# Experiments and simulations of welded joints with post weld treatment

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## Abstract

This paper provides detailed information about experimental investigations of an arc welding process carried out for seam butt welded joints followed by a process of needle peening. The objective is to analyze the difference in fatigue strength between as welded and treated conditions. The results are compared to numerical simulations including contact-algorithm for post weld treatment. Furthermore the fatigue life is calculated numerically with notch strain approach to consider the different residual stress states for both conditions. As result the increase of fatigue resistance due to needle peening known from experimental investigations could now be comprehended also by numerical simulation.

Keywords: experiment, simulaton, needle peening, post weld treatment, notch strain concept

## 1. Introduction

For welded joints subjected to dynamic loads fatigue resistance of the base material and the weld is very important to design steel constructions in fatigue limit state. In most cases residual stresses due to the welding process reduce the fatigue resistance. However, different methods of post weld treatment can be chosen to enhance the fatigue strength of welded structures. One of these methodes is the Ultrasonic-Impact-Treatment (UIT), which introduces beneficial compressive stresses at the weld toe zones and reduces stress concentrations by improving the weld toe. [Statnikov et al., 1977]. The equipment consists of a handheld tool and an electronic control box (Figure 1). The tool is easy to handle during application. It operates at the head movement with a mechanic frequency of 200 Hz overlain by an ultrasonic frequency of 27000 Hz. The method involves post-weld deformation by impacts from single or multiple indenting needles excited at ultrasonic frequency, generating mechanic impulses on the work surface [Statnikov et al., 1997].



Figure 1. Ultrasonic Impact Treatment (UIT) [Applied Ultrasonics Europe].

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The objective of the treatment is to introduce beneficial compressive residual stresses at the weld toe zones and to reduce stress concentrations by improving the weld toe profile. Furthermore, the area being treated is highly plastically deformed which has the effect of work hardening. Figure 1 (right) shows a weld seam which is treated by UIT with one pin along the weld toe line.

For detailed numerical analyses of UIT-effects the process of welding was coupled with the post weld treatment process for two steel plates with a single butt weld. Additionally experimental investigations of welding were carried out for steel plates to verify the numerical model concerning thermodynamics and structure mechanics. Finally the crack initiation life was calculated based on the notch strain approach. Residual stresses and the different elastic stress concentration factors were taken into account for both conditions (as welded and treated). With this demonstrated process coupling critical zones of welds can be identified in steel constructions and can be optimized in fatigue limit state especially for productions in series.

# 2. Experimental investigations

A test setup shown in Figure 2 (left) was chosen to realize an arc welding process. The wire feeder and also the welding head were handled mechanically. The welding head was fixed at a track beam, which was displacement controlled to ensure a constant welding velocity. Furthermore, the head could be positioned exactly with the track beam in x, y and z direction. The coordinate system is shown in Figure 2 (right) with the point of origin at one edge of the plates. Only the boundaries conditions at x = +/-150 mm were fixed.



Figure 2. Test setup (left) and dimensions of test specimen (right).

The dimensions of the steel plates fabricated from S355 J2G3 are 150 x 150 x 4 mm. The seam preparation was carried out with an angle of 22.5° at every flank. The gap at the welding line varied between 0.2 to 0.5 mm for the bottom surfaces of the plates. For the weld material a wire SG 2 with a diameter of 0.8 mm and for the shielding gas a composition of 18 % CO<sub>2</sub> and 82 % argon was used. The butt weld is generated as single pass welding process. Together with the recorded time the welding velocity was estimated to v = 255 mm/min. During the welding process the electric input was measured with U = 18.3 V and I = 125 A. Furthermore, the temperature was measured with three thermo elements from type Newport Omega

TC-GG-KI-30-40 with a range of -90°C to 1370°C. The thermo elements were positioned at the right plate with distances  $x_1 = 5$  mm,  $x_2 = 30$  mm and  $x_3 = 50$  mm transverse to the welding line (s. Figure 2 (right)). Additionally three strain gauges from type HBM 3/120LY11 were oriented at the left plate exactly with the same distances like for the thermo elements at the right plate. The strain gauges were necessary to measure the residual strains during and after the welding process. All measured signals were recorded online with the data logger HBM Spider 8 and analyzed with the software Diadem. The whole testing time included the welding time of 35 s and after then the cooling time which is terminated at nearly t = 2000 s. The results of experimental investigations will be compared in the following chapters with solutions of numerical simulations.

## 3. Numerical investigations

The symmetric half model, implemented in ANSYS<sup>®</sup>, consists of three zones the weld, the heat affected zone and the base material of the steel plate (Figure 3). Material properties are implemented depending on temperature [Wichers, 2006]. The notch at the weld toe has a variable radius to consider the actual weld geometry for as welded and treated conditions. The smallest dimension of an element at the notch has been chosen to 0.2 mm in direction of thickness. The model is driven by displacement boundary conditions like in the test setup. For the simulation of the post weld treatment the head of a 3 mm diameter pin of UIT is modelled including contact elements between the plate and the pin (Figure 3 right).



Figure 3. Numerical model of the steel plate with a butt weld.

The simulation of welding consists of thermal and structural analyses. The coupling for the multiphysic problem is realized with a multifield solver (MFS) available in ANSYS<sup>®</sup>. It is an automated tool for solving sequentially coupled field problems and is built on the premise that each physics is created as a field with an independent solid model and mesh. Surfaces or volumes can be identified for coupled load transfer. The solver automatically transfers coupled loads across dissimilar meshes. The field 1 is defined for transient thermal analysis and modeled with 3D-thermal elements Solid70. These elements have eight nodes with a single degree of freedom, temperature, at each node. The field 2 modeled with Solid45 elements is for structural analysis to estimate the residual strains and stresses. As load for the structural model the nodal temperatures are transfered von field 1 to field 2. For

thermal symmetry the heat flux passing across the surface of symmetry shown in Figure 2 is assumed to be zero, and, for structural symmetry, the translation in the xdirection of the same surface is also zero. It is important to note that the automatically estimated time increment in the analysis drops to a very small values due to the vast difference in the temperatures. This effect can be dramatic for small element sizes of the weld pool at the fusion surface. But the meshing in the weld pool must be fine enough to account for the high temperature gradient calculation. The transient temperature profile during the welding process is analyzed using Goldak's formulation of the double-ellipsoidal heat source [Goldak, 1984]. At the beginning of the simulation all elements for the weld are deactivated with a birth&death function in ANSYS<sup>®</sup>. These elements are activated step by step when the head source is moved along the welding line. Parametric meshing is used in order to easily track the results along a certain predefined path in any direction. Due to the mutlifield solver strategy the kintecis of phase transformation could be also implemented in the numerical model. For every time step the actual content of each phase like austenite or ferrite is estimated. After the process of welding and cooling the process for post weld treatment follows and finally the macro for the calculation of fatigue life is used. The hole path of process coupling is shown in Figure 4.



Figure 4. Multiphysic process coupling.

# 4. Thermo dynamics

The numerical simulation of the transient temperature field was verified with two different measuring techniques. On the one hand with thermo elements (1D) and on the other hand with thermograph cameras (2D). The Figure 5 (a) shows a plot for the field of temperature at the top surface at t = 42 s. The welding started from left side and ended at t = 35 s at the right side. Since the welding head disturbed the view of thermograph camera, a plot during the cooling time without the welding head was chosen. It can be seen that the temperatures over 80°C have a smaller width for the left edge as for the right one. This comparison between numerical simulation and experiment shows a good agreement for the qualitative distribution of the temprature field. The zones with the same temperature levels have obviously the same range.





Figure 5. Comparison of temperature between experiment and simulation.

Additionally temperature curves over time have been measured at two different monitoring points. The thermo elements were positioned at  $x_1 = 5 \text{ mm}$ ,  $x_2 = 30 \text{ mm}$  on the top surface in the mid section (s. Pos\_1 and Pos\_2 in Figure 2). The comparison with the numerical results in Figure 5 (b) shows a very good agreement. The maximum temperature for monitoring point 1 is 900°C at nearly t = 18 s, which is the time, when the head source passes the mid section. Of course, the maximum temperature of point 2 with 200°C is due to the longer distance to the welding line lower as for point 1. With these comparisons it can be concluded that the numerical model is verified concerning the transient temperature field.

# 5. Kinetics of phase transformations

The multifield solution for the welding process includes the effects of solid state phase transformation. The cacluations are based on a TTT-diagram for the used base material S355 according to [S-ZTU from Seyfarth et al., 1992]. Therefore two different types of crystals forms are considered for phase transformations. On the one hand the  $\gamma$ -phase, also called austenite, exist as the only one for temperatures over  $A_{c1} = 718^{\circ}$ C in the case of the used S355. On the other hand different  $\alpha$ -phases (martensite, ferrite, perlite and bainite) exist which start to grow during the cooling time when the notch temperatures decrease under  $A_{c1}$ .



Figure 6. Comparison of the content for different phase transformations.

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How much percent of each  $\alpha$ -phase will appear in the heat affected zone depends mainly on the cooling velocity, the chemical composition of the base material and the actual notch temperature. Is the cooling period  $t_{8/5}$  very short the content of martensite and therfore the hardness will be high. In contrast to this longer cooling periods between 800°C and 500°C prefer phase transformations which allow diffusion of carbon. These effects can be devided in  $\gamma$ -to-ferrite,  $\gamma$ -to-perlite and  $\gamma$ -tobainite phase transformations. According to the TTT-diagram in [Seyfarth et al., 1992] the 1% and 99% borderlines for the growth of each phase are implemented in the numerical model to caculate the start- and end-content for each  $\alpha$ -crystal form. The results obtained clearly demonstrate that the calculated values for all  $\alpha$ -phases agree very well with the values in literature (s. Figure 6). The quality of these values depends mainly on the polynominal function which should approximate the borderlines 1 % and 99 % of each phase as good as possible [Börnsen, 1989]. For example if an element shows a cooling behavoiur like the slowest cooling curve in Figure 6 the  $\alpha$ -phase ferrite will grow at first with a content of 15 %. The value of literature [Seyfarth et al., 1992] in this case is 11 %. After then the perlite phase starts to grow and ends with a content of 5 % (6 % in literature). Finally the bainite phase develops up to 80 % (83 % in literature). The content of martensite is here 0 % because the cooling time  $t_{8/5}$  is to slow for this phase transformation.

## 6. Structure mechanics

The structural analysis was carried out simultaneously to the thermal analysis and phase transformations. Therfore, the nodal temperatures over time were the load for the structural elements. The simulation finished at t = 2000 s to estimate the final residual stresses and strains after cooling. For example the residual strain curves over time and longitudinal to the welding line are shown in Figure 7 for two tests (experiments 26 and 28). The resaults belong to the monitoring point 2 which was located at  $x_2 = 30$  mm transverse to weld (s. Figure 2 right). Furthermore, the curve for this point (notch) calculated with the FE-model is plotted as dotted line.



Figure 7. Comparison of phase transformation.

At first all curves show strains in tension because of the heating during the welding process the material expand. After welding the strains change to compressive values when the plates cool down. The comparison of the curves shows that the numercial result is located in the spectrum of experimental results which have a spreaded strain range like in Figure 7.

# 7. Contact mechanics

The process of post weld treatment by UIT was implemented using a contact algorithm with element types Conta173 and Targe170. For the simulation only the top of the UIT-pin shown in Figure 3 was modeled. The pin was positioned in the mid section from y = 40 - 60 mm with an initial gap to the base plate. After restarting the transient structural analysis the pin moved in an angle of  $60^{\circ}$  to the weld toe and deformed this surface. The residual stress state transverse to welding line (x-direction) for as welded condition is shown in Figure 8 (left) and the changed stress distribution after post weld treatment in Figure 8 (right).



Figure 8. Residual stresses before (left) and after (right) post weld treatment.

The transverse stress in the treated area changed from tensile residual stresses ( $\sigma_{R,T,as\_welded} = +458 \text{ N/mm}^2$ ) to compressive residual stresses near the yield stress ( $\sigma_{R,T,uit} = -327 \text{ N/mm}^2$ ). Additionally, the weld geometry was rounded by the pin and the toe notch radius increased.



Figure 9. Residual stress path before (left) and after (right) post weld treatment.

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Furthermore, the residual stress distribution transverse to the weld toe (x-direction) was compared in Figure 9 for a path in mid section. The stress path for the as welded condition rises up from the welding line (monitoring point 1) to the maximum value at the toe (monitoring point 2) and decreased slowly to a stress level of 300 N/mm<sup>2</sup> in base material (monitoring point 3). In contrast to the as welded condition the stress distribution after post weld treatment had a negative peak located at the weld toe. The compressive stress reached a minimum value of -280 N/mm<sup>2</sup>. In the near of the peak the residual stress were also reduced. But with more distance to the welding line the curve reached the stress level like in the as welded condition.

Finally it can be noticed that the post weld treatment by UIT has a great influence on the local stress state at the weld toe which is often the location for crack initiation. The numerical results are suitable to assess the fatigue strength under consideration of the modified residual stress state at the weld toe.

## 8. Fatigue assessment

The notch strain approach is used for assessing the fatigue resistance of the butt weld up to technical crack initiation. The idea behind this approach is that the mechanical behaviour of the material at the notch root in respect of local damage is similar to the behaviour of a miniaturized, axially loaded, unnotched specimen in respect of global damage. The comparison specimen is assumed to be positioned at the notch root. It should have the same microstructure, the same surface condition inclusive of residual stresses and, if possible, the same volume as the highly stressed material at the notch root [Radaj, Sonsino, Fricke, 2006]. The crack initiation life was calculated based on the notch strain approach using the version of Seeger. The S-N curve was determined with the damage parameter  $P_{SWT}$  assuming the material properties of the base material. Elastic-plastic behaviour, residual stresses and the different elastic stress concentration factors for both conditions were taken into account. The predicted S-N curves for crack initiation of butt weld are presented in Figure 10.



Figure 10. Comparison of phase transformation.

In Figure 10 the numbers of cycles N is plotted against the nominal stress amplitude  $\sigma_a$  for alternating loading (R = -1). The curve for as welded condition has the lowest fatigue strength because of the tensile residual stresses. In contrast to as welded condition the butt weld with the treated toe has higher fatigue strength. The

post weld treatment introducing compressive stresses in the notch root is highly effective in this case. The analysis indicates that the influence of residual stresses at the weld toe is significant for the crack initiation life. The results for both conditions are compared with the S-N curve without considering residual stresses which S-N curve is obviously between these both cases. Finally, the results are shown graphically as plots using the "fatigue tool" which is implemented in ANSYS<sup>®</sup>.



Figure 10. Cycles until crack initiation for as welded (left) and treated condition (right).

For the application of this user specified fatigue tool, it has to be mentioned critically that the iterations for the elastic-plastic stress-strain behaviour at notch and finally the one for getting life cycle is very time-consuming in the calculation. To save computing time the accuracy for the iteration of stress-strain path at notch is set to  $\Delta \sigma = 0.1$  N/mm<sup>2</sup> and for the iteration of life cycle to  $\Delta N = 500$ . This means in every step of iteration the number of cycle is raised by this delta value. The amplitude is set to  $\sigma_a = 0.5 \cdot f_{y,k} = 180.0$  N/mm<sup>2</sup> with a stress range of R = -1 and  $\sigma_m = 0.0$  N/mm<sup>2</sup>. Furthermore, a fine mesh especially at crack critical zones is necessary. However, these plots can be used for qualitative illustrations and detections of areas with number of life cycles which are minimal and therefore critical zones for crack initiation.

## 9. Conclusions

The fatigue strength of welded joints represents the weak point of every very dynamically loaded steel construction. Induced residual stresses or changes in the crystalline structure due to heating are only two of many notch effects. In the underlying research project an arc welding process was analysed in experiments and simulations. The comparisons concerning thermal and structural analysis show a good agreement. Due to the use of multifield solution technique in ANSYS the kinetics of solid phase transformations could be considered. Additionally a following process of post weld treatment by Ultrasonic Impact Treatment (UIT) was investigated. The objective of the numerical investigations was analysing the influence of residual stresses on the fatigue life for welded joints with and without post weld treatment. Finally the fatigue resistance until crack initiation was assessed for both conditions based on the notch strain approach. As result after UIT-treatment of the weld toe in the midsection the predicted location of crack initiation moved from the weld toe towards the heat affected zone. The increase of fatigue resistance due to UIT post weld treatment known from experimental investigations could now be comprehended also by numerical simulation.

# 10. References

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