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Numerical calculation of residual stress development of multi-pass gas metal arc welding

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ABSTRACT

In various applications, welding-induced residual stresses have a substantial impact on the integrity of welded constructions. Tensile residual stress can promote stress-corrosion cracking, brittle fracture, and reduces the fatigue life in service, as well as influences component design due to critical stress concentrations within the component.
In the present paper, a six bead multi-pass gas metal arc weld of 20 mm thick structural steel S355J2+N is experimentally and numerically investigated. The studies include transient 2D and 3D numerical calculations which consider temperature-dependent material properties, phase transformations, "thermal" tempering, transformation plasticity, volume change due to phase transformation, an elastic–plastic material model, and isotropic strain hardening. The experimentally determined and calculated residual stresses are in a good agreement. Furthermore, the influence of the preheat and interpass temperature on welding-induced residual stresses is shown in the present investigation.

1. Introduction and motivation

During welding, residual stresses are developed due to localized heating and non-uniform cooling accompanied with steep thermal gradients that arise in the weld zone. Additionally, phase transformations which occur in the weld metal and adjacent heat-affected zone (HAZ), e.g. in structural steels, contribute to the residual stress evolution [1]. Residual tensile stresses can result in unintended deformations of the welded component, increase the susceptibility to hydrogen-induced cold cracking, and also combine with tensile stresses experienced during service to promote brittle fracture, fatigue failure, and stress corrosion cracking [2].

Numerical simulation of residual stress development of multi-pass welds was first described by [3–6] in the 1980s. At this time, the computational state of art was limiting the abilities of the researchers. Particularly, the limit on the model size and on considerable metallurgical effects asked for suitable simplifications and assumptions. With the progress in computer technology, numerical simulation of multi-pass welding could apply more complex or detailed models, respectively. Thus, the accuracy increased drastically over the last 30 years.

Free et al. [7] predicted residual stresses in multi-pass weldments of BS4360 Grade 50D (corresponds to a S355J2+N; German standard DIN EN 10025-2) with the finite element method in the year 1989. They achieved good agreements in experimental and calculated residual stresses. But they applied several assumptions, which include temperature-independent thermal properties as well as Young's modulus and a yield stress remaining constant to 200 °C and subsequently decreasing linearly to 20% of the room temperature value at 1200 °C. Furthermore, the authors did not validate the temperature field by means of weld pool geometry and thermal cycles.

In 1999, Lindgren et al. [8] already simulated a two-dimensional 28-pass butt weld investigating the applicability of quiet and inactive elements for modeling the addition of filler material. The authors obtained similar calculated residual stresses regarding the application of quiet or inactive elements. However, Lindgren et al. [8] did not apply any heat source in their numerical model but prescribed a user-defined temperature for all nodes within the weld metal.

In the meantime, it became state of the art to use heat conduction models to simulate the weld temperature field relying on heat source formulation as proposed by Goldak [9]. These models result in adequate calculated residual stresses in case of gas metal arc welding (GMAW), as studied by Lawrence et al. [10], but the authors also exhibit the need for convective heat transfer to achieve realistic 3D transient temperature fields in laser or laser-GMA hybrid welding.

De et al. [11] highlighted that the prediction and mitigation of residual stresses still remain an important issue in welding. Furthermore, the authors state that reliable constitutive equations for important engineering alloys are needed considering the influence of solid-state phase transformation on the mechanical behavior of alloys.

The publications of [11] and [12] provide current perspectives on residual stresses in welding covering the historical background, the

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