Recent Advances in Welding Simulation of Aeronautical Components

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ABSTRACT. This paper presents the results of numerical modelling of two welding processes: Friction Stir(FSW) and Laser Beam Welding (LBW). For FSW, the objective was to predict the residual stresses using a simplified approach. For LBW, the objectives were to develop a methodology to predict distortions and residual stresses of welded fuselage panels. In both cases, predicted results agree very well with experiments.

RÉSUMÉ. Cet article présente des travaux de simulation numérique de soudage. Deux procédés sont concernés : le Friction Stir Welding et le soudage laser. Pour le Friction Stir Welding, l'objectif était de prévoir les contraintes résiduelles avec une approche simplifiée. Pour le soudage laser, l'objectif était de développer une méthodologie permettant de prévoir les contraintes et distorsions de panneaux de fuselage soudés. Dans les deux cas, les résultats obtenus sont en adéquation avec l'expérience.

KEYWORDS: modelling, welding, FSW, laser, multi-scale, local/global model.

MOTS-CLÉS : simulation, soudage, FSW, laser, multi-échelle, méthode locale/globale.

1. Introduction

Welding technology is being increasingly used within aeronautical industries. In particular, laser-beam-welded fuselage panels have appeared on the latest generation of AIRBUS civil aircrafts. Friction Stir Welding, though a rather recent technology, is being investigated for many potential aeronautics applications and is already used in production in some cases (Christner, 2002). The welding process tends to supplant the traditional riveting process because of the benefits it offers in terms of cost (increased speed) and mass savings. However, some drawbacks exist such as the distortions induced by the thermo-mechanical phenomena occurring during welding. Removing these distortions may be challenging and adds anyway cost to the manufacturing process either in term of longer development time or by adding extra-operations such as straightening.

Another issue are the welding-induced residual stresses which may have a significant impact on the life time of the components, and thus have to be taken into account in the sizing of the structures.

The numerical simulation of welding is a valuable tool to assess distortions and residual stresses. EADS CCR has acquired a significant experience in the simulation of manufacturing processes and has applied this capability to the modelling of welding. This paper presents some of the work carried out on two technologies: Friction Stir Welding and Laser Beam Welding.

2. Simulation of friction stir welding

2.1. *Description of the process*

Friction Stir Welding has been developed and patented by TWI in the 90's. The process uses a traversing and rotating profiled tool moving along the joint line. This tool simultaneously heats and deforms the material. The seam ("nugget") is formed without fusion. High level of plastification is present since materials of both sides of the plates to join are mixed together in a solid state.

2.2. *Objectives of the simulation*

In order to obtain accurate results in terms of distortions, achieving a correct prediction of the residual stress fields is of utmost importance. One should focus then on having a good description of the mechanical behaviour of the material within the nugget. Unfortunately most commercial mechanical software are not able to handle the material flow exhibited in FSW. Some authors (Shercliff *et al.*, 2002) have proposed to use Computational Fluid Dynamics codes to solve this problem, which is valid for studying tool efficiency but is not suitable for the kind of analysis we are interested in.

For the work we have performed in the framework of the WAFS program (European project), we have chosen a completely different way, since we decided to neglect the material flow in order to be able to use a classical mechanical code. We computed then the residual stress field and compared them to experimental measurements. We wanted to check if such a simplified approach was sufficient or not.

2.3. *Experimental measurements*

Aluminium plates have been welded by GKSS. The material alloy is 6056T4. The plates are 4mm thick, 150mm x 300mm. The tool shoulder outer and inner radius are respectively 13mm and 5mm. The tool rotating speed is 26.67 rot/s, the tool advancing speed is 13.33mm/s. The tool pressure is about 1.1 tons.

2.4. *General methodology*

A detailed description of the model has been made in a previous paper (Lawrjaniec *et al.*, 2003). The simulation was based on a transient fully decoupled thermo-mechanical scheme, performed with MSC.MARC. The thermal analysis used a heat source model whose parameters have been tuned using thermal measurements.

This heat source was moved along the joint line in order to create a temperature field within the plate. For the mechanical step, the detailed tooling geometry, the forces applied to the structure by the tooling were not taken into account.

2.5. *Heat source modelling*

We have designed a heat source model based on the following assumptions:

– heat is generated by plastic dissipation of the material under the shoulder of the rotating tool,

– heat density lowers with the depth of the material since the influence of the shoulder decreases,

– the temperature fields on the advancing and retreating sides were assumed to be identical (measurements have shown a difference of 20°C), allowing us to use a symmetric model.

The heat source has been defined as a conical shape, with a no-heat zone near the axis (there is no material where the pin is) and a density decreasing linearly from the top to the bottom, see Figure 1.

The source parameters are tuned so that computed temperatures match experimental, for the retreating side (Figures 2 and 3).

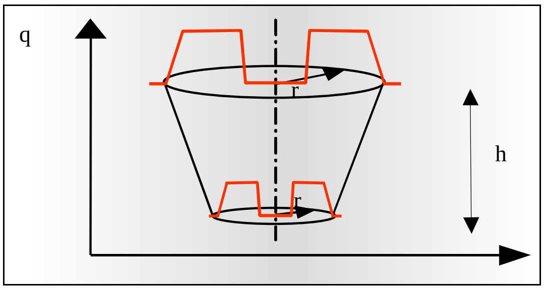

Figure 1. *3D FSW source*

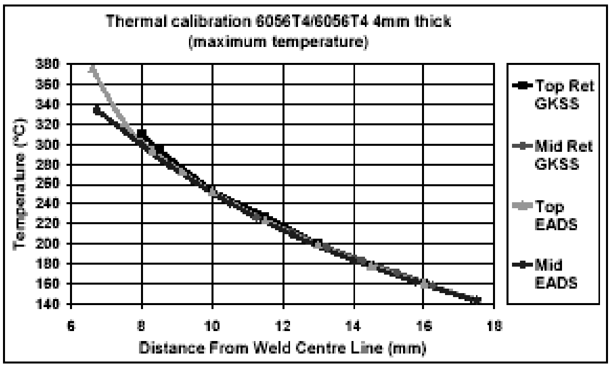

Figure 2. *Comparison between computed and measured temperature*

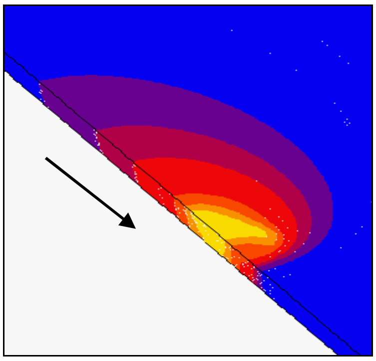

Figure 3. *Computed temperature field*

2.6. *Material properties*

The mechanical properties of all the materials involved (Base Material, Heat Affected Zone, Thermo-Mechanically Affected Zone and Nugget) are taken into account in the calculations. Property distribution is based on a welding zone macrograph (Figure 4).

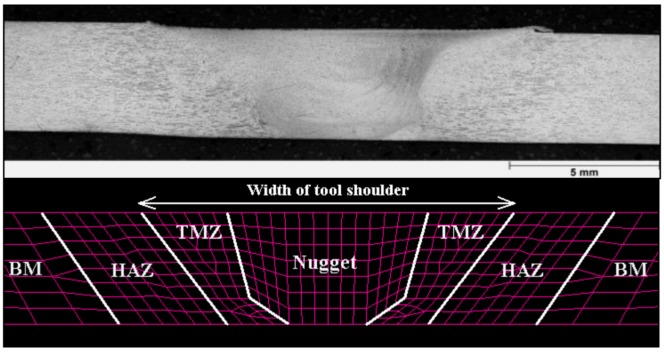

Figure 4. *Transition from the macrograph to the mesh (Courtesy of Institut de Soudure)*

At the beginning of the computation, all finite elements are BM. Then, as the heat source moves, the mechanical characteristics assigned to an element are modified, depending on the element and the temperature.

2.7. *Results*

The thermo-mechanical analysis allows us, after releasing of boundary conditions, to obtain the numerical FSW residual stresses. Comparison have been made between simulated residual stresses and experimental stresses measured by neutron diffraction (GKSS), see Figures 5 and 6.

The transverse and longitudinal residual stresses are plotted as a function of the distance from the weld centre line.

It can be seen from the figure, that the correlation between experimental and numerical results is quite good. Experimentally, there is a residual stresses drop in the nugget zone, which is not so clear numerically.

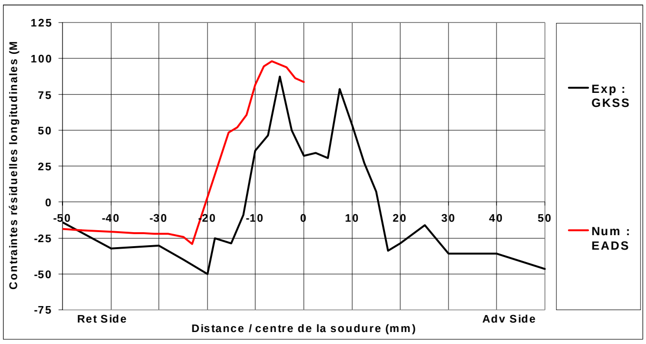

Figure 5. *Comparison between computed and measured longitudinal residual stresses*

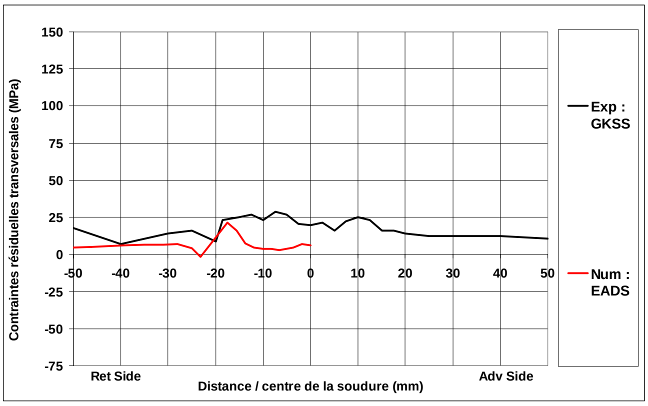

Figure 6. *Comparison between computed and measured transversal residual stresses*

2.8. *Conclusion*

Though our approach neglects material flow, the results agree fairly well with the experiments.

This procedure can thus be used, for a given set of welding parameters, to compute residual stresses and distortions of real structures.

3. Simulation of laser beam welding

3.1. *Description of the process*

Laser Beam Welding process is a high density fusion welding process. Heat is generated through the interaction between the material and the laser beam. High welding speed can be used which is a very interesting feature to reduce manufacturing costs.

3.2. *Objectives of the simulation*

The simulation aims at predicting the welding-induced distortions and residual stress fields of large structures such as fuselage panels (see Figure 7). Such structures feature typically dozens of welded stiffeners, which means until 50m of seam. Each seam has a very small cross-section (a few square-millimetres). This contrast between the size of the zone where the thermo-mechanical phenomena occur and the size of the structure for which the distortions are of interest leads to a real modelling challenge. Indeed, a correct description of the local phenomena around the seam requires a 3D volumic analysis which would lead to a huge model and unacceptable computational times. Thus, we decided to investigate other approaches based on multi-scale analyses.

Figure 7. *Welded A318 Fuselage panel (Courtesy of AIRBUS)*

3.3. *Multi-scale methodology and PREDIST simulation package*

A local/global analysis has been proposed as a feature of a software dedicated to welding (Souloumiac *et al.*, 2002). We propose here a similar approach to be used by a general purpose thermo-mechanical code, such as ABAQUS.

Moreover, we have used different simulations in order to cover the whole chain ranging from the definition of the welding parameters to the global distortions of the panel. These different simulations are the following ones (See Figure 8):

– weld pool simulation using LASIM, in order to define the heat source,

– local thermal 3D simulation in order to compute the local temperature fields, using ABAQUS,

– local mechanical 3D simulation in order to compute the local mechanical response of the structure, using ABAQUS,

– local mechanical shell simulation, in order to build an equivalent shell model to be used for the global simulation (ABAQUS),

– global mechanical shell simulation, which gives the global distortion of the whole panel (ABAQUS).

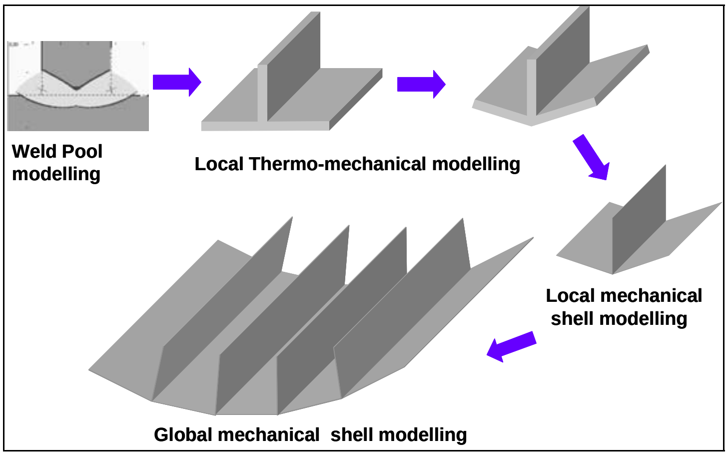

Figure 8. *General scheme for laser beam welding simulation*

A software package called PREDIST© (PREdiction of DISTortions) has been developed for the implementation and links between the different simulations.

The basic assumption which is made in our analysis is that the global behaviour of the structure has no impact on the local one, both from the thermal and mechanical points of view. This means that the local models are built without any description of the remaining structure. This assumption limits of course the range of validity for this method.

3.4. *Heat source modelling*

In order to achieve a correct description of the mechanical response, it is of utmost importance to describe accurately the heat brought to the structure. For this purpose, we use LASIM (Sudnik *et al.*, 1999), a software which computes the cross-section geometry of the seam and thermal field of the stationary weld, for a given set of welding parameters (material, geometry, laser type and power, speed…). A typical output of LASIM is shown in Figure 9.

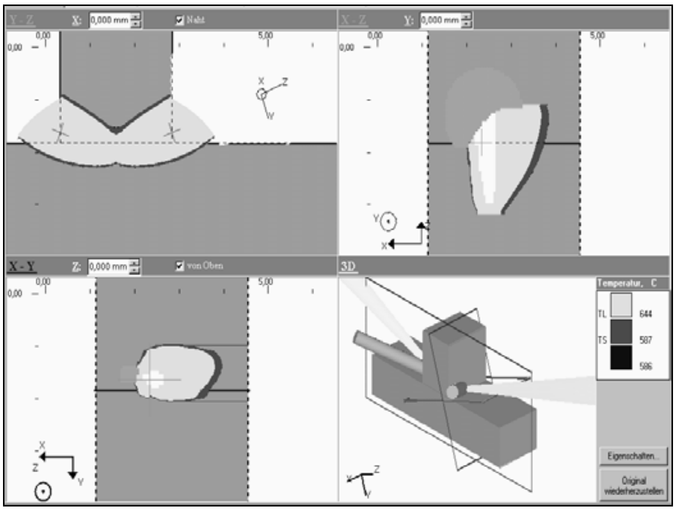

Figure 9. *LASIM output – Weld pool*

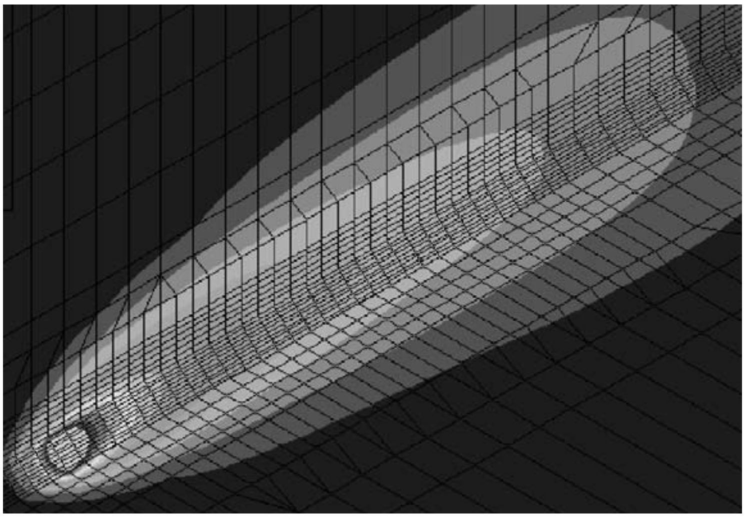

Figure 10. *Temperature field computed with the thermal model*

A thermal local model is built with ABAQUS. The moving heat source is defined using the DFLUX user subroutine. A classical gaussian conical description has been chosen. The heat source parameters are tuned in order to match the temperature fields given by LASIM. A picture of the thermal model is shown in Figure 10.

3.5. *Local 3D mechanical modelling and experimental validation*

The 3D local model is based on the thermal model. An elastic-plastic behaviour law with isotropic hardening has been used. Properties are temperature-dependent.

The 3D mechanical modelling is made in two steps:

– the non linear simulation is performed on a 4-cm-long model,

– the mechanical fields are transferred on a 20-cm-long model.

The results of this local model have been compared to experiments (Figure 11).

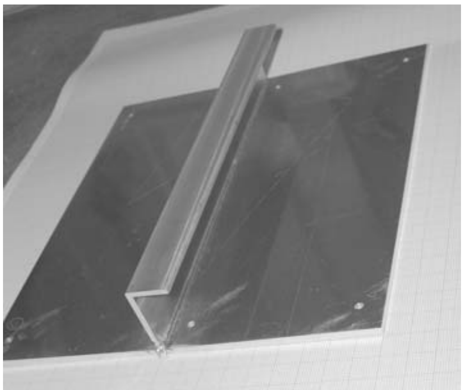

Figure 11. *Welded coupons for the validation of the local model*

Several coupons have been welded in order to have a good experimental reference.

The numerical model predict an angular deflection 7% smaller than the experimental value. This result is judged quite good. Measured longitudinal and transversal shrinkage featured a high level of dispersion, so a real comparison with the computed values has not been made. However, averaged experimental values had the same order of magnitude than the computed one.

3.6. ***Local shell modelling***

The local shell model is built in order to prepare the global model. Shell elements have been chosen because they are the most suited elements for the description of the mechanical behaviour of thin structures such as fuselage panels.

The basic idea is to build a shell model which features the same mechanical response than the 3D model. The following procedure is thus used:

After the welding simulation, the 3D model is unfolded (extremities brought back to their initial position). The reaction forces are then used to compute 3 equivalent stresses:

– a bending stress, which gives the angular deflection of the coupon,

– two in-plane stresses, which pilot the longitudinal and lateral shrinkage.

The computed stresses are then introduced within the shell model, in the elements close to the seam (see Figure 12). After equilibrium, the difference (angular deflection) with the 3D model reaches 7% and less than 1% if we compare with the experimental measurements.

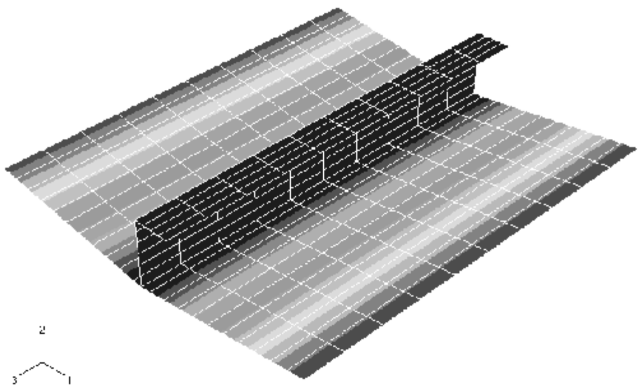

Figure 12. *Local shell model (vertical displacement x 10)*

3.7. ***Global shell modelling***

Once the local shell model has been defined, the simulation for the whole panel is straightforward by transfer of mechanical fields (see Figure 13).

A 1m-long flat panel has been manufactured with 3 welded stringers. The comparison between the computed curvature and the measured one leads to a difference of 5%. The simulation describes thus very accurately the behaviour of the real panel.

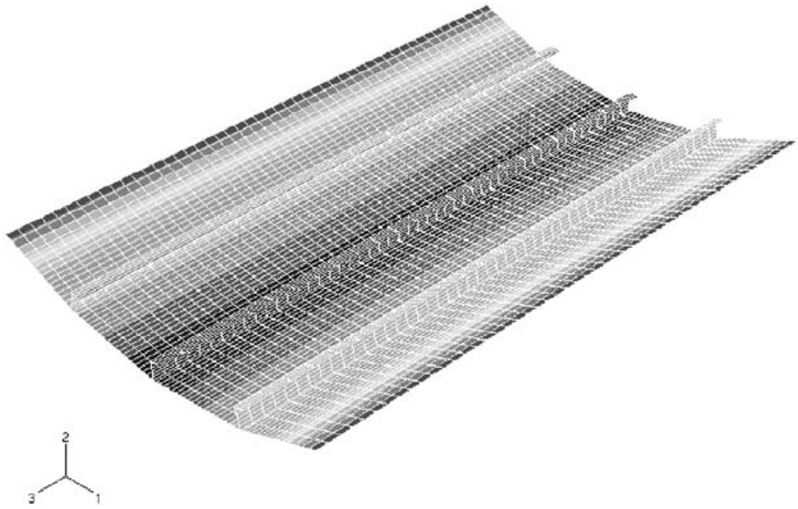

Figure 13. *Global shell model (vertical displacement x 10)*

3.8. *Conclusion*

The methodology presented here has been validated. The achieved accuracy is very good for the studied case. We can thus use this approach and our software package PREDIST© to compute the distortions of large thin structures. A possible application could be the determination of the welding sequence which minimizes the distortions.

Still, the proposed methodology suffers from a lack of generality (no interaction between the global and the local model assumed). Application to real curved panel could require some modifications. However, the presented work constitutes a major milestone and makes us confident in our ability to handle industrial cases soon.

4. Prospects and conclusion

In this paper, the work carried out by EADS CRC and partners on the simulation of welding has been presented. The achieved results are quite satisfactory.

Acknowledgement

The FSW work was carried in the WAFS 5th Framework Programme for EU R&T and was partially funded by CEC.

Claudie Darcourt is preparing a PhD Thesis on the modelling of Laser Beam Welding, with the technical support of the University of Technology of Compiègne, with Professor J.M. Roelandt. The financial support of the French Ministry of the Economy, Finance and Industry is gratefully acknowledged.

LASIM simulations and experiments related to laser beam welding have been carried out by EADS CRC in Ottobrunn.

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