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SIMULATION OF THE INFLUENCE OF FORMING ON RESIDUAL STRESSES AND DEFORMATIONS AFTER WELDING AND HEAT TREATMENT IN ALLOY 718

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Abstract. Manufacturing of components in aero engines requires attention to residual stress and final shape of the product in order to meet high quality product standards. This sets very high demands on involved manufacturing steps. The manufacturing of a V-shaped leading edge of a vane is simulated. It is made of Alloy718, which is a nickel based heat resistant material commonly used in aerospace components. The manufacturing process chain consists of forming, welding and heat treatment. The results show that the remaining residual stresses after a manufacturing process chain are affected when the residual history from the forming process is considered. The residual stress decrease after heat treatment is about 55-65%. Moreover, the von Mises stress profile through thickness at the centre of the radius at the weld joint is about 25% higher when full forming history is considered.

1 INTRODUCTION

Light weight design has been identified as one contribution in the effort to meet the global challenges of reduced CO_2 emissions from aviation. This has resulted in a number of design solutions where fabrication of large structural components is the selected approach to reach a light weight design of aero engine components. Manufacturing simulation technologies supporting design as well as manufacturing engineers in decision making and preparation of new design solutions is a vital tool in this approach. In order to understand and optimize the fabrication concept the component state, in terms of e.g. deformation and residual stresses, will have to be followed through the different steps of manufacturing. Parts have a final outcome in geometry and material integrity (e.g. residual stresses and microstructure) that is influenced by the total manufacturing history, typically going from sheet metal forming through welding operations and heat treatment. It is important to understand how the manufacturing history affects the final shape of the geometry and how residual stresses evolve in the different steps. It is a complex task to optimize the design of a fabricated part in order to achieve a robust solution of manufacturing. Increasing the understanding of the individual processes and their interactions can reduce the need for experimental trials. The understanding can also aid in the selection of the fabrication strategy and estimating the pros and cons with different concepts or manufacturing methods. Earlier work in manufacturing processes simulation has focused on one and sometimes two steps, e.g. simulations with combinations of welding and heat treatment [1-3]. A three step simulation was done in 2004 with a fictive case [4]. More recently there have been three step simulations with forming, clamping and a simplified welding procedure have been made [5, 6]. Moreover, forming, welding and stress relief heat treatment with the emphasis on material modelling has been done [7]. A multi step simulation was carried out in the 6th Framework programme; project Virtual Engineering for Robust Manufacturing with Design Integration (VERDI) [8]. In this study a manufacturing process chain of a V-shaped leading edge (LE), Figure 1, is simulated. The manufacturing process chain consists of forming, welding and heat treatment. The LE is part of a vane made of Alloy718, which is a nickel-based heat resistant material commonly used in aerospace components. The aim of this study is to simulate how the forming residual stresses and deformations are influenced by subsequent welding and heat treatment processes.

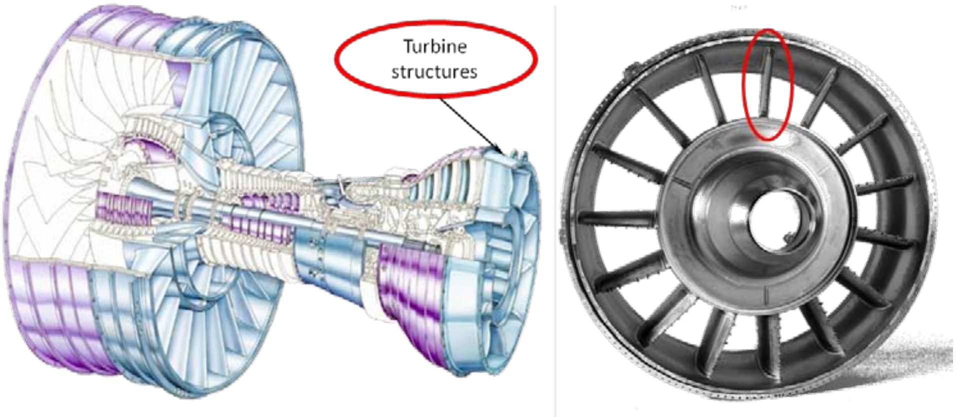

Figure 1: The LE (highlighted to the right) of a guide vane which is situated in a casing at the rear end of the engine.

2 METHODOLOGY

The part of interest is the LE of a guide vane in a turbine exhaust case at in aerospace engine. The cross section of the guide vane is normally both convex (suction side) and concave (pressure side) and there is also a radial bend at the LE. However, here the LE cross section is simplified to a symmetric V-shape. Initially a forming simulation is carried out to establish the V-shape geometry and calculate the resulting stresses and strains. In the welding simulations where two V-formed parts are welded together, here two cases are studied. In the first case the model starts with the nominal geometry after forming as start of the welding simulation, but without residual stresses. In the second case the full forming history is simulated and its residual state is taken as initial state for the subsequent simulation. Both cases are followed by subsequent heat treatment simulations with full residual state from the welding simulations. The simulation scheme is shown in Figure 2. The differences in obtained final shapes and residual stresses for the two approaches are compared.

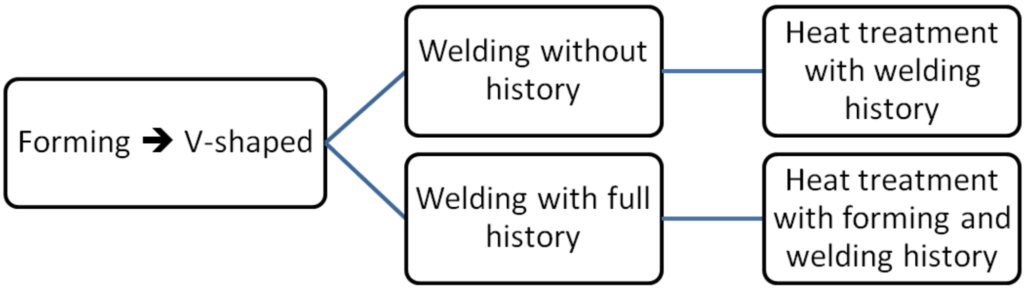

Figure 2: The simulation chain scheme.

All simulations were done with the finite element code MSC.Marc using updated Lagrange formulation with large strain theory. The mesh of each sheet consists of 49266 nodes and 40000 elements. The initial sheet size is 50*100 mm and the thickness is 2.54 mm with the element size of 0.625*1*0.5 mm.

2.1 Sheet metal forming

Forming of thin metal sheets involves stretching, bending and drawing. Normally the most important part is the tool design. The design of the tools is often determined by FE-simulations to achieve the desired shape through an iterative process. The forming tools and the work piece are shown, both initially and at the end of the stroke, in Figure 3. To avoid coining of the sheet the stroke ends just before the sheet reaches the bottom of the die. The two sheets that are to be welded are formed simultaneously. In this case no sheet holders are used and therefore, it is mostly a bending procedure. Moreover, there is no optimisation due to e.g. springback done. Neither is the friction considered in this work.

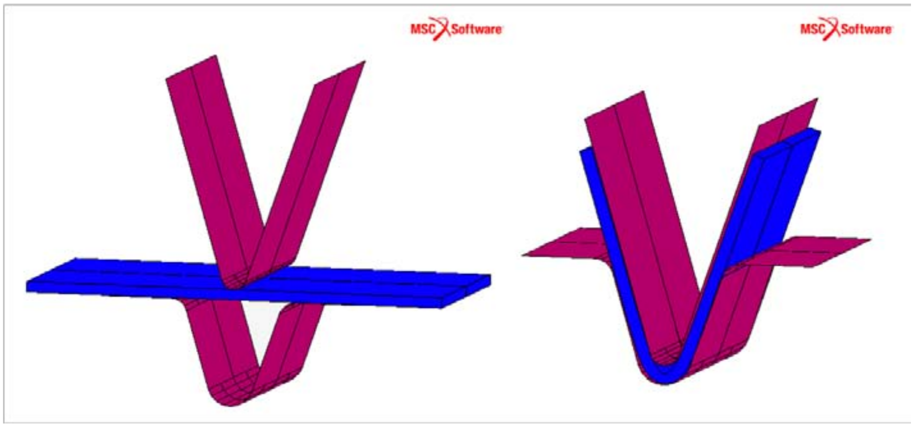

Figure 3: The initial setup and the V-shaped sheet at the end of the punch stroke when the sheet reaches the die, before springback.

2.2 Welding

Welding is a process which purpose is to join two pieces together by melting the boundaries of the weld joint. The weld process creates a strong bonding after cooling. The heat source simulated is TIG (Tungsten Inert Gas) which is modelled with an analytical equation of a double ellipsoid, recommended by Goldak et al [9]. The heat source parameters are the power input and the geometry (width, length and depth) of the melt pool. The FE-analysis was done with a staggered approach to solve the thermo-mechanical problem with constant temperature for each element when solving the mechanical step, [10]. For both cases studied the geometry was obtained from the forming analysis. In the first case no history from the forming simulation was taken into account and considered nominal with respect to residual stresses and strains. However, in second case residual stresses, equivalent plastic strain and state variables was used as input to the welding simulation. The temperature field of the ongoing weld is shown in Figure 4.

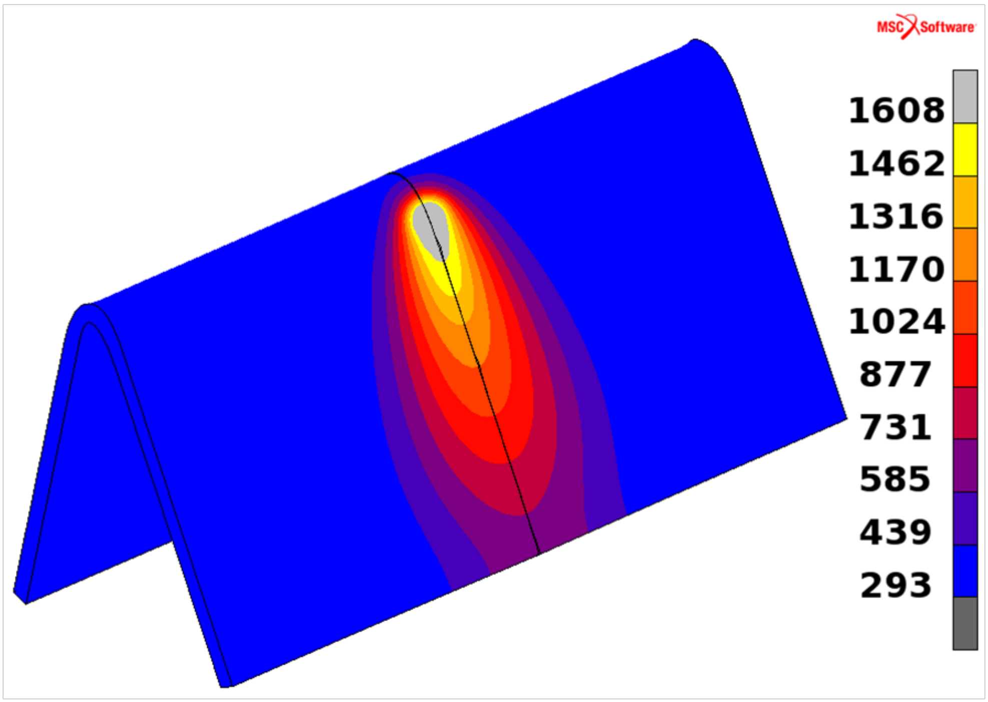

Figure 4: The weld when it is approaching the radius. The grey spot is the weld pool that has a temperature above 1608 K (which is the liquidus temperature for Alloy 718).

2.3 Stress relief heat treatment

Stress relief heat treatment is a process which purpose is to relax the stresses that originates from deformation in the previous manufacturing steps. In this study a simplified heat treatment is used. The temperature is prescribed in nodes during the first two steps in thermal cycle shown in Figure 5 in the last step the cooling occurs by convection. For metals creep becomes important only for temperatures greater than about 40% of T_{melt} (the absolute melting temperature), [11]. The time period for ramping up the temperature is considered as short and especially when the temperature is above $0.4 \cdot T_{melt}$. Therefore, creep is only active during the hold time. Neither is creep active during cooling. The Norton creep model is used.

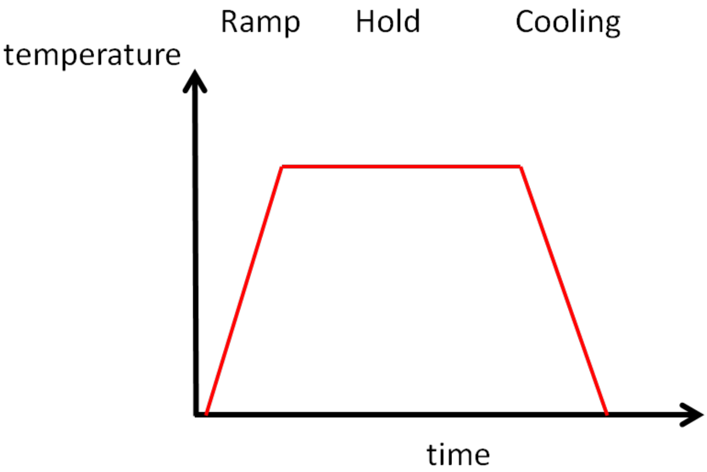

Figure 5: Principal sketch of the temperature cycle for the stress relief heat treatment. The cycle comprises of three parts: ramping up the temperature, hold time (=constant temp.) and cooling.

3 SIMULATION RESULTS

3.1 Sheet metal forming

The residual stress after the forming operation is concentrated to the radius and is reaching nearly 700MPa as shown in Figure 6. The stresses at both inside and outside of the sheet are more or less equal before springback. Thus, the spring back causes a decrease in stress with about 20% at the inner of the radius, which can be seen in Figure 6. However, at the outer of the radius the stresses decrease with about 80%. The angular change is ~6.5° between the both legs as shown in Figure 7.

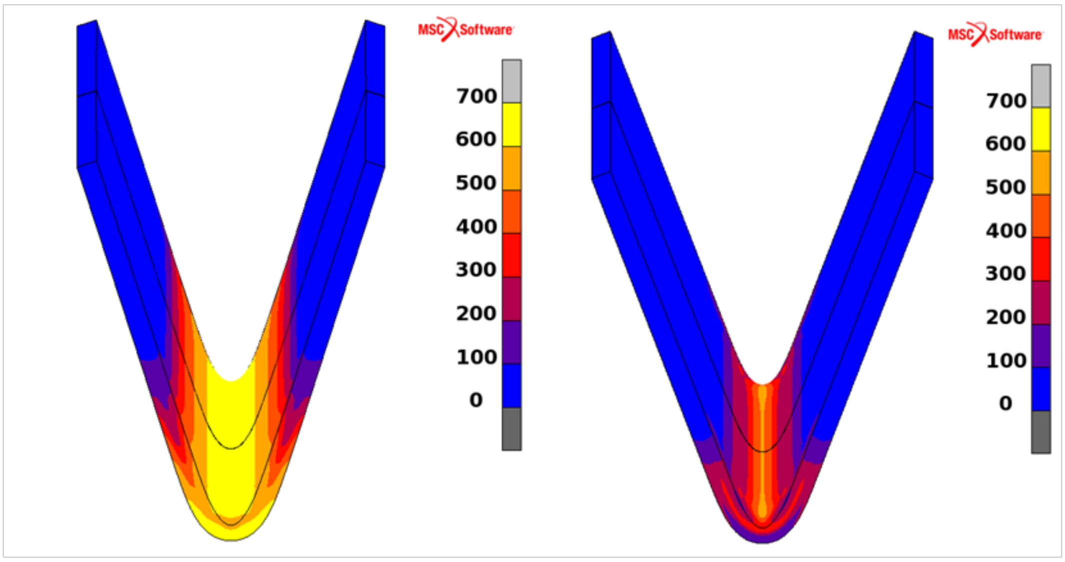

Figure 6: The von Mises stress at the end of the tool stroke (left) and after springback (right) decreases with ~20%. At the inside of the sheet the stress is decreased with ~20% and at the outside with about 80%.

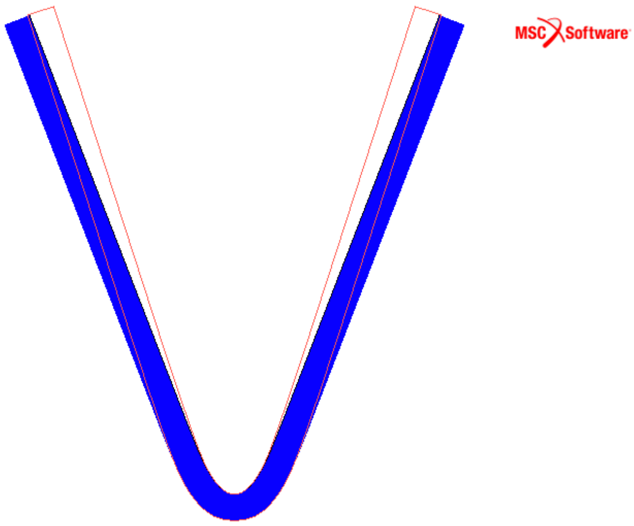

Figure 7: The change in angle from the springback of the V-shaped sheet is about 6 degrees.

3.2 Welding

The welding is carried out in two steps. First six tack welds are made and after cooling to room temperature a subsequent single butt welding is made. As mentioned previously, two cases were simulated. The stress pattern originating from the tack welding is seen within black dotted circles in Figure 8. The weld starts, in both cases, between the lower and middle tack and goes without interruption to the equivalent position at the rear (in the picture) of the sheet. In the first case without the forming history the stresses are concentrated around the weld, Figure 8 (left). The stresses are increased for every tack weld position. In the second case most of the stresses are also around the weld but increased at the tack positions and especially at the radius where the residual stresses from the forming are concentrated, Figure 8 (right). However, the residual stresses from forming along the radius are higher at the inner radius of the sheet, Figure 9 (right), in comparison with the stresses at the outer radius, Figure 8 (right). As seen in Figure 10 the deformation is quite moderate but still ~15% larger for the case with residual history.

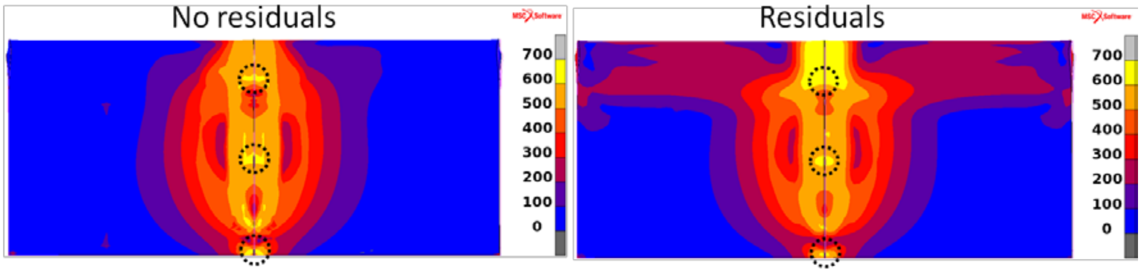

Figure 8: The residual von Mises stress after welding, at left without history and right with full residual history. Both plots are viewed from the outside of the V-shaped sheet with the radius at top. The position of the tacks (three on this side) are highlighted with black dotted circles.

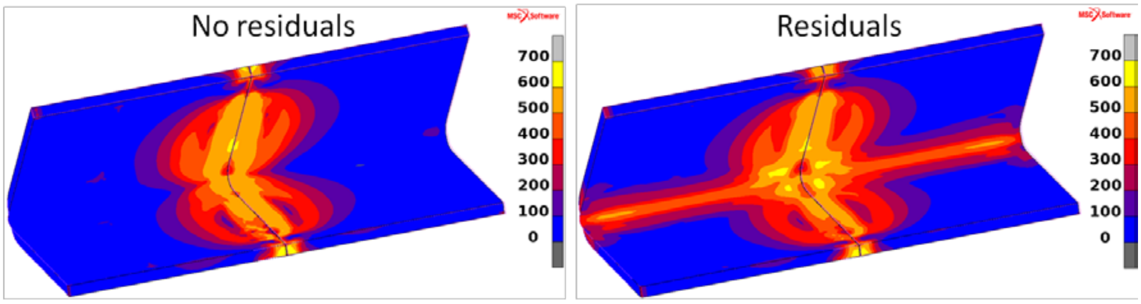

Figure 9: The residual von Mises stress after welding, at left without history and right with full residual history. Both plots are viewed from the inside of the V-shaped sheet.

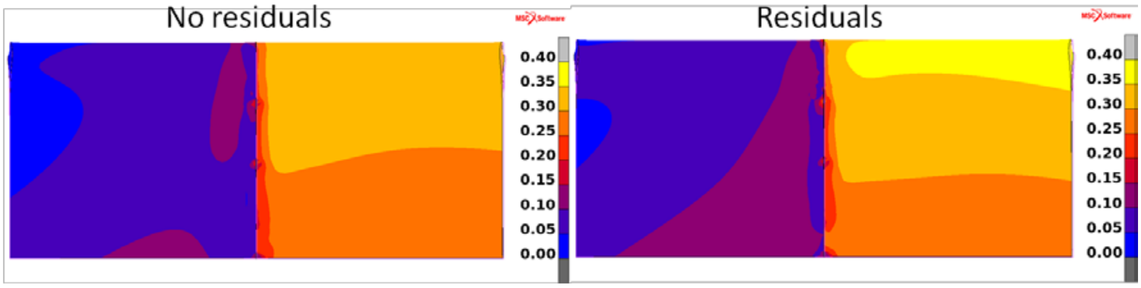

Figure 10: The total deformation after welding for the two cases simulated. There is slightly larger deformation for the case with forming history (to the right).

3.3 Stress relief heat treatment

The stress relief heat treatment was done as described in chapter 3.3. In both cases the stresses are concentrated around the weld, Figure 11. It is also seen that there is, at the radius, higher stresses areas where the residual stresses from forming and welding overlaps. The stress levels in both cases have relaxed within 55-65%. However, the residual stresses from forming along the radius are larger at the inner radius of the sheet as mentioned in chapter 4.1 and shown in Figure 12 (right). There are only small changes in deformation after heat treatment in comparison with after welding as can be seen when comparing the plots in Figure 10 and Figure 13.

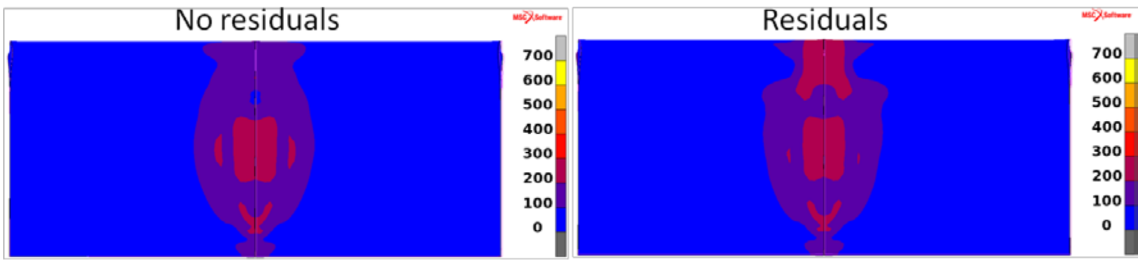

Figure 11: The residual von Mises stress after heat treatment, at left without history and right with full residual history. Both plots are viewed from the outside of the V-shaped sheet with the radius at top.

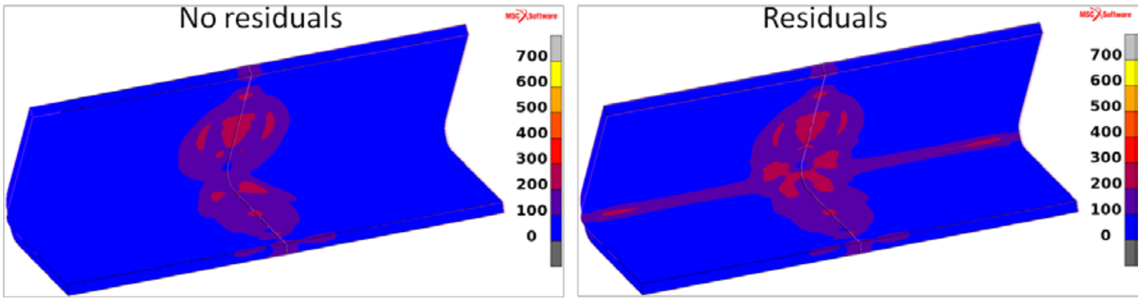

Figure 12: The residual von Mises stress after heat treatment, at left without history and right with full residual history. Both plots are viewed from the inside of the V-shaped sheet.

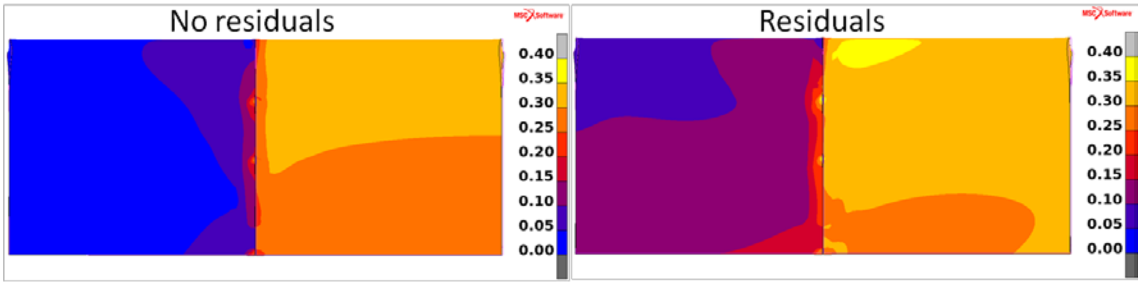

Figure 13: The total deformation after heat treatment for the two cases simulated. There is slightly larger deformation for the case with forming history.

3.4 Stress profile

The stress profile through thickness at the centre of the radius where the residual stresses overlaps is shown in Figure 14. The weld alters the von Mises stress profile for the forming residual stresses. However, the difference in magnitude of stresses before stress relaxation for the two cases remains more or less afterwards.

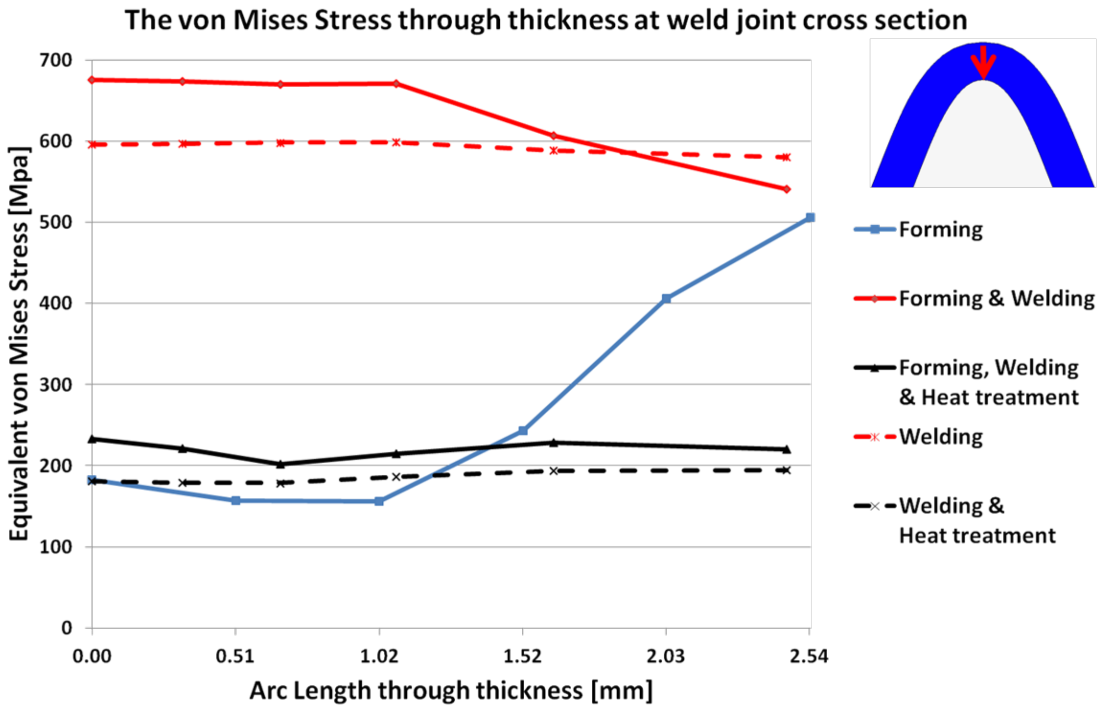

Figure 14: The von Mises stresses profile through thickness for the weld joint cross section at the radius. The arc length is from the outside towards the inside. The direction of the arc length is shown at top right.

4 CONCLUSION

Simulation of a manufacturing process chain consisting of forming, welding and heat treatment has been carried out for an Alloy 718 component. Two cases were studied: with and without using the residual history from sheet metal forming. It is obvious that the welding and heat treatment simulations results are affected when the residual history from the forming process are considered, particularly where the residual stresses from the different processes are overlapping. The results indicate the necessity of including all manufacturing process steps due to substantial residual stresses from the different process steps. At the radius of the weld joint where the forming residual stresses interact with weld residual stresses they are relaxed with 55-65%. The residual stress profile through thickness at the centre of the radius of the weld joint after heat treatment is about 25% higher when the full forming history is taken into account. The design process and decision making is further enhanced including this manufacturing process chain. Furthermore manufacturing uncertainties are avoided. The need of considering all manufacturing processes is also supported by [5, 8, 12].

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