DETERMINATION OF RESIDUAL STRESSES IN STEEL CONSTRUCTIONS DUE TO THE WELDING PROCESS

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ABSTRACT

Welding is one of the most important steel joining technologies. Extensions caused by local melting of a weld are hindered by the unmolten area of the parent material. Due to this, residual stresses exert influences deformation- and bearing capacity of welded constructions. Today, numerical methods based on finite elements allow to describe welding fabrication and to determine residual stress state. This provides a means to the forecast of welding results before the welding is carried out.

Welding is a process where thermal, metallurgical and mechanical processes occur. Therefore the main focus of the numerical simulation is the computation of temperature fields, microstructural distribution and residual stresses. For the numerical application the welding process, thermal and mechanical material behaviors, as well as microstructural transformation of steel are described physically and mathematically. The quality of the numerical calculation mainly depends on these input quantities.

To show the influence of microstructural transformation on distribution of residual stresses an example calculation has been undertaken. The analysis has been proceeded on a butt joint of high-strength fine grained steel S460M, welded with active-gas metal arc welding technology.

KEY WORDS

active-gas metal arc welding, welding simulation, microstructural transformation, residual stress

INTRODUCTION

The influence of welding on the load bearing capacity of a whole construction should be considered for investigation and assessment of weldment integrity. On the one hand, a residual stress state after the welding can increase the failure risk through tensile stress and on the other hand increase the load bearing capacity of a construction by compressive stress. The numerical simulation of the welding process with finite element method (FEM) is the basis

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for a determination of residual stress. The established methods for experimental determination of residual stresses are the hole drilling method and the X-ray diffraction method. Both methods cannot be used on existing structures because their applications require destruction of a structure by drilling or cutting free, which is a great disadvantage of these methods for measurements of residual stresses in realistic large constructions. Due to cutting free of welded connections, changes of residual stress distribution occur. Thus, measuring results undervalue the real residual stress state.

EVOLUTION OF RESIDUAL STRESSES

The basic cause for occurence of residual stresses in welded constructions is thermal strain caused by heating and cooling. Immediately after the end of welding process the cooling initialized shrinking of a weld metal and the surrounding heat-affected zone (HAZ) occurs. Beside HAZ, parent metal, which is not affected by welding, disables the thermal strain and causes internal constraint within a workpiece.

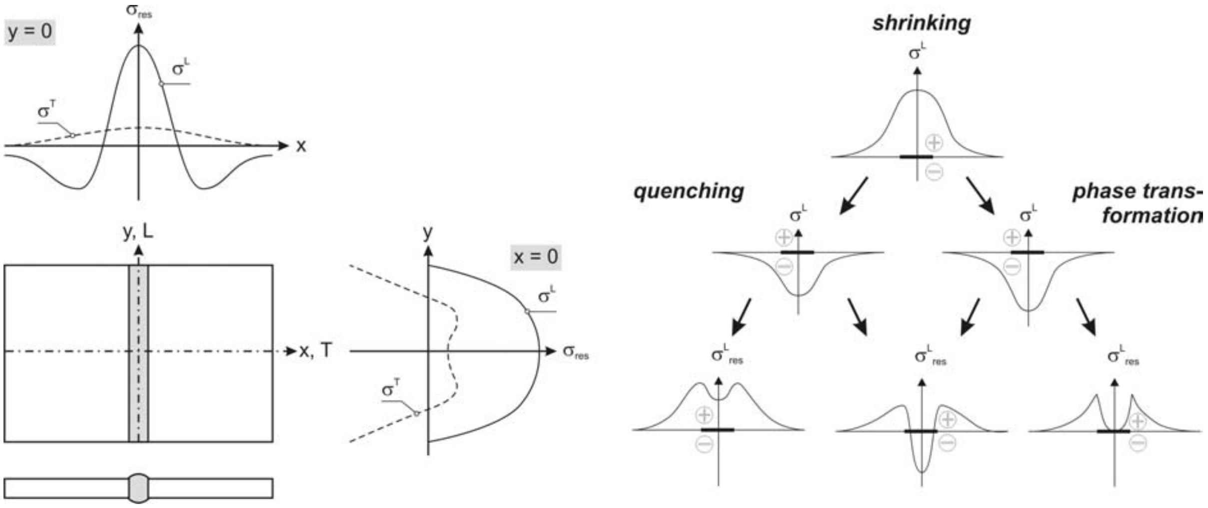


Figure 1: Development of residual stress in a butt joint (Blauel et al.)

A specific characteristic of steel is its ability of microstructural transformation. Due to high state of heat impact, a complex transformation of the steel phases austenite, ferrite, pearlite, bainite and martensite occurs. Different crystal lattice dimensions of each phase cause a local volume change during the transformation process. This transformation initiated strain only takes place in the weld and the HAZ. The reason being high temperature caused by the welding process which initializes phase transformations in that range. The transformation to the martensite phase leads to a permanent deformation of the material. This effect is called transformation plasticity. Transformation strain and transformation plasticity exert influence on the distribution of residual stress. Figure 1 shows a typical distribution of residual stress in longitudinal and transverse direction in a one layered butt joint of thin plates. The residual stresses are macroscopic stresses (residual stresses of 1st order) which are in state of equilibrium in a construction without any external loading. Other than macroscopic residual stresses of 1st order, microscopic residual stresses of 2nd and 3rd order can occur in a grain size range. This paper will only dwell on macroscopic residual stresses.

NUMERICAL DETERMINATION OF RESIDUAL STRESSES

The development and distribution of welding-induced residual stresses depends on a large number of parameters such as welding process parameters, initial conditions, material behaviour and geometry. They represent input quantities of a numerical analysis of residual stresses. The complex interactions between the parameters are difficult to explain analytically. Numerical welding simulation based on FEM makes a determination of residual stresses possible. For this purpose the commercial software SYSWELD® has been used.

Active-gas metal arc welding is characterized by a concentrated heat source in form of an arc. The simulation of the heat source moving across the workpiece is based on a description of the effective heat capacity with a double ellipsoidal model according to Goldak (Radaj 1999). The effective capacity of a heat flow is described by a volume distribution function of the heat flux density which contains welding parameters the welding amperage, welding voltage as well as the heat transfer efficiency factor. The heat transfer efficiency factor takes heat loss caused by splatters and evaporation into account.

Thermal material behavior describes the ability of material to absorb, store and conduct the heat caused by the welding process. For this purpose, specific heat capacity, material density and thermal conductivity have to be defined. Young's modulus and Poisson's ratio represent a mechanical behavior of steel due to elastic deformation. The thermal coefficient gives information about a deformability of material during temperature alteration. The yield limit, material law, as well as the strain hardening mechanism describes the mechanical behavior of material in the range of plastic deformation. Temperature and microstructure have crucial influence on thermal and mechanical material properties. Therefore, it is advisable to consider these two aspects when describing the material behavior for numerical application.

To increase efficiency, the numerical simulation can be carried out as a partly decoupled calculation process. On this account the cognition of each sub process, i.e. calculation of temperature field, phase transformations and residual stresses as well as their interconnection, is necessary (Figure 2).

The transient temperature field in a welded construction results from a heat source acting, temporally and locally concentrated. Moreover phase transformation effects occur in the weld and the HAZ due to the temperature alteration. The energy for the phase transformation process is extracted from the heat energy store of a welded construction and determines a cooling-down (during a heating process) or a warming (during a cooling process). On this account phase transformation affects the temperature distribution in form of latent heat.

Due to the temperature and phase depending definition of material properties, phase transformation strongly influences the distribution of temperature as well as residual stresses. The impact of residual stresses on temperature distribution, as well as on phase transformation, is negligible and unaccounted for numerical simulation of partly decoupled sub-processes.

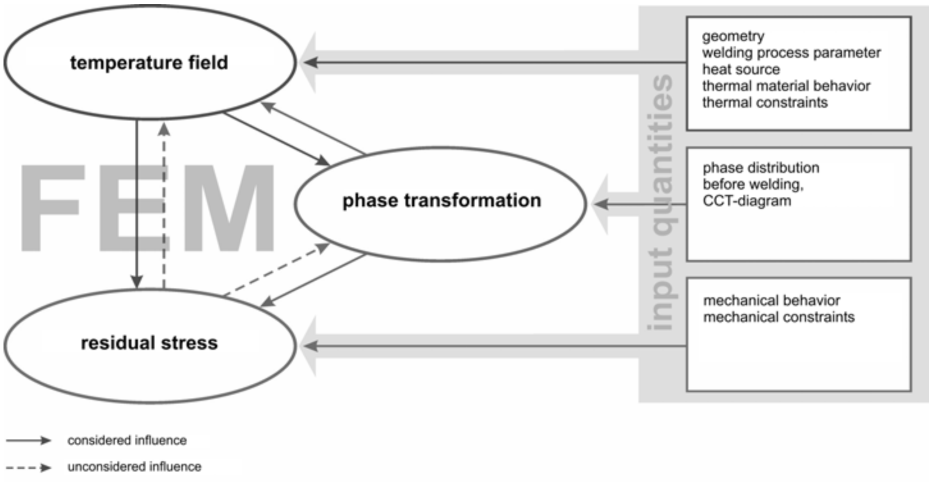


Figure 2: Overwiev - input quantities and interconnection of sub processes during the numerical determination of residual stresses

Based on one geometrical model, residual stresses are carried out in two calculation steps. At first, the simulation of the welding process is implemented with temperature and phase distribution as a result of this thermal calculation. Secondly, mechanical calculation is executed due to results of the thermal calculation to determine the residual stresses in a welded construction.

Thermal calculation is based on a formulation of an equilibrium state of a heat flow in continuum. The following equation of thermal balance results in consideration of the principle of virtual temperatures:

$$\int_V \delta T' \lambda T' \, dV + \int_V \delta T \left(\rho c\right) \dot{T} dV - \int_A \delta T \left(\alpha_k + \alpha_s\right)(T_A - T_U) dA - \int_V \delta T q_{WQ} \, dV = 0 \tag{1}$$

$\lambda T'$ - conducted heat

$(\rho c)\dot{T}$ - stored heat

$(\alpha_k + \alpha_s)(T_A + T_U)$ - dissipated heat (thermal constraints convection and radiation)

q_{WQ} - generated heat (heat source)

The kinetic of phase transformations allows the numerical description of the transformation behavior as a function of temperature and time as well as the determination of phase proportion in weld and HAZ after a welding process. In this case the phase transformation model according to Leblond is used to characterize the transformation behavior. The mathematical application of this transformation model is made, assuming that every phase nearly reaches its temperature dependent equilibrium state in an exactly defined hold time. The kinetic of phase transformations is dependent on reaction inertia of each transformation, i.e. hold times of a ferrite-austenite transformation and an austenite-ferrite-transformation are not identical.

To describe a phase transformation from phase y_i to phase y_j according to the Leblond-model, the following equation is applied:

$$\dot{y}_j = k_{ij}(T)y_i - l_{ij}(T)y_j \tag{2}$$

The functions k_{ij} and l_{ij} represent the temperature depending equilibrium state of the relevant phase transformation. The formulation of these functions allows a description of diffusion controlled transformations and those without diffusion. Thereby, the sum of phase proportions within the workpiece must be 100%.

Numerical calculation of residual stresses is based on mechanical description of material behavior by means of formulation of energetic equilibrium state principles. An energy balance is drawn according to 1^{st} fundamental theorem of thermodynamics which signifies the thermodynamic state in continuum due to its internal energy. The equality of thermal and mechanical energy applies. The generated heat caused by the heat source indicates the transient temperature field, which is incorporated into the mechanical calculation as a load magnitude. The following equation of energetic balance results in consideration of the principle of virtual work:

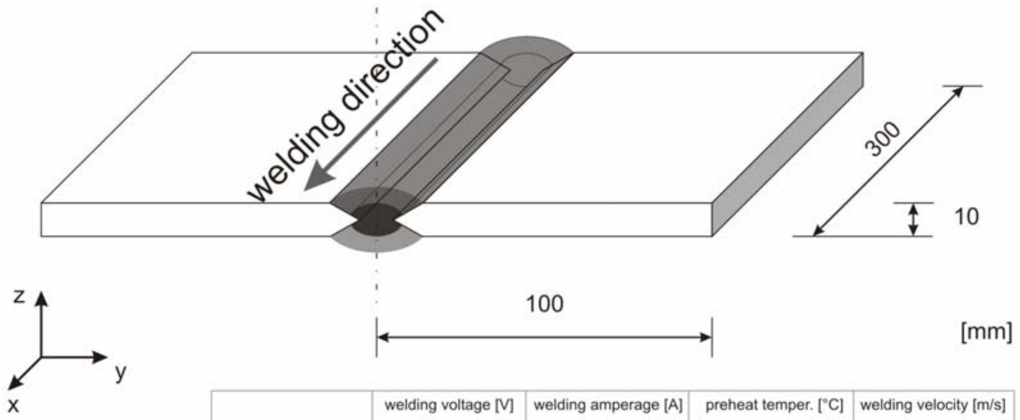
$$\int_V \sigma\,\varepsilon\,dV + \int_S t_k r_0\;dS - \int_V u\,p\,dV + \delta W \quad = 0 \tag{3}$$

$\sigma\varepsilon$	- internal energy
$t_k r_0$	- mechanical constraints
$u\ p$	- external energy
δW	- virtual work

The incremental decomposition of the principle of virtual work in thermal and mechanical calculation provides an opportunity for an iterative solution. The determination of temperature fields and residual stresses are both highly nonlinear numerical problems, due to the high temperature and phase dependence of material properties, as well as the transient calculation.

EXAMPLE OF USE

As an example, a distribution of residual stresses in a butt welded joint of two 10 mm thin plates consisting of high-strength fine grained steel S460M has been calculated. The joining technology of the active-gas metal arc welding has been simulated. The geometry of a welded connection as well as the parameters of the welding process are shown in Figure 3. They are based on an experimental welding which has been preformed to verify the results of the numerical calculation.



	welding voltage [V]	welding amperage [A]	preheat temper. [°C]	welding velocity [m/s]
1st weld layer	31,0	250	65	10,27
2nd weld layer	31,4	246	85	8,02
3rd weld layer	30,8	260	95	7,56

Figure 3: Geometry and parameters of welding process

The symmetry of the workpiece has been used to improve the efficiency of the calculation method. For that reason half of the butt joint connection has been modeled, as shown in figure 4. The geometry of the weld and HAZ has been modelled according to a macrograph of the experimental weldment. The finite element model consists of isoparametric hexahedron 8-node solid elements (H8). Skin elements have been implemented as 4-node surface elements on interfaces between weld - parent metal, weld - environmental media (air) and parent metal - environmental media to take thermal constraints (conductivity and radiation) into account.

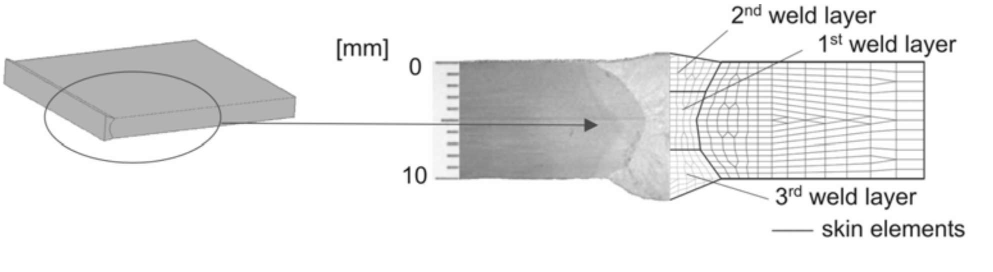


Figure 4: FE-model of butt welded joint

The results of the thermal calculation have been compared with the results of the experimental temperature measurements to verify the FE-model. The temperature has been measured on the surface of the parent material using thermocouples. Figure 5 shows the calculated and measured results of the first layer. The comparison shows the delay of development of measured temperature. The reason for this effect is the cladding of thermocouples as a protection from spattering arc during the welding process which has not been considered in the FE-model.

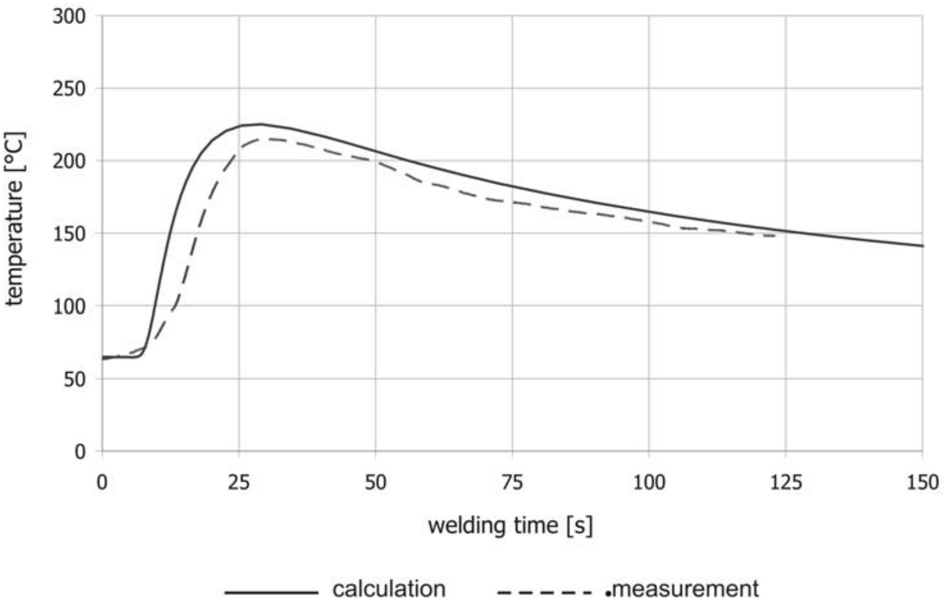


Figure 5: Calculated and measured temperature during the first weld

Because of a higher number of degrees of freedom in comparison to numerical simulation of welding process, the calculation of residual stresses has been executed on a 2D plate model as a cross section of a weldment. The mechanical calculation has been implemented assuming a plain strain state. The mesh geometry is identical to the cross section of the 3D-model. The transient temperature field is the input dataset of calculation of residual stresses. The elements of each weld layer have been activated at the moment of the biggest molten pool. From this moment solidification begins and the weld has a stress state. The HAZ and parent material do not melt during the welding process. Therefore, their elements have always been activated. The material law has been implemented as a multi-linear stress strain function with isotropic hardening effect. Statically determinated constraints have been chosen to avoid any effects on residual stress development. Figure 6 shows transverse residual stress distribution in a cross section.

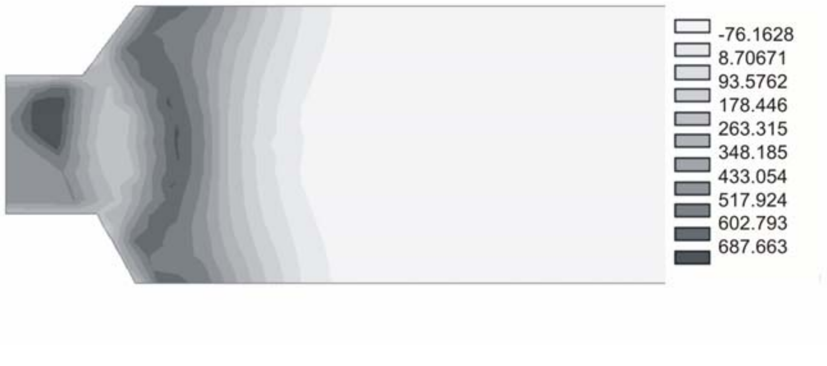


Figure 6: Transverse residual stress [N/mm²] in a cross section (1^{st} weld layer)

The contraction of solidifying weld has been constrained by non-molten parent material and has caused longitudinal tensile stress. In the parent material outlying of HAZ a longitudinal pressure stress has been arisen, due to equilibrium state. An interference of extension in transverse direction has been initialized as a consequence of longitudinal pressure stress. As a result of this effect, pressure stress in transverse direction has been created. The 2D-model can be interpreted as an endless plate in longitudinal direction. The consequence of this assumption is an overestimated interference of extension as well as quantity of residual stresses.

The phase transformation from austenite into other phases during cooling causes volume extension in weld and HAZ. This effect is independent from the type of resulting phase. In the wake of interference of extension of surrounding material, pressure stress has been produced. The influence of transformation on residual stresses becomes minor with increasing distance to a weld.

INFLUENCE OF PHASE TRANSFORMATION ON RESIDUAL STRESSES

To demonstrate the influence of phase transformation on residual stresses, thermal and mechanical calculations have been executed on an equivalent FE-model to the example above without taking the effect of phase transformation into account. The results of both calculations have been compared.

The effect of phase transformation is obvious when comparing thermal strains. Thermal strain without phase transformation is a constant process depending on the temperature. The phase transformation process leads to a decrease of thermal strains. Although the qualitative analysis shows no difference, figure 7 presents minor thermal strain of a calculation with consideration of phase transformation in a border range of the HAZ to the weld.

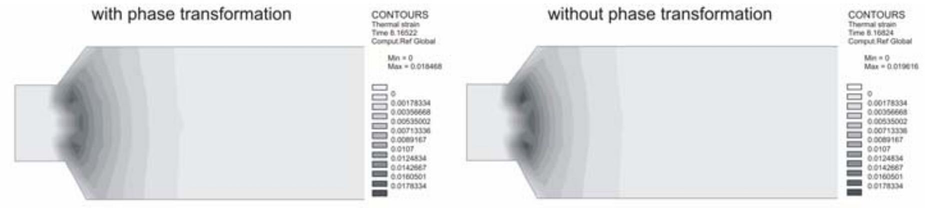


Figure 7: Thermal strain depending on consideration of phase transformation

Apart from thermal strains, the yield strength is sensitive to microstructural phases. Generally, the yield strength decreases with the increase of transformation temperature of phases. In a calculation without consideration of phase transformation, the parent material and weld material consist of 100 % ferrite during a complete heating and cooling process. In this case the yield strength is only depending on temperature. Thus, for temperatures below the existence temperature range of the ferrite, a minor yield strength is used as in the calculation considering phase transformations. For example, if calculating with consideration of phase transformation bainite and martensite form in weld and HAZ. These two phases have greater yield strength than ferrite. By neglecting the effect of phase transformation on yield strength, the overestimation of the residual stress state in the welding connection occurs. Figure 8 shows the distribution of residual stresses due to consideration of microstructural transformation behavior of material.

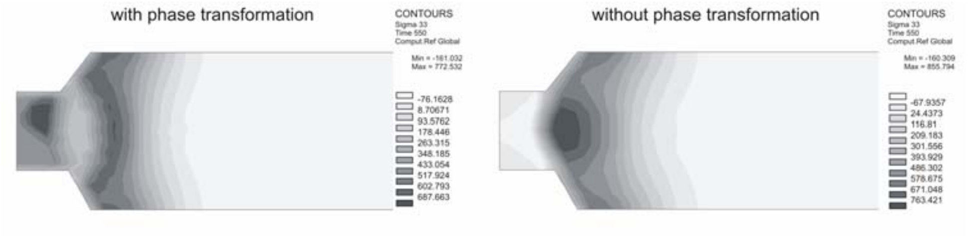


Figure 8: Distribution of residual stresses due to consideration of microstructural transformation

Direct comparison of residual stresses shows qualitative and quantitative differences of stress distributions in the range of weld and HAZ where the phase transformations occur.

CONCLUSIONS

Numerical methods based on FEM facilitate the analysis of welding processes. Thus, it is possible to design and determine constructions appropriate to the type of their duty in consideration of effects due to the welding process, e.g. residual stresses. This is an alternative solution for the experimental determination of residual stresses.

Apart from thermal and mechanical material behavior, microstructural transformation behavior also has to be defined for the numerical application of the welding process and determination of residual stresses. The quality of the numerical calculation mainly depends on initial parameters and implemented presumptions. The appraisal of results shows that the influence of welding effects on distribution of residual stresses, such as microstructural transformation, should be considered for further investigation and assessment of bearing capacity of welded constructions.

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