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MULTI-PASS WELDING SIMULATION OF TIG WELDED AISI 316LN

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ABSTRACT

Residual stresses may have considerable effects on the behaviour of a welded structure. However, these stresses are difficult to measure on site, therefore a numerical tool may provide a suitable means to predict these residual stresses. When dealing with multi-pass welds, numerical procedures found in literature suggest that the user must change the mesh after each weld pass. In doing so, the prediction of the residual stresses becomes quite labour intensive. Therefore, a new approach for the prediction of residual stresses due to multi-pass welding is desirable. In this new approach the plate and the filler material of all the weld passes are present from the start of the analysis. The plate and filler material is modelled using contact bodies. In the thermal analysis the bodies can be (de)activated. The results from the thermal analysis are used for the mechanical analysis, i.e. an uncoupled analysis is performed. At temperatures above the melting point, sliding of the contact bodies is allowed while below the melting point the bodies are effectively glued to their surroundings. For comparison with the thermal analysis, experiments were performed to measure the temperatures in an AISI 316 LN stainless steel plate during the Tungsten Inert Gas (TIG) welding process. The temperatures obtained from the calculations are too high and cooling of the plate is too fast, in comparison with the measurements. The deformation and the residual stresses obtained by the mechanical analysis are found to be too small. However, the approach used here to model a multi-pass weld process can be used with minor adjustments.

KEYWORDS

Welding, numerical simulation, residual stress, AISI 316 LN

INTRODUCTION

When working with welded structures, the residual stresses are a force to be reckoned with. However, these stresses are hard to measure on site, therefore a numerical tool may provide a suitable means to predict these residual stresses. Following the procedures found in literature, the user has to change the mesh after each weld pass, which makes it quite labour intensive. Therefore, a new approach is needed. The new procedure described here allows the use of one finite element mesh and one calculation run for the entire multi-pass weld, thereby making it less labour intensive. The commercial finite element program MARC was used.
For the validation of the numerical results, experiments were performed. A 10mm thick AISI 316 LN plate with a U-butt groove was clamped on a rigid platform to restrain the movement during welding. The groove

was filled using 9 TIG weld passes with filler material SMA 16-8-2 SP. During the welding experiment, the temperature of the plate was monitored at several places.

EXPERIMENTS

An automated welding experiment was carried out to obtain the temperature fields caused by the TIG welding process in a 120x90x10-mm AISI 316LN stainless steel plate. These temperature fields were used to verify the calculations. During the welding process the plate was clamped on an aluminium platform for extra cooling and to restrain the movement of the plate. Figure 1 shows a schematic illustration of the clamp, the stainless steel plate and their dimensions. Prior to the welding, the stainless steel plate was annealed in order to ensure a stress-free initial condition for the residual stress measurements to be performed later.

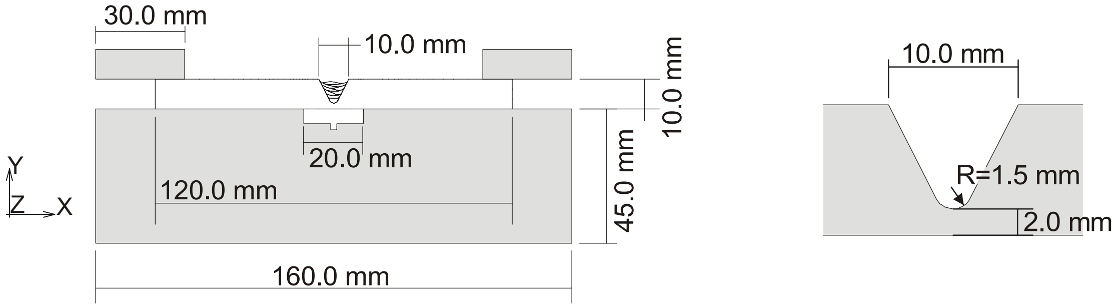


Figure 1: Schematic illustration of the clamp, the plate (a.) and the weld groove and their dimensions.

Ten thermocouples (Chromel-Alumel with an Inconel mantle) were placed on the bottom side of the plate to measure the temperatures. The placement was such that the distance to the weld centre line was 0, 2, 4, 6, 16 and 24 mm.

FINITE ELEMENT MODEL

Argyris [1] has shown that mechanical generated heat has a marginal influence on the temperature field during the welding process. He concluded that the temperature field and the mechanical field during the welding process could be calculated in two separate analyses. First a transient thermal analysis was performed, in which the temperature history of the stainless steel plate was computed. Secondly, a transient thermo-elastic-plastic analysis is performed to compute transient and residual stresses and strains using the results of the thermal analysis.

The filler material of the different weld passes are modelled as individual contact bodies. For the thermal analysis these bodies are linked to each other to obtain the thermal interaction, while utilising the contact bodies during the mechanical analysis.

The final mesh consists of 11 contact bodies, containing 2320 isoparametric, arbitrary quadrilateral generalised plane strain elements, with 4 integration points, and 2717 nodes.

The Thermal Analysis

The temperature distribution during the welding process is a result of the heat input of the welding arc, conduction of heat through the material, surface heat losses and the thermal properties of the material.

The amount of heat supplied to the stainless steel plate by the welding arc can be expressed as:

$$Q = \eta_a U I \tag{1}$$

where Q is the energy of the welding arc, U is the arc voltage, I is the arc current and η_a is the arc efficiency. The arc efficiency is taken to be 90%.

Part of the heat of the welding arc is used to melt the filler material while the remainder of the heat is introduced to the plate as a spatially distributed surface heat flux (figure 2), which shape is determined by equation (2):

$$q(x,t) = \frac{\eta_a Q}{v} \cdot \frac{C}{0.95 \cdot \sigma \cdot \sqrt{2\pi}} \cdot e^{\frac{-(x-m)^2}{2\sigma^2}} \cdot e^{\frac{-v\cdot(\tau-t)^2}{a^2}} \tag{2}$$

where v is the travel velocity of the torch, x is the distance from the weld centre, m is the position of the centre of the weld in relation to the centre of the groove, t is the time, τ is the time at which the torch centre enters the analysis plane, C, a and σ are constants.

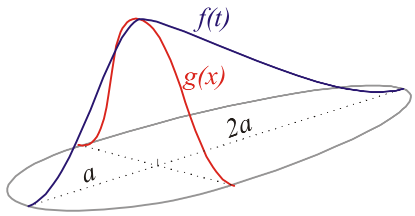


Figure 2: Illustration of the distribution functions for the surface heat flux.

Heat losses from the surface of the plate are modelled using Fourier's law of heat transfer. The heat transfer coefficient for convection was modified to account for the losses of heat due to radiation.

The filler material in the thermal analysis

The deposition of filler material is simulated using the DEACTIVATE/ACTIVATE procedure of MARC [2]. With this procedure it is possible to turn elements on and off to effectively remove material from or add material to the model.

The body representing the filler material of one weld is divided into six rows all being deactivated at the beginning of the analysis. During the analysis, one by one the rows are activated again, simulating the deposition of the filler material. Once a row is activated, the surface heat flux is repositioned so that the surface heat flux always works on top of the activated elements.

The filler material is added hot to the model. The thermal properties of the stainless steel plate and the filler material are assumed to be the same and are temperature dependent, see figure 3. As the temperatures in the aluminium clamp will not be very high, the thermal properties are taken as constants.

To account for the convective heat transfer in the weld pool, the thermal conductivity of the material above melting point is increased. The latent heat used in the analyses is 330 kJ/kg, the solidus temperature is taken as 1400 °C and the liquidus temperature is 1459 °C.

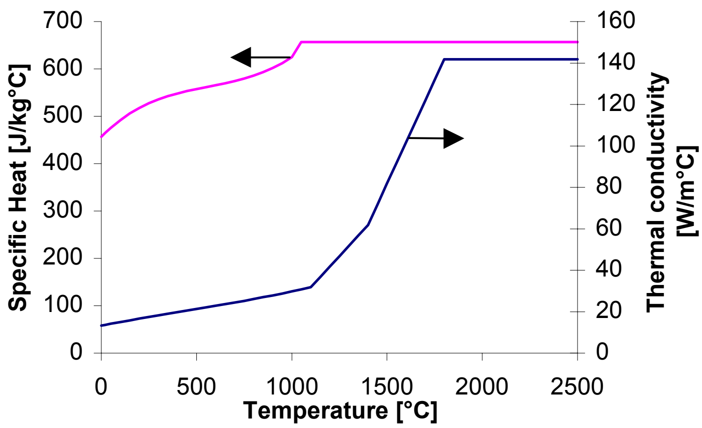
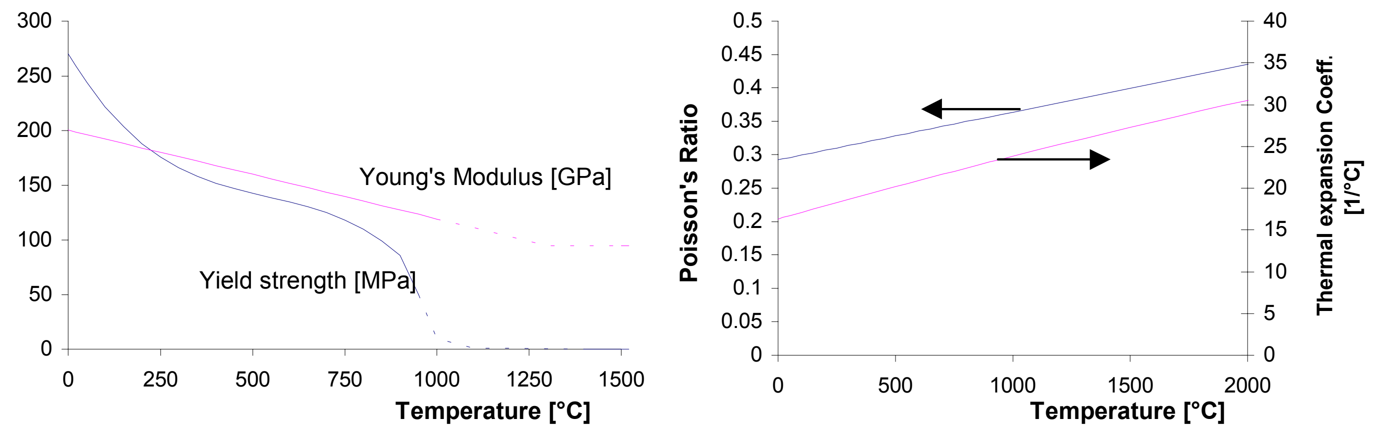


Figure 3: Temperature dependent thermal conductivity and specific heat of the stainless steel.

The mechanical analysis

Rate-independent elastic-plastic equations included with the thermal strain effects are used for the mechanical model. Creep strains are neglected, given that the time period at which the plate is at high temperatures is very short. The von Mises yield criterion is used with the kinematic hardening rule to model the Bauschinger effect and reverse plasticity, which by many researchers is believed to take place during the welding process [3].

The filler material in the mechanical analysis
For the mechanical analysis it is not possible to use the DEACTIVATE/ACTIVATE options to simulate the deposition of the filler material as it would result in unrealistic deformations and severe numerical problems. In this study, the contact analysis option in MARC is used. During the analysis, the contact bodies cannot separate from each other as this would create cavities. Once a body is above melting temperature, the body is allowed to slide with no friction over its surrounding contact bodies. At temperatures below melting point, no sliding is allowed and the body is effectively glued to its surroundings.
The elements representing the part of the plate between the clamping parts of the aluminium platform are rigidly tied to the clamp. The rest of the plate is allowed to separate from the clamp. Between the plate and the clamp, the friction coefficient is taken to be 0.25 [4].
The mechanical properties of the stainless steel plate and filler material are also taken temperature dependent [5]. While the properties of the aluminium clamp are again taken as constants. Furthermore, the clamp is modelled as a linear elastic material. The temperature dependent Young's modulus, yield stress, linear thermal expansion coefficient and the Poisson's ratio of the stainless steel used for the computations are shown in figure 4. The Young's modulus above melting point is taken to be constant. The value corresponds to the value of the Young's modulus just before melting. To avoid numerical problems the Poisson's ratio may not become 0.5 and the yield stresses at high temperatures must have low, but non-zero, values.



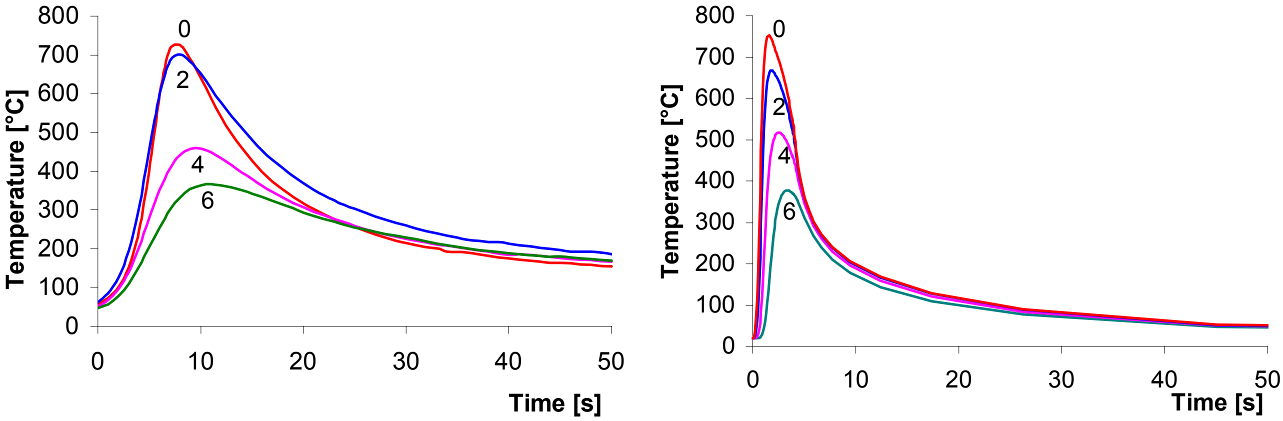
a. b.

Figure 4: Temperature dependent yield stress, Young's modulus, thermal expansion and Poisson's ratio [5].

In reality the plastic strains are relieved when the stainless steel is at a sufficiently high temperature. The presence of nonzero material properties above melting temperature would cause the plastic strains not only to continue accumulating but also to reach artificially high values owing to the very low magnitude of the mechanical properties at these temperatures. Therefore a total relief of stresses and plastic strain is used during the mechanical analyses when the material is above 1150 °C. This is achieved using of the user subroutine UACTIVE. The temperature of 1150 °C is chosen, since this is approximately the temperature at which stress free annealing takes place in seconds.

RESULTS

Thermal analysis
The temperature history for the first weld pass can be seen in figure 5. It shows both the experimentally measured (5a) and the calculated (5b) temperature histories for 4 thermocouples located at 0, 2, 4 and 6 mm respectively from the weld centre.



a. b.

Figure 5: The measured (a.) and the calculated (b.) temperature history for the first weld at 0, 2, 4 and 6 mm from the weld centre line.

The computed temperatures rise and fall too fast in comparison with the measured values. This is most likely caused by a too steep distribution function used for the surface heat flux. The calculated cooling rate that is observed after the weld pass has been completed, is also too high, this is probably caused by a too high convective heat transfer coefficient. Figure 6 shows both the measured and the calculated peak temperatures for two thermocouples. It can be seen that the first weld pass is accurately calculated while for the other weld passes the peak temperatures are too high. Given that the peaks are to high for all thermocouples and that the cooling is too fast, it is most likely that the area of the surface heat flux is too small. The efficiency of the arc is assumed to be 90 %, which is most likely to be too high for the TIG welding process.
From the calculations it followed that re-melting of part of the previous welds and the plate occurred.

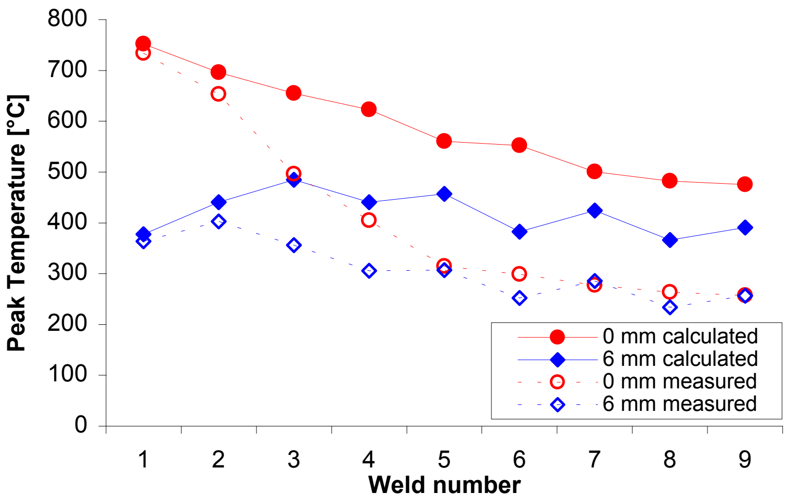
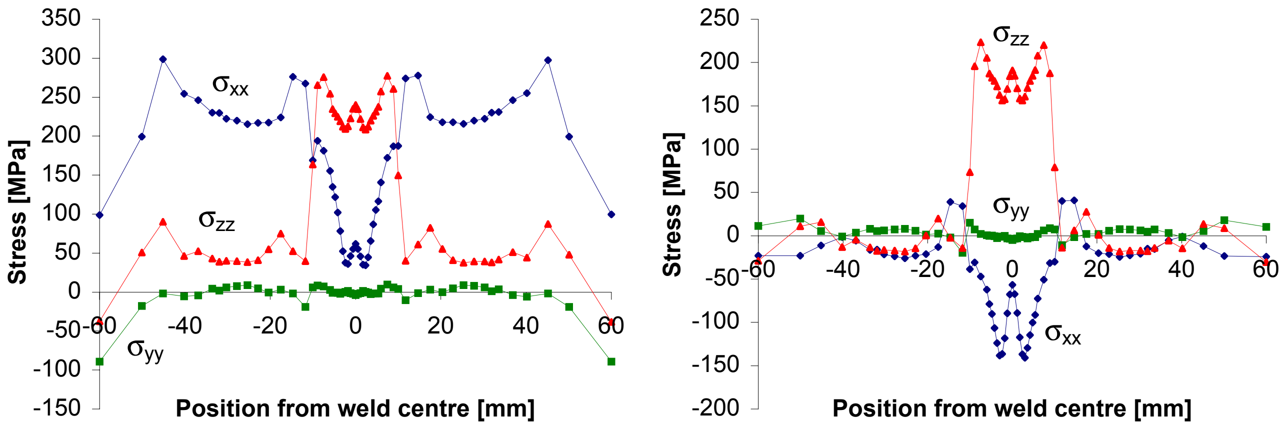


Figure 6: Peak temperatures for the different weld passes for two thermocouples.

Mechanical analysis
The stresses that are present in the plate after completion of the 9 weld passes, can be seen in figures 7a and 7b. The figures show the stresses along the bottom side of the plate before and after the release of the clamp. It is clear that the clamp mainly restrains the plate in the direction perpendicular to the weld (σ_{xx}).
These figures also show that the stresses directly under the weld are approximately 200 MPa, whereas the stresses further from the weld are quite low, approximately 40 MPa.
Figure 8 shows the undeformed plate and the deformed plate after the welding has been completed and the clamp has been released. The majority of the deformation of the plate is located directly underneath the weld zone. This localisation was also seen in the thermal analysis and the residual stresses and may be due to the poor thermal conductivity of the stainless steel. But two other effects may play a role. Firstly, it is believed that the low stresses may also be due to a too low temperature for stress relieve; most stresses generated by

previous welds disappear due to the next welding pass. And secondly, the manner of clamping the plate as implemented in the model is probably too rigid.



a. b.

Figure 7: Stresses along the backside of the plate before (a.) and after (b.) release from the clamp.

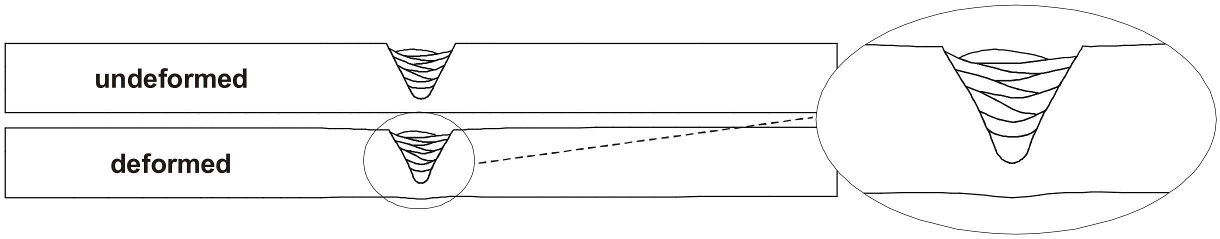


Figure 8: The undeformed plate and the deformed plate after release from the clamp.

Another result from the mechanical analysis is the distortion of the temperature field and temperature jumps of up to 200 °C were present in the deformation of the plate. These temperature jumps are caused by the displacements of the bodies that were not taken into account in the thermal analysis.

CONCLUSION

From the results of the thermal analyses it can be concluded that the distribution function is increasing to fast and the heat transfer coefficient for convection is too high.
A part of the material of the plate and the previous weld are (re)melted upon subsequent weld passes. The results from the mechanical analysis indicate that the deformation of the plate from the experiment is bigger than the computed deformations. This may be due to fact that the temperature at which strains are relieved is too low and that the clamping of the plate is not modelled correctly.
Due to body movement discrepancies occur in the temperature distribution. The use of contact bodies eliminates the need for mesh rezoning during the analyses of a multi-pass welding process. The method of using different bodies to model the filler material during multi-pass welding is promising. Using a coupled model, in which temperatures and deformations are computed at the same time, can solve the problem with the mismatch in temperature that occurs in the mechanical analysis.

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