained by the contour method and both plate surfaces measured by the sectioning method.

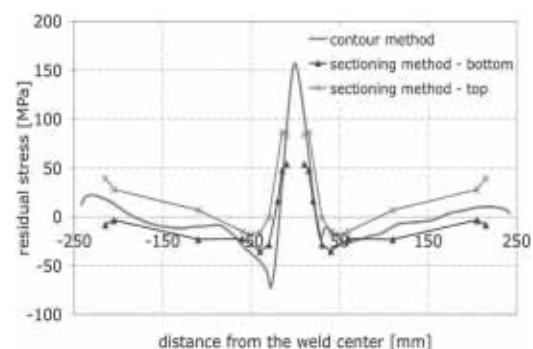


Fig. 2. Comparison between the longitudinal residual stresses on the center-line obtained by the contour method and by the sectioning technique on the top and bottom side of the plate

Now it is possible to say that, even if the stress results are not equal, a good agreement is achieved in most positions of the plate.

Validation of both results by the CEGB-R6 procedure

The yield zone dimension (Y_0) may be calculated for a thin plate as shown in equation 1 using known parameters defined in the CEGB-R6 procedure [8]: process efficiency η , arc power q , weld travel speed v , plate thickness t , yield strength σ_{yp} and a material constant K .

$$Y_0 = \frac{1.003K \eta q}{\sigma_{yp} vt} = 29.1 \text{ [mm]} \quad (1)$$

This is remarkably similar to the values of the order of 27 mm indicated in Figure 2.

Knowing that the maximum yield stress of the filler wire is 120 MPa and the one of the base material is 270 MPa, considering that the weld bead is a mixture of both, according to this procedure, the maximum residual stress is to be expected between these two values.

As can now be verified, the experimentally obtained values of about 180 MPa maximum longitudinal residual stresses in an area near the welding line ($Y_0 \approx 27$ mm) are in very good accordance to the values predicted by the CEGB-R6 procedure [8].

4. FATIGUE LIFE PREDICTION

When external loads are applied to a cracked solid with residual stresses, fatigue crack growth behavior is expected to be different from the behavior in absence of residual stresses.

The objective of this section is to compare predictions of fatigue crack growth with and without considering residual stresses in the model. A shell model will be used as an approximation since it provides a good approximation for this narrow plate.

Finite element modeling

As crack opening load for the comparison done in this section, a constant 50 MPa remote stress on the top of the plate is applied. As a result of this remote stress and the locally applied residual stress, depending on the crack length, either compressive or tensile stresses act on the crack tip, resulting in a variation of crack growth rates along the calculated crack lengths.

In order to be able to apply nodal loads equivalent to the calculated residual stresses, the stress values are multiplied by their area of influence, as represented in Figure 3.

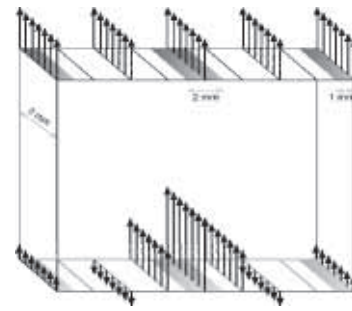


Fig. 3. Scheme to transform calculated stresses into nodal loads

As it is evident, in a shell model, the nodal loads are evenly applied throughout the defined thickness of 3 mm. Since the elements have a 2 mm long side, the area on which each nodal load acts is 6 mm², with an exception for the nodes on the extremities where the nodal loads act only on 3 mm². This means that in order to be able to apply nodal stress to a node as a load, the value has to be multiplied by the area on which it is supposed to act so that a discrete stress model can be created; each node will be loaded with 300 N.

Two solutions with 100 steps each are shown using ABAQUS for the cases with and without applied residual stress. The initial crack length considered was 4 mm and the crack grows 4 mm in each step. Since this shell model has only 14460 S4 elements and 14762 nodes, the computational effort is not very high; the analysis takes approximately 40 min to complete on a dedicated workstation running Linux using an Intel P4 processor at 2.4 GHz and 2 GB RAM.

Stress intensity factor calibration

Virtual crack closure technique (VCCT) [9] is used to calculate the stress intensity factor (SIF) for both cases on the left side of the crack.

After retrieving the necessary data from the FE (finite element) model, equations 2 to 4 allow the determination of the SIF by an energetic method for a model considering symmetry:

$$\Delta E_{step_i} = \frac{1}{2} (2U_{step_i+1} * RF_{y_step_i}) \quad (2)$$

$$G_1 = \frac{-\Delta E}{thickness * distance_between_nodes} \quad (3)$$

$$K_1 = \sqrt{G_1 * E} \quad (4)$$

In Figure 4 a comparison of K_1 vs. $2a$ can be seen for both cases using the VCCT method. The residual stress values were applied as nodal load to the crack surface as is shown in Figure 3.

It should be noted however that the sum of the residual stress and the applied remote stress is very near the yield strength of the material. This does not influence the calculated results, since as an approximation a linear elastic model was used with no yielding effects.

In this model no relaxation is considered because of the growing crack as it exists in reality. Since the difference visible in Figure 4 is small as the crack grows beyond $2a = 30$ mm, this simplification is not expected to introduce significant errors. As can be verified, only in the longitudinal position where high tensile residual stresses act (near the center of the weld bead), higher SIFs are found.

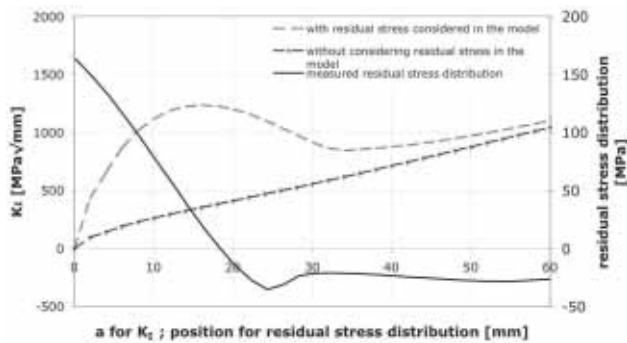


Fig. 4. Superposition of the residual stress distribution and the SIF calibration

It is easy to see that only the high residual stresses in the center do have a significant effect on the stress intensity factor of the analyzed specimen.

The effect of residual stress on the SIF calibration has already been shown by *e.g.* Masubuchi [10], albeit expressed in terms of strain energy release rate (G) and not K as in the present work.

Fatigue life prediction

The basic crack growth law parameters for material Al6082-T6 may be found in the NASGRO database, [11].

In conjunction with the SIF calibration presented before, the NASGRO equation for plain stress is applied to obtain the crack growth rate for each crack increment of 4 mm as follows:

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-R} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(\frac{K_{max}}{K_c} \right)^q} \quad (5)$$

As value of ΔK the mean of two consecutive steps was taken. This has been done because it seems to be a reasonable approximation for the SIF that would exist if the mesh was more refined. The parameters of equation 5 are defined in the NASGRO database being the most important ones the threshold value for ΔK , K_{th} and its critical value K_c .

The stress ratio R was taken as $R = K_{min}/K_{max}$, being $K_{max} = K_{res} + \Delta K_{applied}$ and $K_{min} = K_{res}$, in order to contemplate for the residual stress effect.

This is necessary, since R is affected and ΔK is not affected by residual stress.

Finally the number of life cycles estimated by equation 6 is shown in Figure 5.

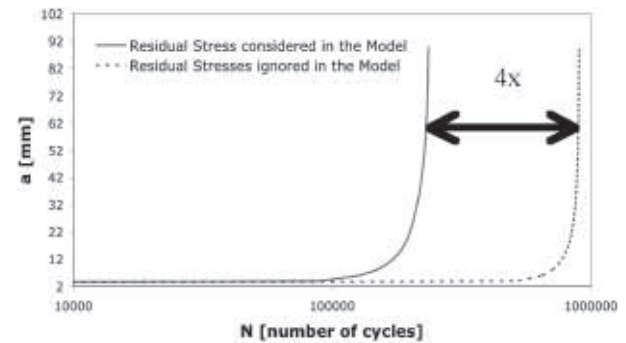


Fig. 5. Comparison of both crack growth cases; representation of the difference between expected life with and without considering residual stress in the prediction model

$$N^i = N^{i-1} + \frac{(a_i - a_{i-1})}{\frac{\Delta a}{\Delta N}} \quad (6)$$

It is now clear that residual stress greatly influences the fatigue life of components. When comparing this result to Figure 4, one notices immediately that the crack growth rate of both models is quite different in the zone where the residual stress has its main influence. This leads to a premature acceleration in crack growth which will end up in significantly reducing the components fatigue life, a trend discussed recently for example in [12].

5. CONCLUDING REMARKS

Both the contour method and the sectioning technique lead to a good approximation of existing residual stress. The contour method provides higher spatial resolution, while the sectioning technique is easier to apply since almost no calculations are needed.

The transformation of stresses into nodal loads using an affected area should be seen as an approximation, possible for the case of a shell model. Other more complex ways to apply residual stresses to FE models exist within the ABAQUS FE package.

Residual stress has a strong influence on the SIF calibration, and should therefore not be ignored in life prediction models.

The detrimental influence of positive residual stress on the fatigue life of components was demonstrated through numerical modeling based on the NASGRO equation.

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REFERENCES

- [1] P. J. Withers, H. K. D. H. Bhadeshia, "Residual stress, Part 1 - Measurement techniques", *Materials Science and Technology*, vol. 17 (April 2001) pp. 355-365
- [2] ASTM E 8M, American Society for Testing and Materials
- [3] Lanema catálogo técnico 05 (2005)
- [4] M. B. Prime, "Cross-sectional mapping of residual stresses by measuring the surface contour after a cut", *Journal of Engineering Materials and Technology*, Volume 123 (April 2001) pp. 162-168
- [5] M. B. Prime, M. R. Hill, A. T. DeWald, R. J. Sebring, V. R. Dave, M. J. Cola, 2002, "Residual stress mapping in welds using the contour method", in: *Trends in Welding Research, Proceeding of the 6th International Conference*, April 15-19, 2002, Pine Mountain, Georgia, eds: S.A. David *et al.*, ASM International (2003) pp. 891-896
- [6] A. Lanciotti *et al.*, presentation at the Porto meeting of the European Union DaToN project (April 17-18, 2007)
- [7] R. Galatolo, A. Lanciotti, "Fatigue crack propagation in residual stress field of welded plates", *International Journal of Fatigue*, vol. 19, (1) (1997) pp. 43-49
- [8] British Energy R6 Rev.4 Section IV.4
- [9] R. Krueger, "The virtual crack closure technique: history, approach and applications", ICASE report, NASA (2002)
- [10] K. Masubushi, "Analysis of welded structures", Pergamon, 1st edition (1980)
- [11] NASGRO 4.0 database (<http://www.nasgro.swri.org/>)
- [12] L. Edwards, M. E. Fitzpatrick, P. E. Irving, I. Sinclair, X. Zhang, D. Yapp, "An integrated approach to the determination and consequences of residual stress on the fatigue performance of welded aircraft structures", *Journal of ASTM International*, vol. 3, No. 2 (February 2006) pp. 1-17