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Numerical fatigue assessment of welded and HFMI-treated joints by notch stress/strain and fracture mechanical approaches

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ABSTRACT

Post-treatment methods enhance the fatigue strength of welded high-strength steel joints significantly. In industrial applications, one commonly applied technique is the high frequency mechanical impact (HFMI) treatment. Attained local benefits increasing fatigue strength are the compressive residual stress state, the reduced notch effect at the weld toe, and additionally the local work hardening of the material. This paper presents the set-up of a closed simulation loop including structural weld simulation, numerical computation of the HFMI-process, and a numerical evaluation of the local fatigue life.

A thermo-mechanical coupled weld process simulation using *Sysweld* is built-up to assess the course of residual stress and strain due to welding. The resulting local material behavior is transferred as mechanical cards to the solver *Abaqus* for the subsequent numerical simulation of the HFMI-process. Hence, major influences such as transient change of material parameters during welding and subsequent cool-down, effect of process dependent clamping conditions and changing contact characteristics are considered. Finally, a numerical evaluation of the local fatigue behavior by the local stress/strain approach and by crack propagation is performed by the aid of the software packages *Femfat*, *nCode* and *Franc2D*. A comparison of the simulated fatigue life with experimental test results proofs their basic applicability; but also numerical limitations of the presented simulation tools are determined. The major benefit of the established simulation chain is the opportunity to study different weld process and HFMI-treatment parameters in regard to fatigue strength without the need of comparably expensive fatigue tests.

1. Introduction

In general, welding leads to significant amounts of distortion and residual stresses in a component or structure. Acting external loads and internal weld residual stresses are superimposed which may affect the local stress condition. For high-cycle fatigue applications, the notch topography, microstructure in the heat-affected zone (HAZ), and the residual stress state have a significant influence on the fatigue lifetime.

This paper is based upon [1] and additionally provides enhanced information about the specimen manufacturing, simulation work including process definitions, material data and representation of the results, and a fatigue assessment by a linear-elastic fracture mechanical approach. According to the IIW-recommendation [2], the fatigue strength of welded steel joints is independent of the steel grade. One opportunity to utilize the potential of high-strength steels offers an optimization of weld process parameters, such as filler metal and shielding gas, as investigated in [3,4]. A further major enhancement is provided by post-treatment methods. One widespread technique in industrial applications represents the high frequency mechanical impact (HFMI) treatment. This post-treatment method is statistically proven to increase fatigue life of welded joints significantly, especially for high-strength steels [5]. Thereby, a hardened metal pin is hammering onto the weld toe surface with high frequency and causes local plastic deformation in this area. The weld toe geometry is round-out; this reduces thereby the notch stress concentration, compressive residual stresses are induced, the top surface layer is hardened and welding induced small cracks on the surface are closed. The change in local geometry and material properties due to welding and HFMI-treatment changes the geometric and metallurgical notch at the most-stressed weld toe of full-penetrated joints. In this work, numerical investigations based on experimental data are made to build-up a closed three-dimensional simulation loop and to determine the change in local lifetime of a butt joint specimen.

2. Objectives

The aim of the work is to built-up a simulation loop including structural thermo-mechanical coupled weld simulation, transfer of

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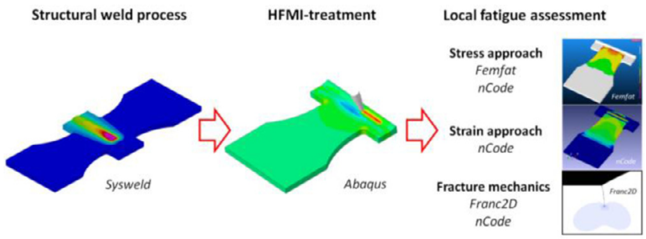

Fig. 1. Steps of numerical simulation loop.

the transient results into a structural finite element code, numerical investigation of the HFMI-treatment and finally a computation of the local fatigue strength or lifetime. Fig. 1 depicts a flowchart of the characteristic process steps and the involved software packages.

3. Experimental work

The benefit of fatigue strength due to high frequency mechanical impact (HFMI) treatment of welded joints depends on a reduction of residual tensile stresses, shallower geometric notch, and a local hardening of the hammered surface layer. In the following, detailed insight in the manufacturing process of the investigated *S355* butt joint specimens and fatigue testing is provided.

3.1. Manufacturing of specimens

In Fig. 2, the design and manufacturing set-up of the investigated butt joint is illustrated. The weld process is defined as GMAW (MAG – metal active gas welding) and the specimens are continuously welded in arrays in order to assure similar weld seam qualities, stiffness and residual stress states. The lateral run-on and off parts of the base plate are to stabilize the arc during ignition and further on to avoid end crater cracks in the testing section. In a subsequent manufacturing step after welding and HFMI-treatment, these lateral ends are truncated from the fatigue testing specimen. Reproducible clamping conditions for every specimen are ensured by a systematically positioning of the tacking points at the array. Furthermore, additional tackings at the joint clearance between the specimens minimize the magnetic arc blow and lead to a more consistent welding process.

The nominal mechanical properties of the applied base and filler material are summarized in Table 1. For the GMAW welding process, a solid wire *G3Si1* in combination with a standard weld process gas M21 (82% Ar, 18% CO_2) is utilized.

Table 1
Nominal mechanical properties of base and filler material.

Type	Yield strength [MPa]	Ultimate strength [MPa]	Elongation [%]
Base material	*355*	*575*	*22*
Filler material	*440*	*530*	*30*

Table 2
Nominal mechanical properties of base and filler material.

Current Current	Voltage [V]	Traverse speed [cm/min]	Wire feed rate [m/min]	Heat input [kJ/cm]
290.0	*27.5*	*60.0*	*10.0*	*8.0*

Table 2 provides an overview of the welding process parameters which are applied for the GMAW-process in spray arc mode without pulsed current pattern.

Subsequently to the welding process and final cool-down, half of each specimen lot is mechanically post-treated by HFMI using the Pneumatic Impact Technology (PIT). For the pneumatic actuation energy, a common industrial air pressure of 0.6 MPa (87 psi) is applied. The angle of the pin-axis with respect to the plate surface is set between 80° and 100°, the angle of the pin-axis with respect to the direction of travel about 90°, and the working speed between 1 and 3 mm/s. The radius of the hardened pin used in this study is $R = 2$ mm, which fits to the weld seam size of the investigated specimens. To ensure a high-quality post-treated weld toe, the HFMI-treatment is performed in accordance to the proposed procedures and quality assurance guidelines depicted in [6]. The post-treatment is applied without additional static pre-stressing or former cyclic damage. Due to the HFMI-treatment, the pulsed transaction of the hardened pin rounds-out the curvature of the weld toe region and thereby reduces the geometric stress concentration factor at the weld toe. In addition, compressive stresses are induced which counteract the superposition of residual weld and external load applied tensile stresses.

3.2. Fatigue tests

Fatigue tests at a tumescent stress ratio of $R = 0.1$ involving butt joint specimens are carried out to investigate the influence of the post-weld treatment technique on the lifetime experimentally. The results are part of an extensive test program for HFMI-treated joints focusing on the effect of different high-strength steel grades and joint geometries, see [7]. As the weld toe notch factor of the investigated thin-walled butt joint is comparably low, the

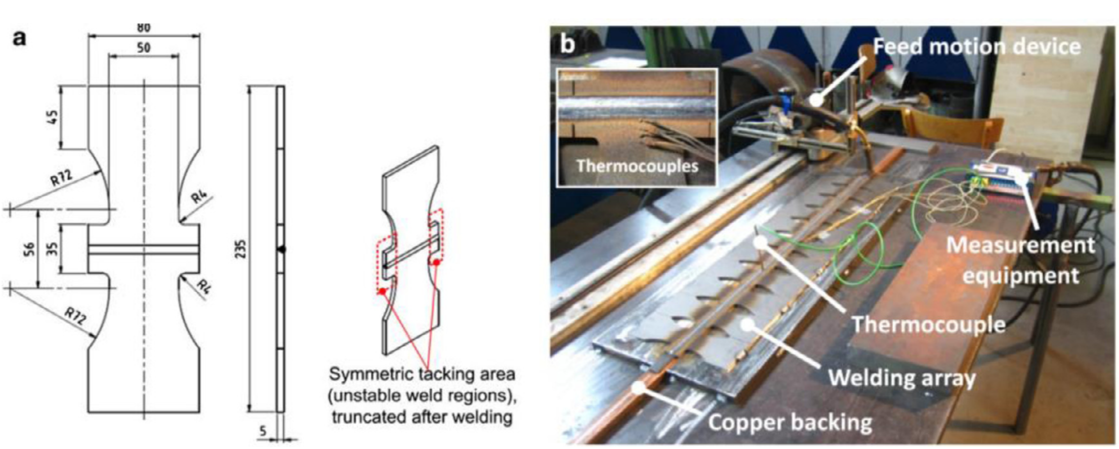

Fig. 2. Specimen geometry and set-up of welding array [4].