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Study on the residual stress relaxation in girth-welded steel pipes under bending load using diffraction methods

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ABSTRACT

This research is dedicated to the experimental investigation of the residual stress relaxation in girth-welded pipes due to quasi-static bending loads. Ferritic-pearlitic steel pipes are welded with two passes, resulting in a characteristic residual stress state with high tensile residual stresses at the weld root. Four-point bending is applied to generate axial load stress causing changes in the residual stress state. These are determined both on the outer and inner surfaces of the pipes, as well as in the pipe wall, using X-ray and neutron diffraction. Focusing on the effect of tensile load stress, it is revealed that not only the tensile residual stresses are reduced due to exceeding the yield stress, but also the compressive residual stresses for equilibrium reasons. Furthermore, residual stress relaxation occurs both parallel and perpendicular to the applied load stress.

1. Introduction

The residual stress effect on the fatigue behavior of welded steel components has not been quantified sufficiently yet. Current fatigue design standards and recommendations, like the ones given by the International Institute of Welding (IIW) [1], are based on the assumption of yield strength magnitude tensile residual stresses if the actual residual stress state is unknown. This postulate reflects uncertainties about the initial residual stress state after welding, which may depend on numerous parameters, as well as about the possible relaxation of residual stresses. The latter can occur as a result of different effects, such as annealing [2] or the loss of material containing residual stresses due to corrosion [3]. The most important effect with regard to the fatigue behavior, however, is the interaction of residual and load stresses, which may lead to local plastic deformation when the static or cyclic yield strength is exceeded, thus reducing the residual stresses. An overview about relaxation of residual stresses resulting from different manufacturing processes and their influence on the fatigue behavior is given in [4]. According to a model by Vöhringer [2], static and cyclic effects can occur separately or in combined form. In welded joints, significant residual stress relaxation is often observed during the first load cycle, followed by only small changes during further cycling [5–11] or no changes at all [12,13], as long as no fatigue crack is present.

It is obvious that information about the amount of residual stresses remaining in a component after relaxation, thus acting equivalent to a mean stress, is highly desirable. Since measurements are costly and provide only punctual information, great efforts are made in the area of numerical welding simulation. However, differences between numerical and experimental results, which are often observed as e.g. in a recent round robin organized by the IIW [14], show the need of further research in this area. While the current study is dedicated to the experimental characterization of residual stress relaxation in girth-welded steel pipes, it will serve as a reference for numerical computations of the residual stress state both after welding and after subsequent loading. Due to the fact that relaxation in welded joints is mainly observed in the first load cycle [4–13], this study will focus on the effects of quasi-static one-time loading. The experimental investigation of residual stress relaxation due to cyclic loading and of the fatigue performance of the pipe welds, as well as the results of the numerical computations, will be matter of future work.

The residual stress state in girth-welded pipes differs significantly from the one observed in plates. It has been shown that the pipe geometry and the heat input are the governing factors for the residual stress development [15,16], apart from material parameters. The characterization of the welding residual stresses in the pipe welds analyzed in the current paper has already been carried out by the authors [17–19], using mainly X-ray and neutron diffraction. It was found that the circumferential contraction of the weld and the highly heated areas in its vicinity during cooling is constrained by the adjacent

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material, thus causing tensile hoop residual stress in the former and compressive hoop residual stress in the latter areas. Due to the self-constraining tubular geometry, the contraction of the weld also leads to necking of the pipe and thereby to pipe wall bending, which accounts for characteristic axial residual stresses, being highly compressive near the weld toe and tensile at the weld root. Since both spots are potential crack initiation sites due to the notch effect, residual stress relaxation is of special interest at these locations.

2. Experimental work

2.1. General remarks

In order to investigate the residual stress relaxation under load, the residual stresses must be analyzed both before and after loading. Ideally, the measurements would be taken on the same samples to study the residual stress evolution as accurately as possible. However, this was only possible for the X-ray diffraction measurements on the outer surface of the pipes. For the measurements on the inner surface, as well as for the neutron diffraction measurements, different samples were used to study the residual stresses in the two states. Nevertheless, it is expected that this fact does not affect the results significantly, as extensive analyses had shown that the scatter of the residual stresses after welding is rather small in different nominally identical samples.

2.2. Sample preparation

Pipes of the ferritic-pearlitic structural steel S355J2H+N were used in this study. The chemical composition of the steel was 0.190 C, 0.266 Si, 1.131 Mn, 0.0092 P and 0.0067 S in mass% with a balance of Fe, resulting in about 3 mass% cementite. According to tensile tests, the upper yield stress of the base material is 355 MPa; its nominal stress-strain curve is shown in Fig. 1. The tubular specimens were machined on the inner and outer surface in order to remove geometrical imperfections, resulting in an outer diameter of 100.5 mm and a wall thickness of 7.75 mm. Two different types of samples were prepared: Relatively short pipes of 200 mm length were mainly used for the residual stress analysis in the as-welded state, whereas samples with a total length of 550 mm served for investigations under load. While the former were made from one piece with a v-shaped groove being introduced at half-length as a weld preparation, see [17,18] for details, the latter consist of two halves as shown in Fig. 2. Before welding, all pipes were stress relieved thermally at 600 °C for 30 min and cooled uniformly at about 1 °C/min.

Two sample halves as depicted in Fig. 2 were aligned coaxially with no gap, manually tack-welded at four points, each 90° apart, and welded in the same way as the short samples. All specimens were metal active gas (MAG) welded with the filler wire ISO 14341-A-G 4Si1 of 1.0 mm diameter using a shielding gas of 82% Ar and 18% CO_2. Mechanized welding was performed in flat position with a fixed welding torch and the sample being mounted on a motor-driven rotary table. Two passes were applied at room temperature, the second one with a pulsed current, resulting in nominal energy inputs of about 9 kJ/cm for the root pass and 12 kJ/cm for the second pass. The welding parameters can be taken from Table 1. Both passes were welded in the same direction, the second pass being slightly offset circumferentially.

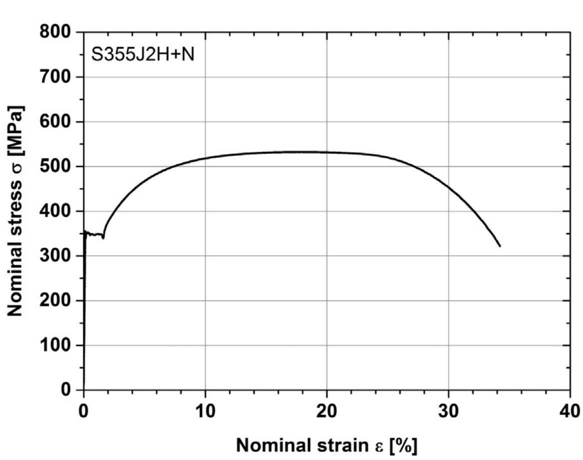

Fig. 1. Nominal stress-strain curve of the base material.

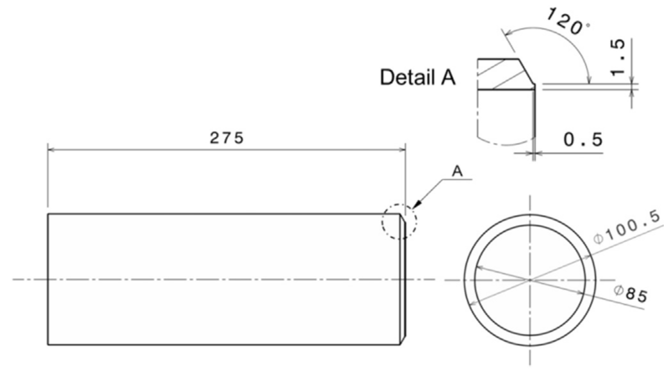

Fig. 2. Half of a sample used for studying residual stress relaxation with weld preparation.

After welding, cross-sections of the weld and its vicinity were metallographically prepared in order to determine the microstructure and the hardness in the weld seam, the heat-affected zone and the base material. The two-dimensional hardness distribution was determined by the Ultrasonic Contact Impedance (UCI) method with a measuring point distance of 0.2 mm in both axial and radial direction of the pipe.

2.3. Residual stress analysis

The residual stresses in the welded samples were determined both in the non-loaded state and after releasing the load using X-ray diffraction (XRD) and neutron diffraction (ND). The measurements were taken at points along lines perpendicular to the welding direction at φ=90°, where φ is the circumferential angle marking the welding direction and the start/stop location at φ=0°. Due to the symmetry, measurements were only performed on one side of the weld centerline up to a distance of 60 mm. The axial distance between two measurement points was chosen to be between 0.5 and 1 mm in close proximity to the weld, and between 2.5 and 5 mm far away from the weld. The coordinate x specifies the axial distance of a certain point from the weld centerline, see also Fig. 5a.

An Ω-diffractometer was used to determine the residual stresses in hoop and axial direction on the outer and inner surfaces of the pipes by XRD. The inner surfaces were only accessible after sectioning the tubes into four quarters, the released stresses being monitored by strain gauge measurements. Interference lines of Cr-K_α radiation originating from the {211} lattice planes of ferrite, bainite or martensite were recorded in a 2θ interval of 151–161° using a point detector that was moved in steps of 0.1° and held for 2 s at each position. This was done for eight tilt angles ψ of 0°, 13°, 18°, 27°, 33°, 39°, 42° and 45°, allowing for an analysis of the shift of the interference line's center of gravity by the $\sin^2\psi$ method. Previously, the $K_{\alpha2}$ doublet was eliminated using the Rachinger technique [20] and the remaining $K_{\alpha1}$ peak was smoothed with a Savitzky-Golay filter [21]. Exemplary raw peaks are shown in Fig. 3a for every region of the weld. For all measurements, a collimator of 2 mm in diameter was used. The average penetration depth in steel is about 5 μm for Cr-K_α radiation.

The neutron diffraction measurements for the residual stress