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Residual stresses formation in multi-pass weldment: A numerical and experimental study

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ABSTRACT

In this study, the residual stresses distribution induced by multi-pass arc welding of the steel S355J2+N are investigated experimentally and numerically. An extended approach is used for the simulations, which considers the change of the local microstructure properties due to multiple reheating. Experimental material data obtained from physical welding simulations with Gleeble® are used for the model calibration. The experimental stress study is performed using a neutron diffraction method on a fourier stress diffractometer. Numerical analysis of the welding stresses formation in the weldment is performed and compared to the experimental study. The results explain the influence of the welding thermal history on the resulting local thermo-mechanical properties in the heat-affected zone and, thus, on the residual stress distribution. The consideration of the local microstructure properties in the welding simulation leads to a significant increase in accuracy of the numerical results. The major influence factor on the residual stress formation is the change in the interpass microstructure yield strength. When a root pass with short cooling times is subjected to re-austenitisation in the fine-grained zone, the yield strength increases in this area and affects consequently the residual stress distribution. The influence of the reheating is detectable in the depth of the weldment, but it is less significant for the residual stress formation near the surface of the welded joint.

1. Introduction

Complex structures are assembled from thick-walled components and are primarily joined with multi-pass welds. As a result of the repeated heat exposure, the local domains of the heat affected zone (HAZ) are subjected to cumulative thermo-mechanical influences. This affects the microstructure transformations in a complex way, which leads to changes in the local thermo-mechanical properties and the development of welding residual stresses. These changes can significantly reduce the quality and reliability of the welded components, as described by Nitschke-Pagel and Wohlfahrt [1]. Therefore, accurate prediction of the residual stress distribution is of major importance for the precision design of welded structures and to improve their quality and reliability.

Numerical welding simulations allow to predict the residual stresses considering the thermo-mechanical history of the local mechanical properties subjected to the heat input from welding. However, the accuracy of the results strongly depends on the complexity of the mathematical model of the welding process as well as on input data. Numerical models applied in computational welding mechanics exist for a broad range of problems, such as HAZ microstructure composition, welding distortions, and residual stresses as described by Radaj [2], Goldak [3], and Michailov et al. [4]. The mathematical models for the microstructure transformation of steels by Koistinen and Marburger [5] or rather Leblond [6] are based on the cooling time concept. For the model calibration, continuous cooling transformation (CCT) diagrams are needed. However, these models are developed based on correlations of single thermal cycles of single-pass welding. Moreover, in contrast to the maximum temperature austenitisation cooling time concept suggested by Michailov [7], they are not able to predict the changes of the microstructure and mechanical properties over the sub-domains of the HAZ according to different peak temperatures from the repeated heat treatment during multi-pass welds.

As a result of single-pass welding, the base material is subjected to the thermal influences and a changed microstructure in the HAZ is formed. During the subsequent welding, the HAZ microstructure is again subjected to thermal influences and the resulting microstructure properties are dependent on this full thermal history. Data for welding CCT diagrams previously published by Seyffarth et al. [8] and peak temperature cooling time diagrams by Berkhout et al. [9] are obtained during single thermal cycles, i.e. for single-pass welding. Further experimental mechanical properties [10] and calculated material properties [11] are available for single thermal cycles. Recently, Knoedel et al.

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[12] studied practical aspects of welding residual stress simulations of single-pass welding using literature data. The evaluation of hardness distributions by numerical simulations of welding thermal cycles and microstructural phase fractions is studied by Mikami et al. [13,14]. Physical simulations of the microstructure during repeated welding cycles using Gleeble® is described in [15]. The lack of data on thermo-mechanical properties during repeated heating and cooling is an obstacle for the development and calibration of microstructure models for numerical multi-pass welding simulations. Thus, the majority of published numerical studies of welding residual stresses in multi-pass welds including the consideration of phase transformations only use material properties for single-pass welds, i.e. with a single thermal cycle. Deng and Murakawa [16] predicted the welding residual stresses in a multi-pass butt-welded steel pipe with a 2D axisymmetric analysis that considered phase transformation effects by single thermal cycles. Heinze et al. [17] studied the residual stress development of multi-pass gas metal arc welding using thermo-mechanical properties for single-pass welding. The deviation between numerical results and X-ray measurements is related to the larger differences in the literature data for bainite and martensite yield strength.

After the first welding pass, mixed microstructures can be formed on structural low alloyed steels, such as perlite, ferrite, bainite, and martensite. This local microstructure state becomes the initial condition for the next welding pass and, as a result of the subsequent heating, a different microstructure forms with further changed properties. The influence of the local interpass microstructure on the resulting thermo-mechanical properties, particularly after re-austenitisation, and its impact on the residual stress distribution are not sufficiently investigated. Since the multi-pass arc welding leads to a 3D stress state with inhomogeneous stress distribution and gradients in the thickness, several locations in the welded joint should be considered for the stress evaluation.

The aim of this work is to develop a validated simulation model for the investigation of residual welding stress distribution in multi-pass welds. The simulation considers the local microstructure properties changes due to the multiple welding thermal cycles. Therefore, the maximum temperature austenitisation cooling time approach (STAAZ) [7] previously suggested is extended here for repeated thermal cycles. The fundamental model describes the resulting thermo-mechanical properties as a function of the local welding thermal cycles, characterised by the three relevant model parameters: maximum temperature T_{max}, austenitisation time t_A, and cooling time $t_{8/5}$. The extended multiple maximum temperature austenisation cooling time approach (M-STAAZ) [18] takes into account the resulting microstructure properties formed after the preliminary welding thermal cycle as the initial state for the thermal cycle of the next welding pass. Physical Gleeble® simulations of the HAZ microstructure are performed and experimental material data are obtained for the model calibration.

The experimental study of residual stresses distribution is very complex due to the 3D stress state in the multi-pass welds. Experimental methods to determine residual stresses, such as X-ray diffraction or hole drilling method, are not suitable for this purpose, because they provide results only on the surface or near to the surface of the specimen. For this reason, the neutron diffraction method is chosen, which allows for the investigation of residual stress distribution to depths of several centimeters in the bulk of the material due to the high penetration power of neutrons.

2. Materials and methods

2.1. Materials, welding parameters, and test sample

The application example used for this study is a multi-pass butt welded joint of the low alloyed steel S355J2 + N. The experimentally determined chemical composition, yield strength $Rp_{0.2}$, and Vickers hardness of this base material are shown in Table 1.

The dimensions of the samples are shown in Fig. 1. The Gas Metal Arc Welding (GMAW) method is used for the root pass and the Submerged Arc Welding (SAW) method is utilised for the second and third welding passes. The welding parameters, filler material, shielding gas for GMAW, and flux for SAW are shown in Table 2.

The initial sample temperature as well as the interpass temperature are always equal to room temperature. Welding experiments and thermal cycle measurements are performed using thermocouples. The neutron diffraction method is used for the experimental evaluation of the residual welding stresses. The measurements are performed on the Fourier Stress Diffractometer (FSD) at the Frank Laboratory of Neutron Physics, Joint Institute of Neutron Research (Dubna, Russia). For the experimental study of the stress distribution, a specimen was cut from the entire welded joint. Fig. 1 illustrates the preparation of the specimen for the neutron diffraction study by cutting from the entire multi-pass welded joint. The measurements on the FSD diffractometer were performed in the middle of the sample's width and at a depth of 7.5 mm from the sample's bottom surface, i.e. along the path “R” (dashed line) in Fig. 1.

2.2. Residual stress measurements by neutron diffraction

Diffraction of thermal neutrons is one of the most informative methods when solving many applied engineering and materials science problems, and it has a number of significant advantages as compared to other techniques. The main advantages of the method are deep scanning of the material under study (up to 2–3 cm for steel) due to high penetration power of the neutrons, non-destructive character of the method, good spatial resolution (up to 1 mm in any dimension), determination of stress distributions for each component of the multiphase material separately (composites, ceramics, alloys, etc.), possibility to study materials microstructure and defects (microstrain, crystallite size, dislocation density, etc.). In combination with the time-of-flight (TOF) technique at pulsed neutron sources, this method allows to record complete diffraction patterns in wide range of interplanar spacing at fixed scattering angle and to analyze polycrystalline materials with complex structures. In addition, with TOF neutron diffraction it is possible to determine crystal lattice strains along different [*hkl*] directions simultaneously, i.e. to investigate mechanical anisotropy of crystalline materials on a microscopic scale.

Internal stresses, e.g. residual welding stresses, existing in a material cause corresponding lattice strains, which, in turn, results in shifts of Bragg peaks in the diffraction spectrum. This yields direct information on changes in interplanar spacing in a gauge volume, which can be easily transformed into data on internal stresses, using known elastic constants (Young's modulus) of a material. The principle of the determination of the lattice strain is based on the Bragg's law

$$2d_{hkl} \cdot \sin\theta = \lambda, \tag{1}$$

Table 1
Chemical composition, yield strength, and Vickers hardness of S355J2+N.

Chemical composition in weight %												
C	Si	Mn	P	S	Cr	Mo	V	Cu	Ni	Al	N	Nb
0.14	0.35	1.38	0.012	0.004	0.024	0.002	0.004	0.024	0.011	0.038	0.0033	0.04
Yield strength $Rp_{0.2}$							Vickers hardness					
385 MPa							165 HV					