Prediction of welding residual stresses and displacements by simplified models. Experimental validation

A. Barroso[1], J. Cañas[1], R. Picón[1], F.París[1], C. Méndez[1] and I. Unanue[2]
[1] Group of Elasticity and Strength of Materials, School of Engineering, University of Seville, Spain.
[2] Industria de Turbo Propulsores S.A. (Planta de Zamudio, Spain)

Abstract: Numerical simulations of welding processes are complex and computationally expensive. Several simplificative hypotheses are typically used in the simulations for time saving considerations, some of which have been explored in this work. The simulations carried out have been performed at process level (butt weld of two thin Nickel alloy plates). Looking for a representative simplified model, the study carried out basically affects the use of different well known temperature field solutions taken as input data, and the influence that the variation of the mechanical properties with temperature has on the solution of the problem. Experimental validations have been performed to check the influence of the simplificative hypotheses on the residual stress and displacement fields. The comparison between numerical and experimental data shows that, in most cases, the simplificative hypotheses lead to quite acceptable results. The application of these simplificative hypotheses is useful at preliminary design stages, allowing a higher number of simulations for the search of an optimum design to be carried out. This study, performed in the framework of the European Project "VERDI", is oriented towards helping complex manufacturing processes involving different stages (metal deposition, welding, heat treatment, shot penning, machining,...) each of them requiring expensive numerical simulations. The creation of a simulation chain in which each step would be analyzed by simplified fast simulation tools would allow these preliminary stages of design to be optimized.

1.- INTRODUCTION

Welding is a highly complex process which requires expensive numerical models (expensive in terms of computational time) to be reproduced in detail. The complexity of these numerical simulations is determined by the scale in which we are interested and the accuracy needed for the weld design. The constitute laws which have to be used for the numerical simulation and the scale of the analysis are very different if the phase changes and microstructure are the key variables or if, on the contrary, only the macroscopic residual stresses and displacements are of interest, as will be the situation considered in this paper. In complex manufacturing processes where each step (e.g. metal deposition, welding, heat treatment, shot penning, machining,...) creates or modifies the residual stress and displacement fields (at macro-scale) in the components, it becomes necessary to reduce costs to have a tool to reproduce the manufacturing chain in a simplified, easy and non-expensive way. Focusing on the welding stage, the influence of the different welding sequences in the final residual stress and displacement fields is of interest, but from a macroscopic point of view. Simplified models help to find approximate solutions with a reasonable computation time, but assuming, of course, lack of detailed information in accordance with the level of simplified assumptions used in the simulation. At preliminary stages, and taking into account that welding is part of a complex manufacturing chain, preliminary results have to be achieved by means of a simplified simulation chain. An attempt has been made to cover the welding contribution in this work, which is part of the VERDI project of the 6th Framework Program.

An excellent overview of the different aspects of performing numerical, Finite Element analysis of welding can be found in Lindgren [1]. There are, of course, alternative proposals not using Finite Element Analysis, such as a self-developed one-dimensional model in a Fortran code by Cañas *et al*. [2,3] for simplified analyses of the longitudinal residual stress state and angular distortion of the weld pool. In the framework of this study, the main input data for global analysis of residual stresses and displacements after welding is the temperature field. A number of different proposals have been used, which can be roughly sorted by increasing complexity as follows:

- Cañas *et al*. [2,3] one-dimensional bar model, considering elastic-plastic behaviour and temperature fields which do not vary along the weld direction.
- Michaleris et al. approach [4,5], using an equivalent temperature field and a pure-elastic analysis.
- The thermal envelope model, which applies at each location the maximum temperature value, obtained, for example, using Rosenthal [6] equation.
- Line heat model, which is time dependent, but only considers heat flow in the direction perpendicular to the weld seam. The temperature profiles are obtained using, for example, Rosenthal [6].
- Rosenthal [6] model for thin plates, using a temperature profile which moves together with the heat source location.

All these models, which will be briefly described in Section 3, comprise different levels of simplification, from a one-dimensional model, passing through pure elastic analysis, to the most complex elastic-plastic analysis with the moving temperature field. Other well known existing proposals, with higher levels of complexity, like the one by Pavelec *et al*. [7] using a circular disc heat source model with Gaussian distribution of heat flux on the surface of the workpiece, and Goldak *et al*. [8,9] using a double ellipsoidal power density distribution of heat source model below the welding arc, have not been taken into account in this paper as they are computationally expensive compared with these previously mentioned thermal solutions. These more complex models, which must be used for detailed local analysis of the welding process, do not fall within the scope of this work, as their formulation and numerical implementation can hardly be considered simplified models.

The scope of this work is the analysis of the residual stresses and displacement fields appearing in the butt welding of thin Nickel alloy plates. The use of different simplificative hypotheses has been studied in terms of time saving and accuracy of results. The simulations have been compared with experimental results. The main assumptions have been focused on the use of simplified temperature fields arising from the heat input of the weld process, which are detailed in Section 2. For local analyses, at the scale of the weld pool, most of the heat input models, which are useful for macroscopic stress analysis, are no longer valid, due to the fact that the heat source can not be considered a concentrated source at this scale level.

In addition, a parametric study regarding the non-linearity of the temperature dependency on the mechanical properties of the material has been carried out in Section 3. The influence on the residual stress field of mechanical properties which are considered to be temperature dependent (or not) is fully explored. Comparisons between models are presented in Section 4, while the validation with experimental results is detailed in Section 5.

To conclude this introduction, it has to be emphasized that the main aim of this work is to check the level of accuracy of macro-scale residual stress and displacement field predictions when using different simplified thermal solutions in non-expensive models (from a computational point of view) to be used in a simulation chain and not to propose new complex models.

2.- DIFFERENT MODELS FOR SIMPLIFIED WELDING ANALYSIS

A brief overview of the different models introduced above will be presented in this section. The order of presentation of the models has been altered with respect to the previous section due to the fact that the "Thermal Envelope" and the "Line Heat" models have been deduced using "Rosenthal" model, which is described in advance for the sake of clarity. A common coordinate system is adopted for all models, y being parallel to the weld seam, x the perpendicular in-plane direction and z the thickness direction, Fig. 1. As all thermal models are quite well known in the literature, only the main aspects will be outlined. It is important to stress out that, although the thermal analysis is typically faster than the stress analysis, models having time dependency need a higher computation time as they need to solve several steps, each one of them having both the thermal and stress analyses. One of the aims of this work is to check out if numerical solutions not having this detailed time history information, lead to acceptable results which could be used in preliminary stages of design and manufacturing.

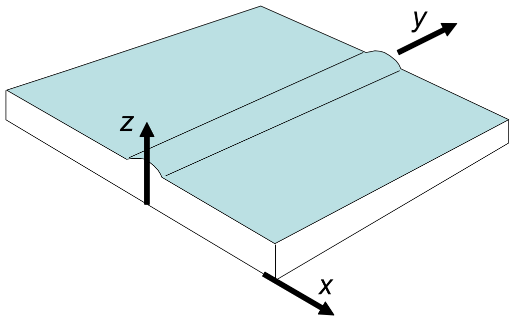


Fig. 1.- Geometry and coordinate system.

2.1.- The Bar problems by Cañas et al. [2]

A simplified 1D bar model developed by Cañas *et al*. [2], see also [3] has been proved to give precise results for evaluating longitudinal residual stresses σ_{yy} and angular distortion at the neighbourhood of the weld line. The model has been developed in a Fortran code and is extremely fast in CPU time when compared to usual Finite Element problems.

Two different problems can be modelled using this tool: a) longitudinal residual stresses σ_{yy} in the plate, using bars parallel to the weld seam, and b) angular distortion in the transversal section, using bars in the thickness to model the weld pool shape. Mechanical properties can vary with temperature and ideal elastoplastic non-holonomic behaviour is considered for the bars. Forces, momentum equilibrium and compatibility equations associated to the corresponding degrees of freedom are considered.

The results available in this model are associated to the orientation of the bars. Thus, in terms of welding parameters of interest, the longitudinal residual stresses σ_{yy} in one case and the angular distortion at the weld pool zone in the second case are evaluated.

2.2.- Michaleris et al. [4,5] approach.

Michaleris and DeBiccari [4], and Deo and Michaleris [5] obtained satisfactory approximations of the longitudinal stress distribution σ_{yy} using an artificial equivalent temperature field in the plate. This equivalent temperature field, which has variations only along the perpendicular direction to the weld seam, is applied by means of a pure elastic analysis in a single cooling step.

Due to the fact that a simple elastic one-load-step analysis is performed, it is computationally cheap when compared with typical elastic-plastic non-linear analysis.

In the particular case of a butt weld, a constant temperature value close to the weld line (the rest being zero) has been proved to give reasonably good results. The extension of the non-zero temperature value zone is directly related to the extension of the yielded zone at the neighbourhood of the weld line, while the value of this constant temperature is responsible for the σ_{yy} stress value. The underlying idea for this temperature distribution is that, since the longitudinal stresses σ_{yy} have their origin in the temperature gradients along the x direction, it is only necessary to adjust the parameters of this temperature gradient.

σ_{yy} stresses using Michaleris approach fit the experimental values reasonably well because the temperature gradient in the x direction has been suitably adjusted, but other stresses (e.g. σ_{xx}) need, in order to be properly calculated, their corresponding variations in the temperature field in other directions which are not included in the model. u_y values have also been shown to fit reasonably well with experimental results due to their direct relationship with σ_{yy}.

2.3.- Rosenthal model [6].

Rosenthal [6] obtained the temperature field solution for a concentrated heat source moving at a constant speed (v). The solution applies for a coordinate system ($x,w,z,$ with $w=y-vt$) which moves with the heat source (w or y direction), and assumes long weld distances and constant thermal properties among others, x is the in-plane direction perpendicular to the weld seam. This solution is available for thin and thick plates. The 2D solution (2D heat conduction) for thin plates (which has no dependency on the thickness, z coordinate) is shown in (1).

$$T - T_0 = \frac{Q}{2\pi\lambda h} e^{-\frac{v}{2k}w} K_0\left(\frac{v}{2k}\sqrt{w^2 + x^2}\right) \qquad (1)$$

where T_0 is the reference temperature, Q the heat input, λ the thermal conductivity, h the thickness, k the thermal diffusivity, x the distance to the weld line, t the time and K_0 the modified Bessel function of the second kind and order 0.

Solution in (1) gives the stationary temperature field which is observed in the coordinate system attached to the heat source. Transient temperature fields at the beginning and ending of the welding process are not covered by this model.

The temperature distribution obtained by (1) and all subsequent expressions have to be bounded by the fusion temperature of the metal (1260º C for the particular case of the Nickel alloy used in this work).

2.4.- Line Heat model.

The Line Heat model only considers heat flow in one direction, perpendicularly to the weld seam (x axis), so the temperature gradients only appear transversely to the welding direction.

The temperature distribution can be obtained from Rosenthal (1) considering an infinite welding speed, which eliminates the dependency of the w coordinate, and gives rise to the following final expression:

$$T - T_0 = \frac{q_w}{2\pi\lambda h\sqrt{\frac{\pi}{k}t}} e^{-\frac{x^2}{4kt}} \qquad (2)$$

where q_w is the heat input per unit weld length, and the rest of the parameters have already been defined in Rosenthal equation. The temperature profiles only depend on the distance to the weld line and on the time t.

For a detailed definition of the temperature evolution with time, small time steps have to be considered at the beginning, when higher temperature gradients exist close to the weld seam, whereas larger time increments can be used when the temperature profile is becoming uniform.

2.3.- Thermal envelope model.

An additional level of simplification in the temperature distribution can be achieved by eliminating the time dependency, only storing the maximum temperature value at each position of the welded plate. The resultant temperature distribution is the envelope of the temperatures at each point. This envelope then depends on the temperature-time model used to obtain the maximum values, which, once the model has been selected, permits the envelope to be numerically evaluated.

Nevertheless, analytical expressions for the temperature envelope are available, which can be used instead of the numerically evaluated envelope. For thin plates, the following expression applies, which is a good approximation to the numerical evaluated temperature envelope:

$$T - T_0 = \sqrt{\frac{2}{\pi e}} \frac{q_w}{2hc\rho x}, \tag{3}$$

where c is the specific heat, ρ is the specific weight, and the rest of the parameters have been previously defined.

Simulations using the Thermal Envelope temperature distribution have only two loading steps, one for the heating up to the thermal envelope value, and a cooling stage down to room temperature. This two-stage analysis makes the FE analysis significantly faster in computation time with respect to the Line Heat FE analysis, where all temperature profiles have to be included sequentially as different load steps.

3.- TEMPERATURE DEPENDENCY ON THE MECHANICAL PROPERTIES

Another level of simplification has also been considered, consisting of a parametric study of the influence of temperature dependency on the mechanical properties of the materials on the residual stress results.

As the mechanical properties vary with temperature, the influence of considering this dependency, or not, for one or more material properties has been investigated.

Fig. 2 and Fig. 3 show respectively the residual stress distribution (normal stress parallel to the weld seam σ_{yy}) on a butt-welded Aluminium alloy plate with two of the previously described models: the 1D ideal elastoplastic bar model (Section 2.1) and a 2D Finite Element elastoplastic plane stress numerical simulation, both using the Thermal Envelope (Section 2.3) temperature distribution as the only external loading. The temperature field is applied as a known external action, so no thermal simulation is solved.

Several combinations of the following three material properties, E: Young modulus, σ_y: yield stress and α: thermal expansion coefficient, were analyzed, taking and not taking into account temperature dependency on these material properties.

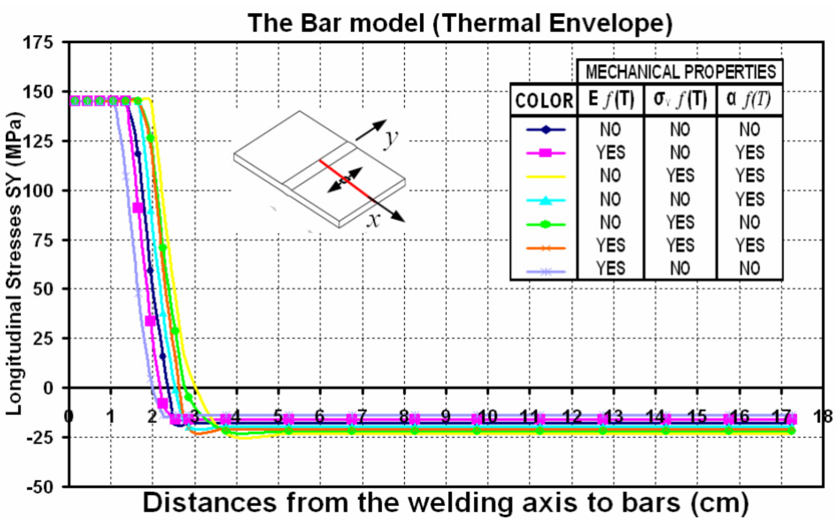


Fig. 2.- σ_{yy} results using the 1D bar model and the thermal envelope.

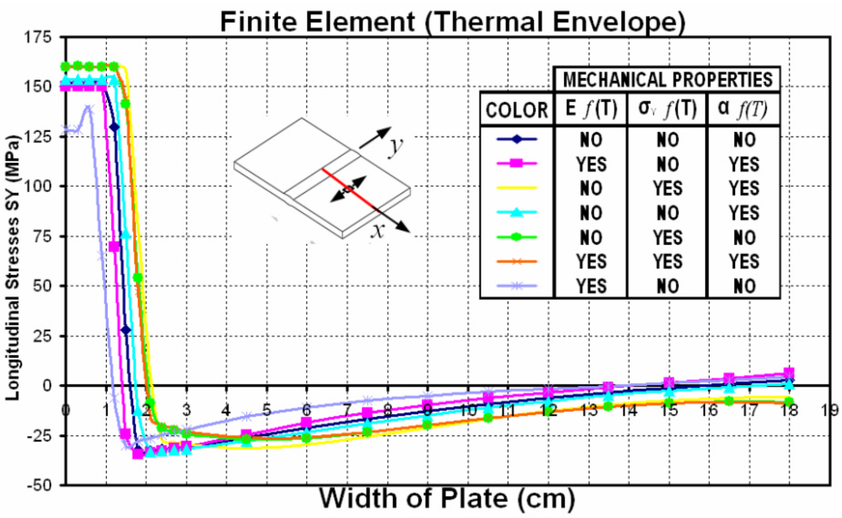


Fig. 3.- σ_{yy} results using the Finite Element model and the thermal envelope.

Results of σ_{yy} represented in Figs. 2 and 3 indicate that at least for preliminary numerical results, constant values (independent of the temperature) for all mechanical properties lead to similar σ_{yy} results. From a quantitative point of view, it was shown, Méndez [10], that the main influence of the dependency of the properties involved in the model on the results, particularly on σ_{yy}, came from the consideration of the variation of the yield stress, σ_Y, with the temperature. This assumption, of constant values of material properties with temperature, represents an important computational time improvement as the non-linearity in the material properties is eliminated.

4.- COMPARING MODELS AT PROCESS LEVEL

Although several variables of the model could be compared, depending on the models used, there is no doubt that σ_{yy}, available in all models, is the one of most interest. This is due not only to the role that the tension at the neighbourhood of the seam can play in presence of welding defects but also to the role that the compressions far from the seam can play in the local buckling of the plates. All numerical models have been solved using an elastoplastic constitutive law except in the case of Michaleris which is purely elastic.

The model, created using solid elements (with 3D displacement capabilities) will not have out of plane displacements if the external loadings do not vary along the thickness direction. Although none of the described temperature solutions, which are valid for thin plates, have temperature variations across the thickness direction, some trials considering these variations have been performed in order to obtain the out-of-plane displacements without losing the 2D easy-to-use equations. The out-of-plane displacements are necessary to predict the deformed shape of the welded plates.

In this context, temperature far from the weld line (10 ~ 15 times the thickness) can be considered constant through the thickness but is clearly non-constant at the neighbourhood of the weld line. The experimental evidence, which will be detailed in the following sections, gives the average shape of the weld pool for the welding parameters used in this work for butt-welds of Nickel alloy, Fig. 4, and has been used to locally affect the temperature profile at the bottom face of the plate. The modification consists of replacing the distance to the weld seam x by $(x+h\cdot f)$ in the temperature profiles given by (1-3), where h is the plate thickness and f is a factor which can be adjusted to obtain the fusion temperature at the weld pool boundary of the root surface. Far from the weld line, when $x>>h$, $x+h\approx x$ and the temperature is uniform along the thickness. This fact provides the model with a 3D displacement capability, displacements u_z (perpendicular to the plate) appearing as a new result. A detail of the FEM mesh is shown also in Fig. 4 (only half model is shown due to the symmetry of the problem) where it can be observed a progressive refinement of the mesh towards the weld seam and the use of only one element in the thickness direction. The solid elements used in the mesh have eight nodes and three degrees of freedom (u_x, u_y, u_z) per node.

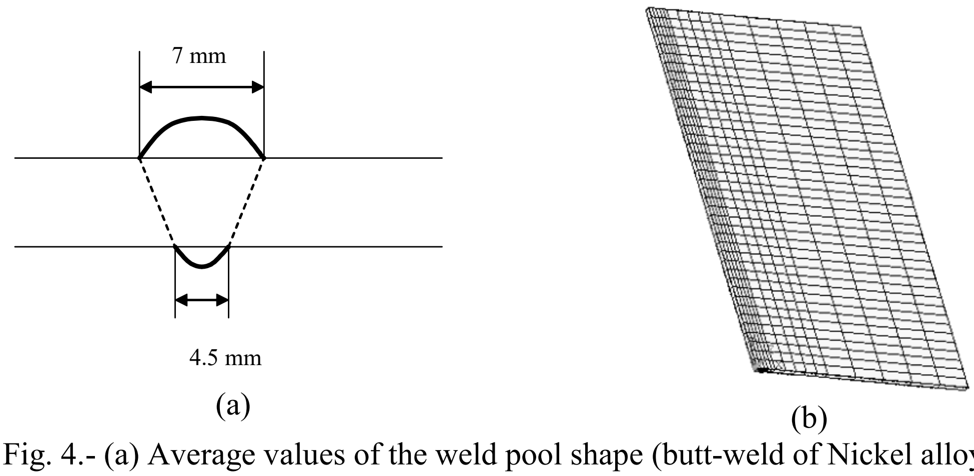


Fig. 4.- (a) Average values of the weld pool shape (butt-weld of Nickel alloy) and (b) mesh (half model due to symmetry).

The study will be carried out on two Nickel alloy plates, 200 mm long (y direction), 60 mm wide (x direction) and 2.5 mm thickness (z direction) which are butt welded (single pass), and without any external load except the thermal input (the boundary conditions only prevent rigid body motions). The constitutive law used in the FE models includes elastic-plastic behaviour (except in Michaleris analysis, which is an elastic one, considered to be much faster) and only one isoparametric 20-node hexahedronal element was used in the thickness, as recommended by Radaj *et al* [11]. Simplified numerical simulations for preliminary design purposes suggest using the temperature field as a known input parameter and as few elements as possible, both of these being in close agreement with the aim of the project.

Fig. 5 shows the longitudinal stress σ_{yy} along the x direction (at the centre of the plate, y=100 mm) for all the previously introduced models. Due to symmetry, only half geometry is modelled. All models predict almost the same level of residual compressive stress and almost the same stress gradient close to the weld seam. The main difference between the models is the extension of the yielded zone at the neighbourhood of the weld seam.

If there is interest only in the σ_{yy} component, any model should give reasonably similar results, the one-dimensional Bar Model being the fastest in CPU time, its main limitation being the need for a plane geometry. In Fig. 5 results from the FE models have been obtained considering, or not, the pseudo 3D effect at the neighbourhood of the weld seam (indicated with 2D or 3D). The text "NL GEOM OFF" indicates that the large displacement option was not activated for the analysis, and the "AVERAGE" text indicates that an average value of the σ_{yy} along the thickness is computed.

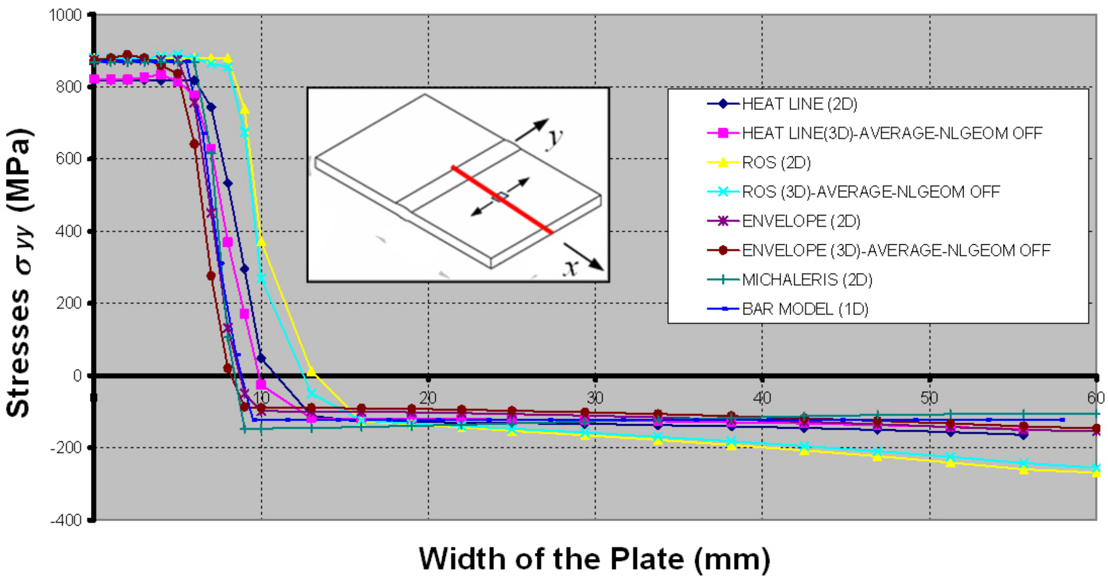


Fig. 5.- Comparison of σ_{yy} at y=100 mm for all models.

The comparison of σ_{xx} residual stress for all models (except the 1D Bar model) is shown in Fig. 6. For the modelled symmetry (at x=0)-free (at x=60) boundary conditions, the level of σ_{xx} residual stress is much lower than σ_{yy}.

From a qualitative point of view, all models behave in a more or less similar way, with the exception of the modified 3D models (Thermal Envelope, Line Heat and Rosenthal) which show an irregular behaviour at the neighbourhood of the weld seam. 2D models do not suffer the bending effects and present smother behaviours (compared with the 3D models) for the mean value (through the thickness) of the transversal stress.

It has to be stressed that although the Rosenthal 3D solution is available, the aim of the analysis was to investigate the possibility of using these simpler 2D solutions slightly modified to try to catch the 3D effects.

All previous comments on results appearing in Figures 5 and 6 have to be framed in the different scales at which both figures have been represented, σ_{xx} being of an order of magnitude smaller than σ_{yy}. The differences between the models should significantly change for clamping simulation (u_i=0 at x=±60 mm), a case where the residual transversal stresses play an important role.

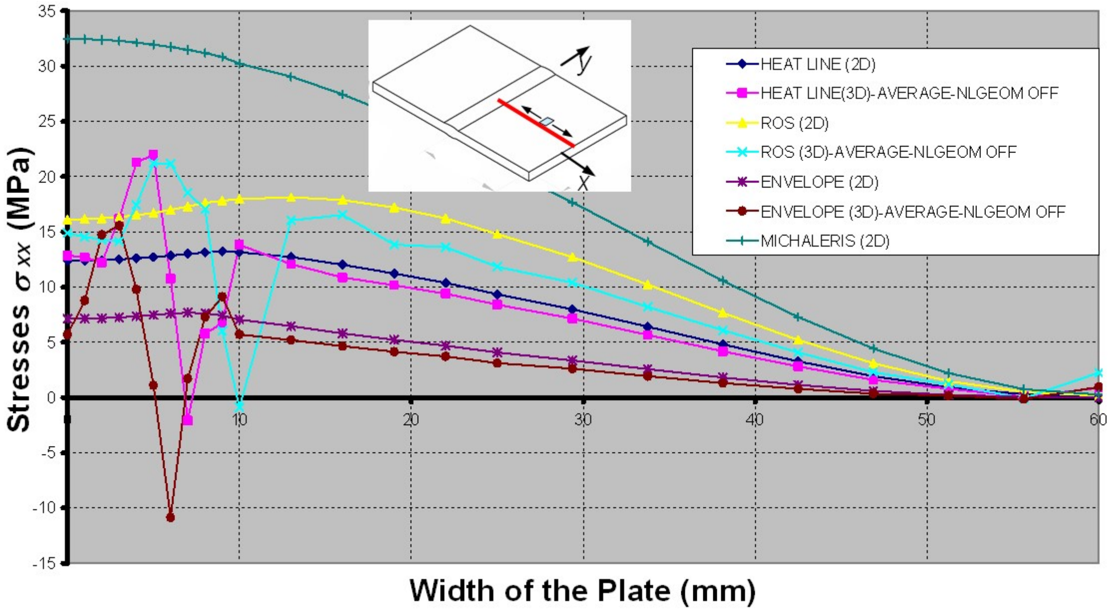


Fig. 6.- Comparison of σ_{xx} at y=100 mm for all models.

The distribution of σ_{xx} residual stress along the weld seam is shown in Fig. 7, where three different behaviours can be observed. Michaleris results for this stress component are slightly different from the rest of the models, which present tensile stress concentrations near the ends and almost zero values at the centre of the plate. The Thermal Envelope and the Line Heat models show a symmetric behaviour along y direction due to their independence from the temperature distribution along y. Rosenthal model, although quite similar to the Thermal Envelope and the Line Heat models, presents higher values than the rest of the models, and a slight lack of symmetry due to the inherent lack of symmetry of the analysis in the weld direction.

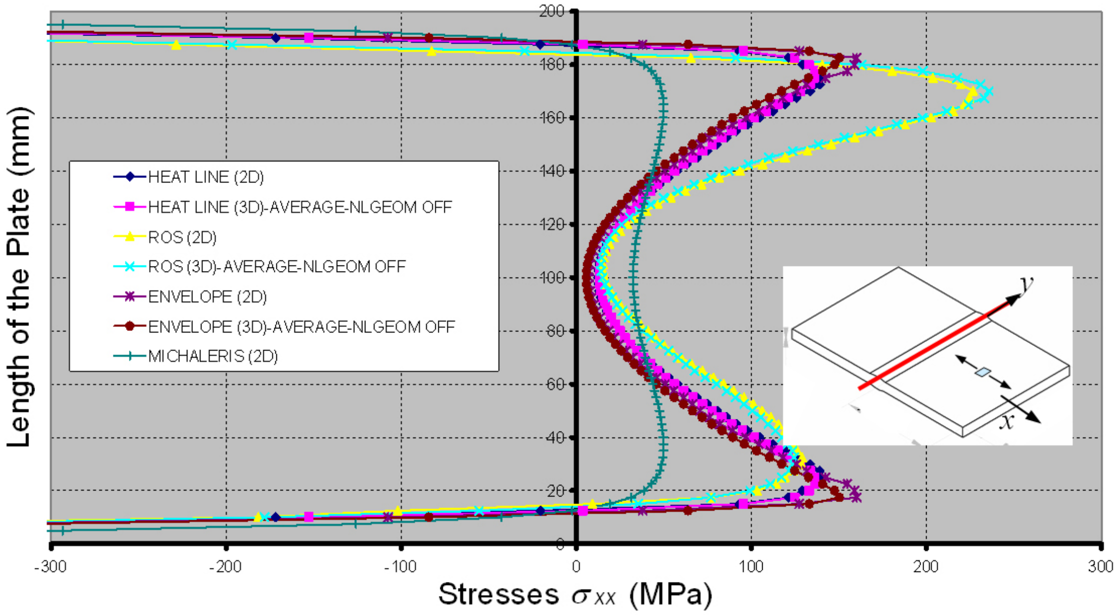
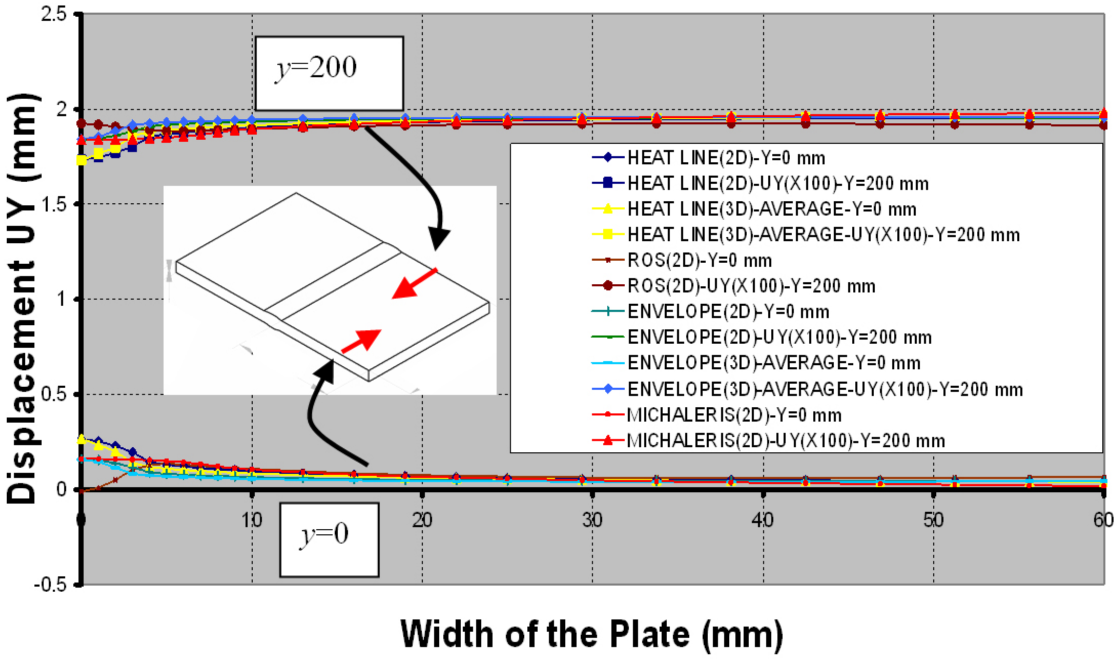


Fig. 7.- Comparison of σ_{xx} at x=0 mm.

The displacements u_y at both ends of the plate (y=0 mm and y=200 mm) are shown in Fig. 8 (including details at the weld ends). The numerical results are quite similar for all the models, with the exception of the local behaviour very close to the weld seam. The sign of the displacements is the one indicated with arrows in the scheme inside Fig. 8, so all simulations predict a shortening effect in the length of the plate at the weld seam.



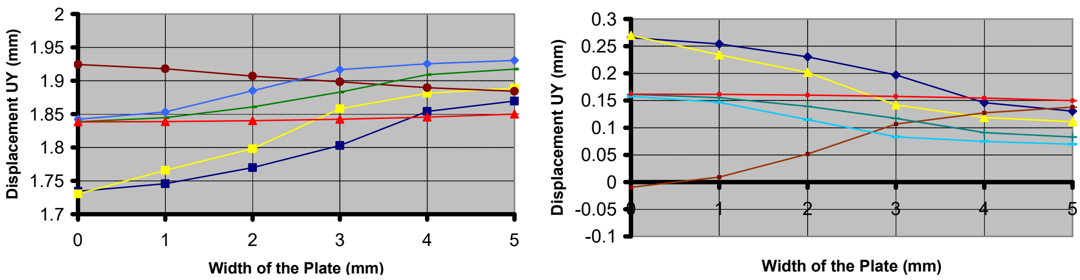


Fig. 8.- Comparison of u_y at y=0 and y=200 mm (and details at weld ends).

Numerical results at x=0 of the weld line shortening are summarized in Table 1 (all displacements in mm), the numerical results always indicating the shortening effect at the weld line in the range between Δu_y=-1.461 mm and Δu_y=-1.927 mm.

model	u_y (y=0)	u_y (y=200)	Δu_y
Heat line (2D)	0.265	-1.734	-1.469
Heat line (3D)	0.269	-1.730	-1.461
Rosenthal (2D)	-0.009	-1.918	-1.927
Envelope (2D)	0.161	-1.838	-1.677
Envelope (3D)	0.157	-1.842	-1.685
Michaleris (2D)	0.161	-1.838	-1.677

Table 1.- Comparison of u_y displacement at weld line ends (y=0 and y=200).

A comparison of the different computational time consumptions is summarized in Table 2 (using a Pentium IV@3GHz, 1GB RAM). As the total CPU times of the Line Heat and Rosenthal analyses are dependent on the total number of time steps considered, this computational time has been evaluated using, for example, 200 steps. In the table TEP means thermo-elastic-plastic simulation and TE means thermo-elastic simulation. Some remarks clarifying the comparison are also included in Table 2.

	Model	CPU time	Remarks
1	No simplification		
2	TEP Rosenthal	~ 1.5 min/step	200 steps ~ 4.5 h.
3	TEP Line Heat	~ 1 min/step	200 steps ~ 3 h.
4	Thermal envelope	~ 7 min	Only two steps
5	TE (Michaleris)	~ 3 min	Elastic solution
6	TEP Bar model (1D)	~ 5 sec	Only σ_{yy} and angular distortion

Table 2.- Comparison of CPU time for the different models.

Rosenthal and Line heat models, which are time dependent, are the most expensive simulations (in terms of time consumption), having an average CPU time of 1.5 and 1 minute per step respectively. The thermal envelope, which has the heating and cooling steps, takes around 7 minutes. Michaleris approach, with only one step, elastic solution, takes around 3 minutes, and finally, the bar model, running in a Fortran code, takes seconds to obtain the solution.

5.- EXPERIMENTAL VALIDATION

An experimental validation has been performed welding (butt weld) two thin Nickel alloy plates with the geometry and heat input data summarized in Table 3, which were the same used in the numerical simulations for the plate geometry and heat input evaluation. The validation procedure includes comparison between the numerical and experimental values of the following field variables: temperature during welding, residual displacements and residual stresses. The sample was welded with a lateral boundary fixed and then released for the final displacement and residual stress measurements. The numerical solution corresponds to the Finite Element model using Rosenthal and the thermal envelope solutions for the temperature field, as the two extreme models in terms of CPU time consumption.

Length	200 mm
Width (each plate)	60 mm
Welding speed	150 mm/min
Voltage	11.4 V
Intensity	108 A

Table 3.- Geometry and heat input data for the validation sample.

5.1.- Temperature

The temperature profile was measured at four different distances from the weld seam using thermocouples at distances 3*e*, 5*e*, 7*e* and 9*e*, *e* being the thickness of the plate, Fig.9. The thermocouples have been placed in the opposite side to the welding side and in the middle of the length of the plates (*y*=100 mm). This information has been used to adjust the only unknown parameter (the efficiency) which defines the heat input that finally reaches the base metal. Using a least squares procedure between the experimental temperature profile at each thermocouple location and the Rosenthal equation (1) particularized at the thermocouple location, the value of the efficiency was obtained.

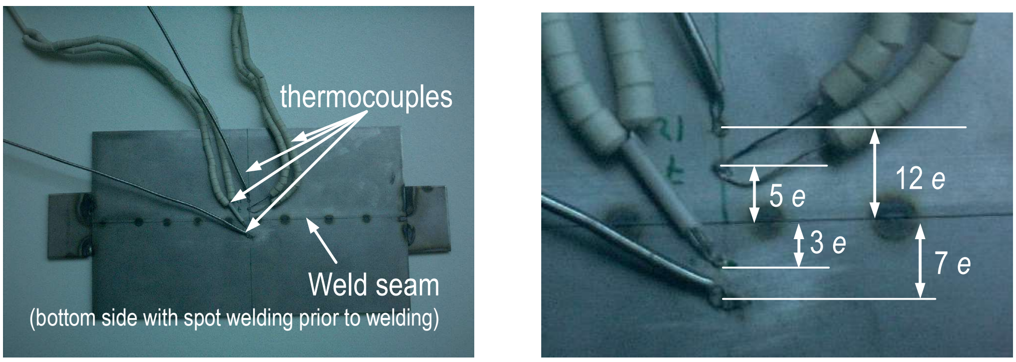


Fig. 9.- Experimental set-up for temperature measurements.

To make a decision on which were the most adequate fittings between experimental results and the analytical formula, the area where higher temperature gradients were observed was taken as the reference, as can be observed in Fig. 10 for the four thermocouple locations.

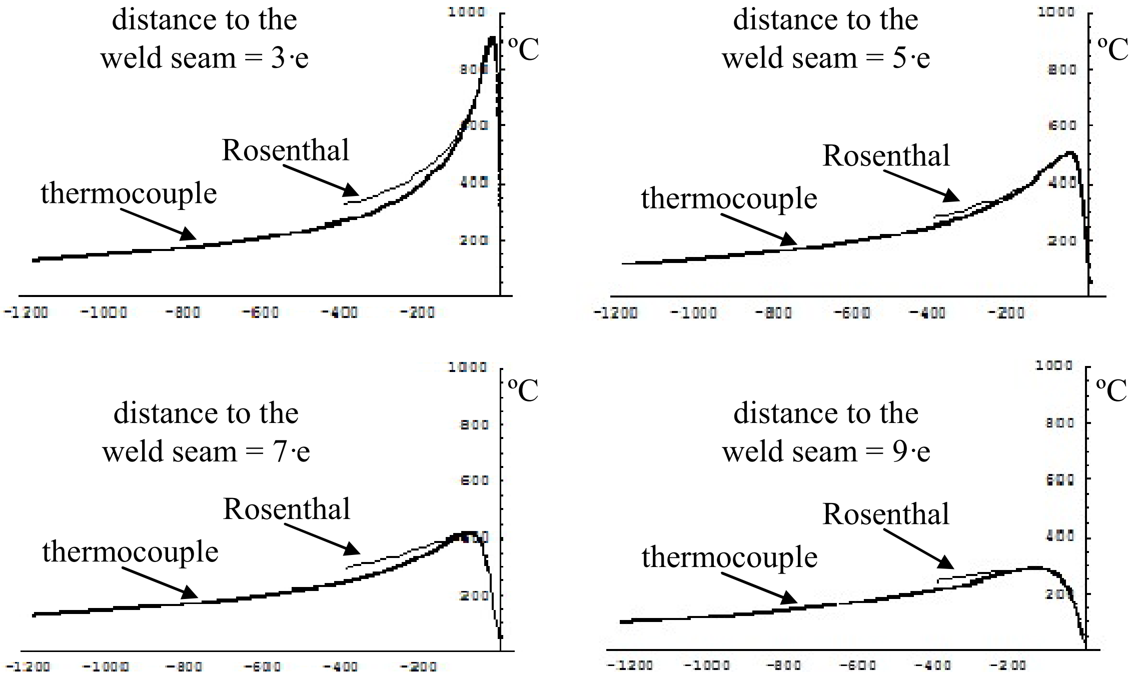
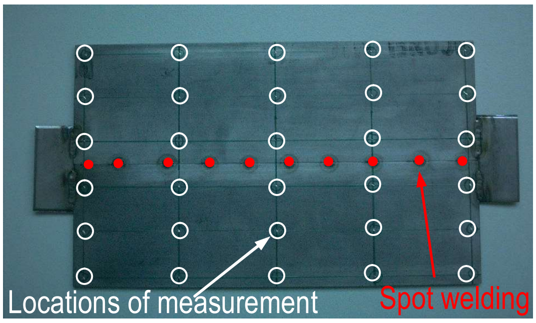


Fig. 10.- Experimental and Rosenthal profiles at each thermocouple location.

The overall adjustment is very good at every thermocouple location, a lower cooling rate being predicted by the analytical equation (1) (the thin line in Fig. 10). The high temperature gradients and the maximum values are well predicted, these being of major importance for the numerical simulations, as the high temperature gradients are responsible for the generation of stresses. The worse fittings at the cooling stage, when the temperature gradients are smaller, have a minor influence in the residual stress field.

5.2.- Residual out of plane displacements

The residual out of plane displacements (u_z) have been measured at many locations (see experimental set-up in Fig. 11) along lines parallel and perpendicular to the weld direction, and have been compared with the predictions obtained from the numerical simulations. The experimental measurements of u_z displacements are relative, and therefore rigid body motions, which consist of a constant displacement in z and rotations in x and y, have to be introduced in the numerical predictions to compare with experimental results.



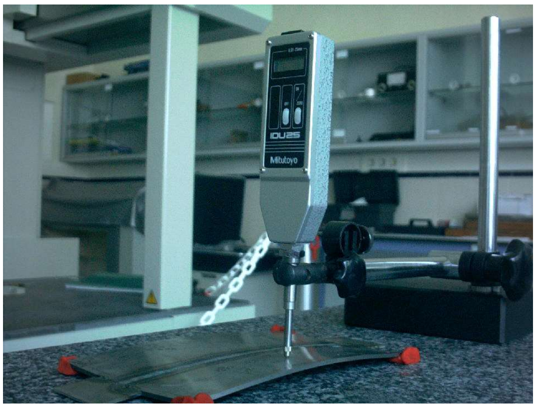


Fig. 11.- Locations for displacement measurements and measurement device.

The numerical predictions that will be presented correspond to simulations using the two extreme cases in terms of the complexity of the FE models, one corresponding to the simplest model (Thermal Envelope), and the other to the most complex (Rosenthal), both using elastoplastic constitutive law and the corresponding temperature field as a known external datum. The simulations were carried out using large displacements and variation of the mechanical properties with temperature.

The experimentally measured u_z displacements after welding, in lines perpendicular to the weld seam, are shown in Fig. 12 (with dots) together with the numerical prediction using Rosenthal (lines), the agreement being very satisfactory.

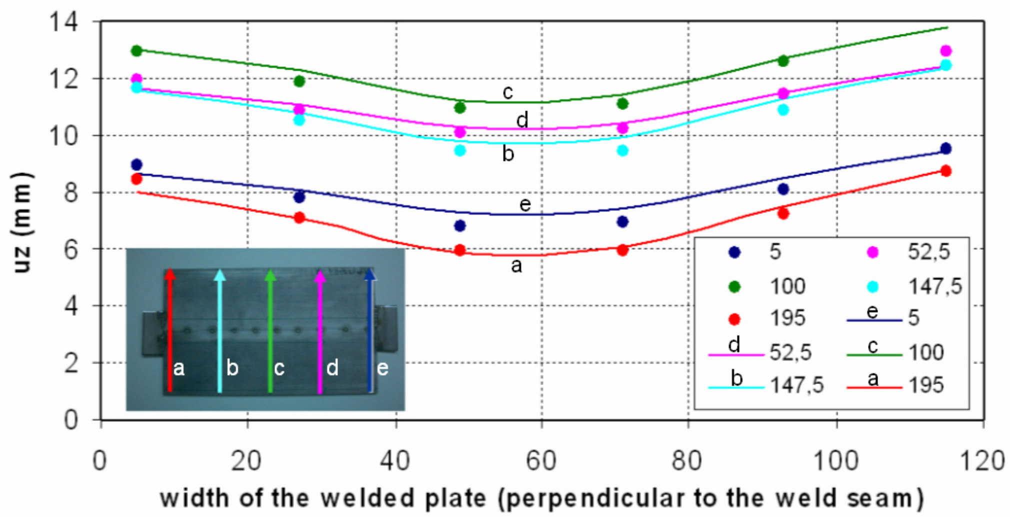


Fig. 12.- Comparison of u_z displacements (perpendicular direction, Rosenthal).

The comparison of the u_z measured residual displacements (with dots) with the numerical prediction (lines), in lines parallel to the weld seam also using Rosenthal solution, is shown in Fig. 13. The agreement is also excellent, though with some underestimation of the bending effect along the longitudinal line.

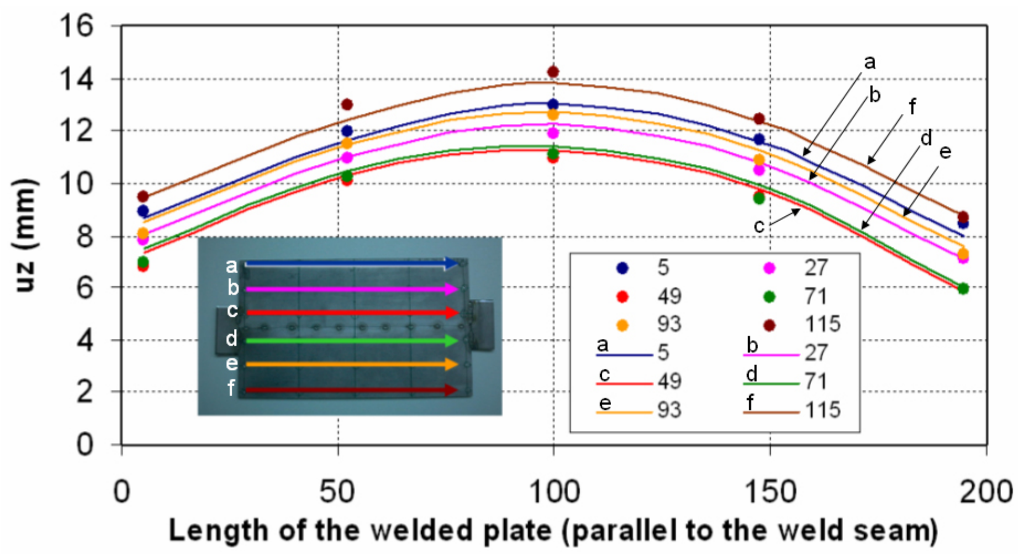


Fig. 13.- Comparison of u_z displacements (parallel direction, Rosenthal).

The same comparisons, using the Thermal Envelope, are shown respectively in Fig. 14 for the perpendicular direction and in Fig. 15 for the parallel direction. The results are very similar to those obtained in Rosenthal model, but with a significant improvement in computational time consumption (see Table 2).

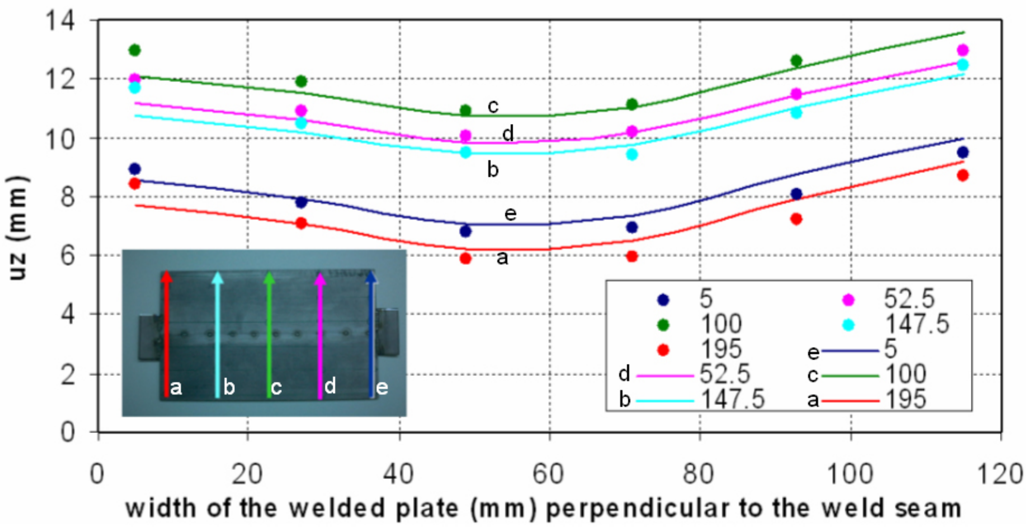


Fig. 14.- Comparison of u_z displacements (perpendicular direction, Thermal Envelope).

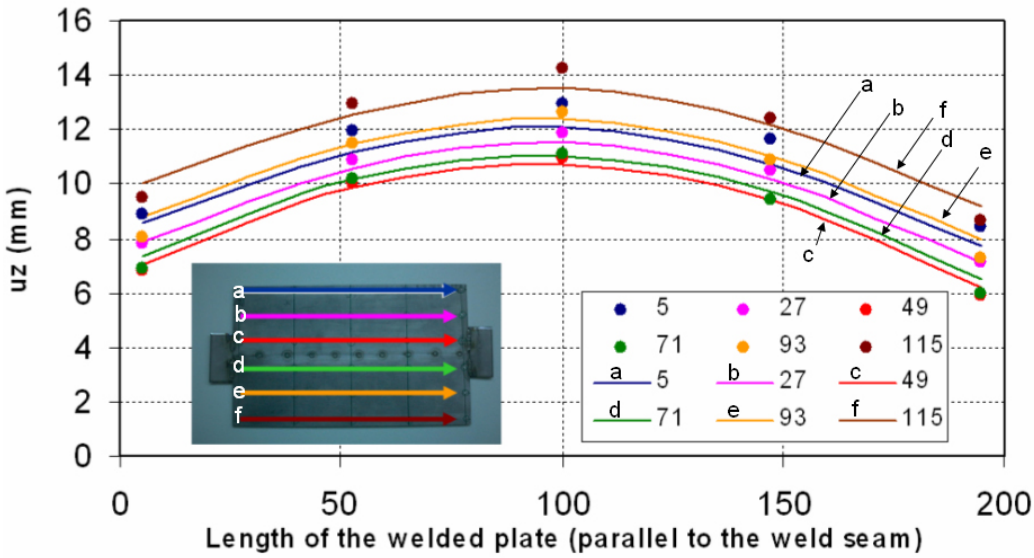


Fig. 15.- Comparison of u_z displacements (parallel direction, Thermal Envelope).

The results obtained with the pseudo 3D analysis using the Line Heat simulation do not agree at all the experimental results, giving u_z displacements which predict opposite bending effects in the welded plates.

5.3.- Residual stresses

The main residual stress component which can be expected to appear is the normal stress in the weld seam direction σ_{yy}, other stress components which also appear, such as σ_{xx}, having much lower values. σ_{yy} was measured along lines perpendicular to the weld seam, where higher variation is also expected (in the weld seam direction the stress field is quasi-uniform, excluding the edge effects).

Two methods have been used to measure the residual longitudinal stresses: unidirectional strain gages with sectioning of the plate (for a complete relief of stresses) and the blind hole technique, ASTM E837 standard [12].

In the former case, the unidirectional strain gages were bonded (oriented along *y* axis) along lines perpendicular to the weld seam (left-hand side of Fig. 16) and then the residual stresses were released by cutting both sides of the strain gages normal to the weld seam direction. The released strain measured by the strain gages was used to evaluate the longitudinal residual stress. Due to the high bending effect in the samples, strain gages were bonded at both sides of the sample. The devices for the measurement are shown at the right-hand side of Fig. 16.

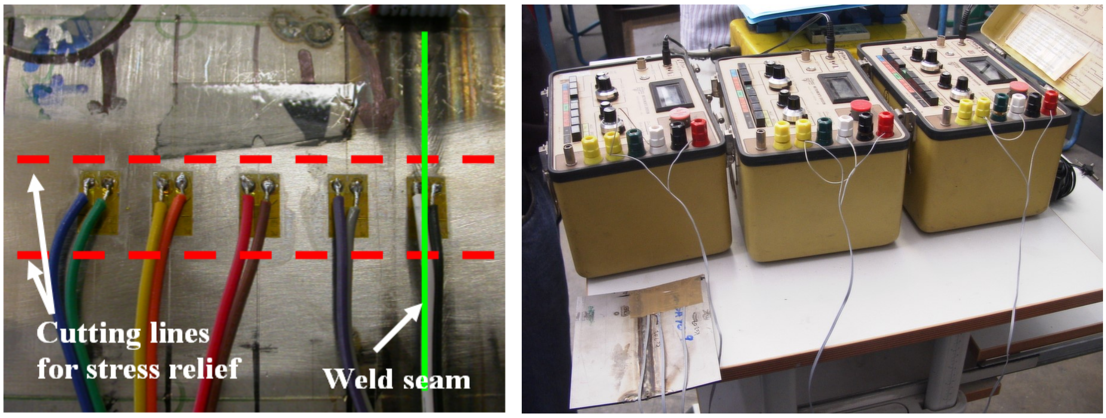


Fig. 16.- Measuring residual stresses using unidirectional strain gages.

The blind hole technique (see Fig. 17) was also used to evaluate the residual stresses. The problem associated with this technique is that the ASTM E837 standard [12] is only valid for uniform stress profile along the thickness, which is not fully correct in this case. However, the measurements were performed simply to have an alternative evaluation to that previously described.

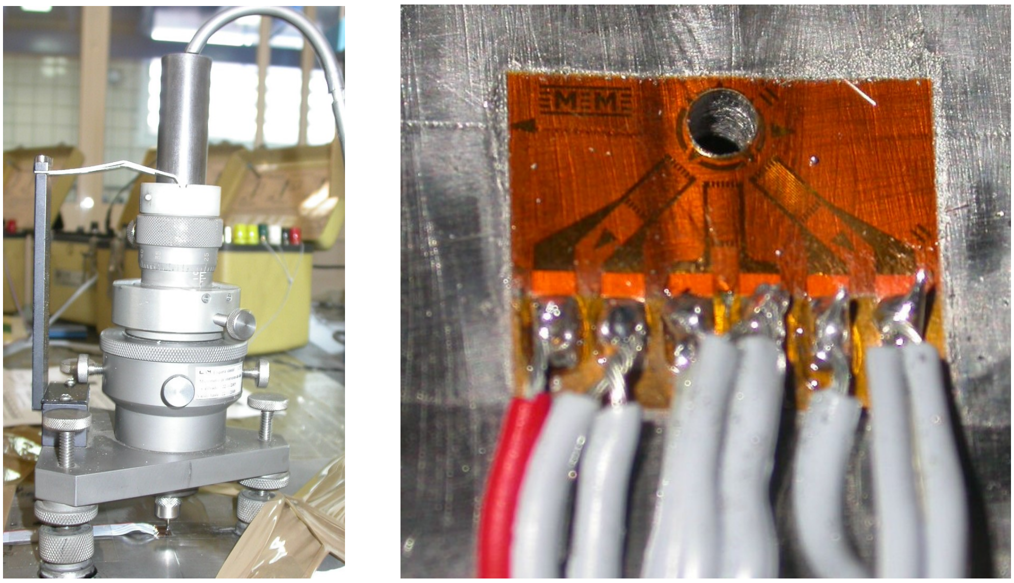


Fig. 17.- Measuring residual stresses using the blind hole technique.

Fig. 18 and Fig. 19 show the residual stress distribution of the normal longitudinal stress with the weld seam at three distances (75, 100 and 125 mm from a total length of 200 mm) from the weld start, for the top (opposite to the weld root, Fig. 18) and bottom (weld root, Fig. 19) surfaces. The similarity of these three σ_{yy} profiles, at three different y locations, shows the uniformity of the σ_{yy} stress distribution along the longitudinal direction. The numerical results have been obtained using the Thermal Envelope, which is the simplest model and has shown a satisfactory behaviour in the residual displacement validation, Section 5.2. The experimental data were evaluated at the weld seam, 8, 14 and 39 mm from the weld seam.

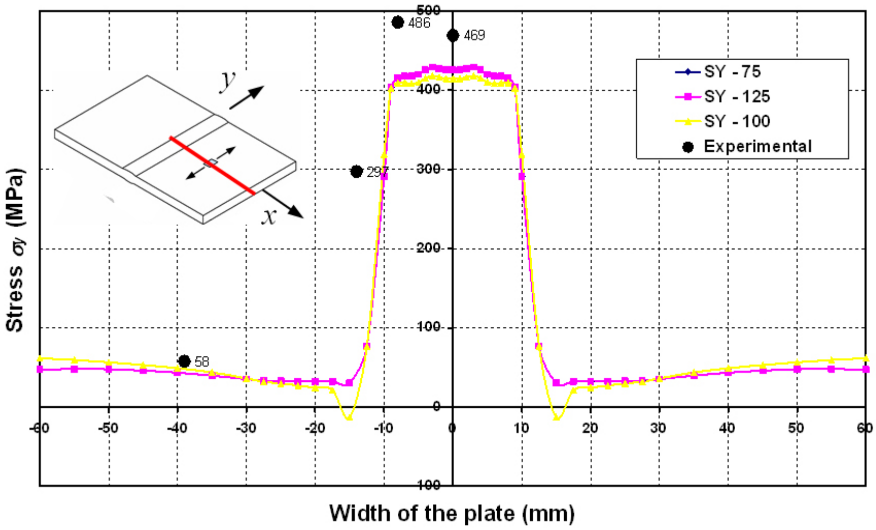


Fig. 18.- Residual normal stress at top surface.

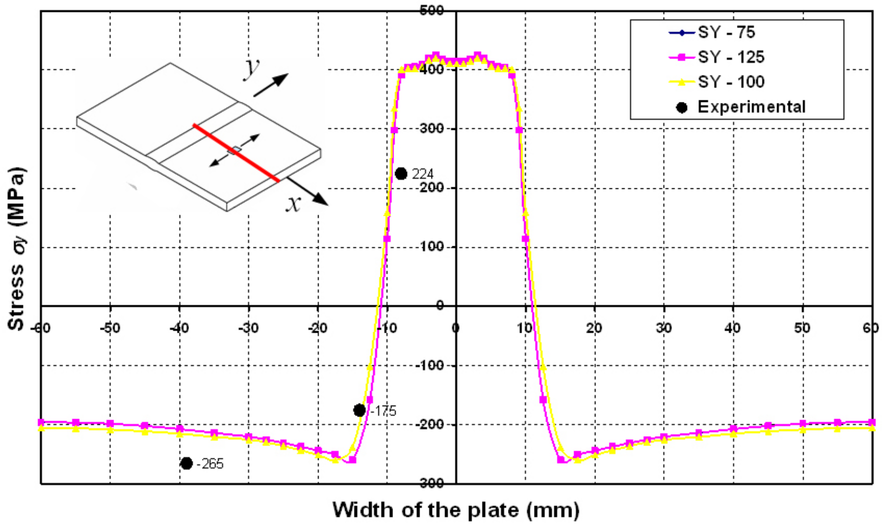


Fig. 19.- Residual normal stress at bottom surface.

Fig. 18 and Fig. 19 show a good agreement far away the weld seam and also show (as mentioned in the displacement verification) some underestimation of the bending effect along the weld seam direction, which makes the numerical predictions of the tensile and compressive stresses at the weld seam lower (Fig. 18) and higher (Fig. 19), respectively, than the experimental measurements. Similar results were obtained using Rosenthal model, but with a significant increase in computational time.

6.- CONCLUSIONS

Several simplification hypotheses for time saving considerations regarding welding numerical simulations at process level (butt welding of Nickel alloy thin plates) have been analyzed. These simplifications have been divided into two main groups. The former group deals with the temperature dependency of the material properties, while the latter deals with the temperature field solution adopted for the simulation.

The parametric analyses performed, including, or not including, the temperature dependency of each material property in the simulations, indicate that, for preliminary results, constant values of the mechanical properties with the temperature are accurate enough to obtain reasonable results, eliminating the material non-linearity.

The numerical simulations carried out include a 1D bar model, by Cañas *et al* [2], and some finite element models with different simplification considerations: from a purely elastic analysis of the welding process following the approach by Michaleris [4-5], and some elastic-plastic simulations using different solutions for the temperature field (which in increasing complexity and computational time consumption are: thermal envelope, line heat and Rosenthal [6] models). The temperature fields used in the simulations have been modified in a very simple way to take into account the weld pool shape and the possibility of obtaining the out of plane displacements. Numerical predictions obtained from the models have been compared with experimental results for the temperature field, the residual out of plane displacements and the residual normal stresses parallel to the weld seam.

The temperature was measured at four different distances from the weld seam. The comparison has shown basically that the models have, as a general tendency, a cooling rate lower than the real temperature evolution.

The out of plane displacements comparison has shown an excellent agreement for both Thermal Envelope and Rosenthal models, while the Line Heat simulation was not able to predict the out of plane displacements, the bending effects not being predicted properly.

The residual stress comparison between the numerical models and the experimental measurements was carried out with the most significant stress component appearing in the welded samples, which is the normal stress longitudinal to the weld direction. The comparison has shown a general satisfactory agreement, only some underestimations of the bending effects in the longitudinal direction having been detected.

The present study shows that the numerical analysis of welding processes can be carried out, at preliminary stages, using simplified models both in the dependency of the material properties on temperature and in the use of simplified temperature fields and types of analysis. In particular, the Thermal Envelope, which only takes into account the maximum temperature level at each location, has been shown to accurately predict out of plane displacements and residual normal stresses parallel to the weld seam, with very low computational time consumption. The numerical simulations were performed using only one element in the thickness direcction, large displacements and variation of mechanical properties with temperature.

In complex problems, a chain of fast numerical simulations can help to reduce the costs of the manufacturing process.

ACKNOWLEDGMENTS

This work was co-funded by the European Commission within the Sixth Framework Programme (2002-2006), Project VERDI "Virtual Engineering for Robust Manufacturing with Design Integration". The work herein was conducted in co-operation with ITP. Background knowledge, experimental work in the framework of this project and the discussions arising from it are gratefully acknowledged.

REFERENCES

[1] Lindgren, L.-E. “Numerical modelling of welding”, Comput. Methods Appl. Mech. Engrg. 195 (2006) 6710–6736.

[2] J. Cañas, R. Picón, F. París and J.L. del Río "A one dimensional model for the prediction of residual stress and its relief in welded plates", *Int. J. Mech. Sci*. 38 (1996) 735-751.

[3] J. Cañas, R. Picón, F. París, A. Blázquez and J.C. Marín "A simplified numerical analysis of residual stress in aluminum welded plates", *Comput. Struct*. 58 (1996) 59-69.

[4] P. Michaleris & A. DeBiccari "Prediction of welding distortions", *Welding Journal* 76 (1997) 172s-181s.

[5] M.V. Deo, P. Michaleris & J.Sun "Prediction of buckling distortion of welded structures", *Science and Technology of Welding and Joining* 8 (2003) 49-54.

[6] D. Roshenthal "Mathematical theory of heat distribution during welding and cutting", *Welding Journal* 20 (1941) 220s-234s.

[7] V. Pavelec, R. Tanbakuchi, O.A. Uyehara and P.S. Myers, "Experimental and computed temperature histories in gas tungsten-arc welding of thin plates" *Welding J. Res. Suppl*. 48 (1969) 295–305.

[8] J. Goldak, A. Chakravarti and M. Bibby “A new finite element model for welding heat source”, *Metall. Trans*. B 15B (1984) 299–305.

[9] J. Goldak "Thermal analysis of welds", *Modeling in welding, Hot Powder Forming and Casting* (1997) 17-22.

[10] Méndez, C. "*Residual stress analysis and instability predictions in welded plates*", Ph.D. Thesis (in Spanish), University of Seville, 2007.

[11] Radaj, D., Sonsino, C.M. and Fricke, W. "*Fatigue assessment of welded joints by local approaches*", Second Edition, Woodhead Publishing Limited, 2006.

[12] ASTM Standard E 837, 2001e1 "Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method", ASTM International, West Conshohocken, PA, www.astm.org.