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Numerical calculation of residual stress development of multi-pass gas metal arc welding under high restraint conditions

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ABSTRACT

During welding, residual stresses build-up created by the steep thermal gradient that occurs in the weld zone from localized heating and cooling, and phase transformations appearing in low-alloyed structural steel is inevitable. Welding of rather simple test plates do not cover the actual structural effects, which have to be considered during real component welding. However, the resulting welding-induced residual stress state is highly influenced by the structural characteristics, i.e. restraint conditions, of the welded construction. Therefore, a unique large-scale testing facility providing a specific shrinkage restraint while welding and subsequent cooling was used for the present investigations. Hereby, a six bead multi-pass gas metal arc weld of 20 mm thick structural steel S355J2 + N was welded under shrinkage restraint. The residual stresses were experimentally and numerically investigated, and compared to an analysis of plates welded under force-free support and free shrinkage conditions.

The experimentally determined and calculated residual stresses using both 2D and 3D numerical models are in a good agreement. Furthermore, the influence of a shrinkage restraint on the residual stress distribution is both experimentally and numerically shown for the present test set-up.

1. Introduction

Components and constructions often undergo weld repair procedures due to extension of lifetime and cost reductions. While doing so, the repair weld is subjected to shrinkage restraint provided by the surrounding component and its geometry. Related to the aforementioned, Satoh [1,2] introduced the intensity of restraint, which quantitatively describes the global shrinkage restraint of welded components. The intensity of restraint enables the transfer of the structural stiffness of a real component weld on test welds on the laboratory scale. In the literature, there is a variety of equations for calculating the intensity of restraint. Böllinghaus [3] introduced a uniform definition, which differences between a symmetrical and unsymmetrical joint geometry.

By means of experimental weldability studies, Hoffmeister et al. [4–6] improved the principle of intensity of restraint and developed the instrumented restraint cracking (IRC) test taking into account the real structural effects on shrinkage restraint. The calculated or measured intensity of restraint of a weld at a real component can be transferred to the test set up and vice versa [7]. Nevertheless, the IRC test is limited to small test samples and no additional forces could be applied. Consequently, a large-scale testing facility, which provides shrinkage restraint and the possibility to apply additional forces during welding of large test samples with high thicknesses, was designed. The reaction forces and moments built up during welding and subsequent cooling can be measured by the developed facility.

Besides the literature focused on the present unique large-scale testing facility, there are further publications about restraint conditions in welding. Zhang et al. [8] investigated the mechanical interaction between welded panel and fixture and found a remarkable influence on the distribution of the welding-induced residual stresses and distortions. They conclude that considering restraint conditions plays an important role in accurate modeling and is inevitable for a good agreement between model and experiment. Liu and Zhang [9] studied the effect of external restraining forces including clamp, clamping strip, and worktable on welding-induced residual stresses and distortions. Their results show that the simulated transverse residual at the welding center-line clearly varies with increasing restraining force.

Leggatt [10] presents the effect of restrained transverse shrinkage on welding-induced transverse residual stress in a 50 mm multi-pass weld of 316L type stainless steel. The higher the restraint the larger the through-thickness transverse residual stresses became, accompanied with a shift from compressive to tensile residual stresses at mid-plate thickness.

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Table 1
Experimentally determined chemical composition of test material; glow discharge optical emission spectroscopy.

Element (wt.%)	C	Mn	Si	Al	Cu	P	S	Fe
Test material	0.14	1.59	0.33	0.035	0.17	0.009	0.020	Balanced
DIN EN 10025-2:2004 (maximum values)	0.23	1.7	0.6	min. 0.015	0.6	0.035	0.035	Balanced

Table 2
Experimentally determined mechanical properties of base metal and weld metal.

	YS (MPa)	UTS (MPa)
Base metal	420	570
Weld metal	560	570
Standard – 20 mm (DIN EN 10025-2:2004)	min. 345	470–630

In the present investigation, the test weld was performed in the mentioned testing facility enabling high transferability of the test weld to real component welds due to the determinable intensity of restraint.

2. Experimental procedure

The experimental procedure includes test welding of 20 mm thick S355J2 + N (material number 1.0577) plates. The chemical composition of the present material determined by glow discharge optical emission spectroscopy is shown in Table 1.

The mechanical properties of the base metal and the weld metal were determined in a uniaxial tensile test, Table 2. These preliminary investigations confirm the classification of the present material as S355J2 + N.

The experimental set-up used for the test welds performed is shown in Fig. 1. The 16 MN large scale testing facility represents a unique testing facility, which was constructed and build for real component weld testing under high restraint conditions, Fig. 1a. In this investigation, the testing facility restrained transverse shrinkage during welding and subsequent cooling. Fig. 1b shows a close-up of the test plate including temperature and strain gauge measurement.

The test plates, depicted in Fig. 1b, had run-on and run-off plates at both ends of the plate. Before applying the anchor welds, the test plates were stress relief heat treated to reduce any prevalent residual stresses at 570 °C for 3.5 h with subsequent furnace cooling to ambient temperature (cooling rate approx. 5 K $\min^{-1}$).

Further details to the clamping set-up of the GAPSI 16 are given in Fig. 2 including the joint preparation of 50° V-groove and zero-gap.

The present welding procedure is performed based on the welding parameters given in Table 3. Additionally, Fig. 3 provides a scheme of the weld bead positioning.

During welding, the thermal field was monitored by thermocouples at the bottom and the top of the plate. Therefore, type-K thermocouples with a wire diameter of 0.25 mm were applied on the top and bottom surface of the plate. The distance of the thermocouples to the weld centerline is in the range of 2-4 mm for the bottom and 11–13 mm for the top surface. Strain gauge measurements were performed as well and used to determine the optimal elastic constraint in the simulation representing the experimental transverse shrinkage conditions. Subsequent to welding, the residual stresses were determined by X-ray diffraction method using a Xstress 3000 Goniometer G3 diffractometer. A 2 mm aperture was applied, which provided a suitable balance of time, costs, and resulting stress values. The measurement positions of all techniques applied are schematically shown in Fig. 4.

After performing residual stress measurements, the test plates were prepared for metallographic investigations, which is necessary for temperature field validation by means of weld pool cross-sections.

3. Numerical procedure

The numerical investigations include a 2D and 3D model of the present welded test plates. The mesh of the 3D model is shown in Fig. 5. The force-free support is modeled by three nodes on the plate bottom at the positions indicated by the circles. The corresponding conditions applied on the nodes for the *y*, *z*, and *x* direction is given next to the circles. The restrained transverse shrinkage is highlighted in Fig. 5 by the ellipse at the outer planes normal to the *x*-direction. All nodes on these two planes are restrained in *x*-direction or transverse direction, respectively.

In the present mesh, the element edge length in the welding direction is 3 mm. The element size transverse to the welding direction of the elements representing the weld metal and the heat affected zone (HAZ) is 0.25 mm in minimum.

To reduce the demand on the present PC system, a 2D model representing the cross-section of the 3D model is additionally established, Fig. 6.

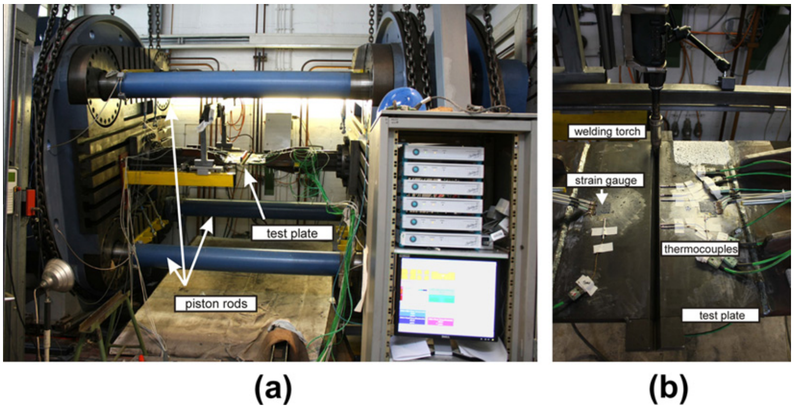

Fig. 1. Experimental set-up; (a) 16 MN large scale testing facility for component weld testing and simulation (GAPSI 16) with test plate indicated and (b) close-up of a test plate equipped with strain gauges and thermocouples; plate dimensions 500 mm × 400 mm × 20 mm; material: S355J2 + N.