Development of a FE-based fracture mechanical method for fatigue life assessment of double-submerged welded pipelines considering residual stresses and local microstructures

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Abstract: To meet the cost and weight reduction requirements in modern steel and pipeline engineering the use of high-strength fine-grained steels is necessary. In this work, the applicability of thermomechanically rolled fine-grained structure steel of quality API 5L-X80 as substitution for nowadays commonly used steels, for example X65, should be assessed with respect to their fatigue behaviour. Due to the lack of fatigue life assessment standards in combination with the complex microstructural features of such high-strength steel welded structures, a finite-element (FE) based, fracture mechanical approach for fatigue life evaluation has to be developed.

Introduction

Commonly used fracture mechanical assessments for fatigue life evaluation of welded joints [1] do not capture the stress state exactly. In most cases only residual stresses due to the welding process are considered but this is not always sufficient. It is true that the residual stresses due to e.g. bending during manufacturing of the pipes are rearranged in the heat-affected zone (HAZ) due to local heat treatment processes from the welding process. But if subsequent weld treatment processes such as high-impact treatments are performed the complete history of the pipe manufacturing process must be considered. In this case the crack initiation can occur outside the HAZ in the base material where the stress states of earlier processes still play an important role. Changes in the residual stress state caused by manufacturing processes after welding – like an expansion of the pipe – influences in turn all microstructural zones and are therefore in any case of importance for the local loading.

Crack-propagating and crack-arresting effects due to the different microstructural zones in the HAZ of welded joints are commonly only considered with corresponding high safety factors. According to the IIW recommendation [1] a crack propagating threshold of 2 MPa√m, independent from the local microstructure, is suggested. This results in a very conservative design which leads in turn to heavier and more expensive constructions. So both the consideration of residual stresses due to manufacturing and the influence of the different microstructures are necessary for an enhanced, sophisticated evaluation of the fatigue life.

Residual stresses generally produce a shift in the stress ratio R. The base of this enhanced approach is therefore the measurement of crack propagation curves and fatigue limits for different R-ratios and microstructures of the welded joint. The three characteristic zones of a welded joint are shown in Fig. 1. The base material for following investigations is a thermomechanically rolled fine-grained steel of quality API 5L-X80. The chemical properties of the base material are shown in Table 1.

Table 1: Chemical composition of the base material X80 [%]

C	Si	Mn	P	S	Al	Cr	Ni	Mo	Cu	V
0.045	0.330	1.820	0.009	0.0006	0.035	0.170	0.014	0.140	0.010	0.003

The heat affected zone of a welded joint can be arranged in three different zones, where the microstructure differs significant from the base material (Fig. 1). The so-called intercritical (IZ) zone has a fine microstructure with an average grain size of about 5µm, whereby in the fined-grained zone (FZ) and the coarse-grained zone (CZ) an average grain size of about 6µm and 30µm, respectively, was determined.

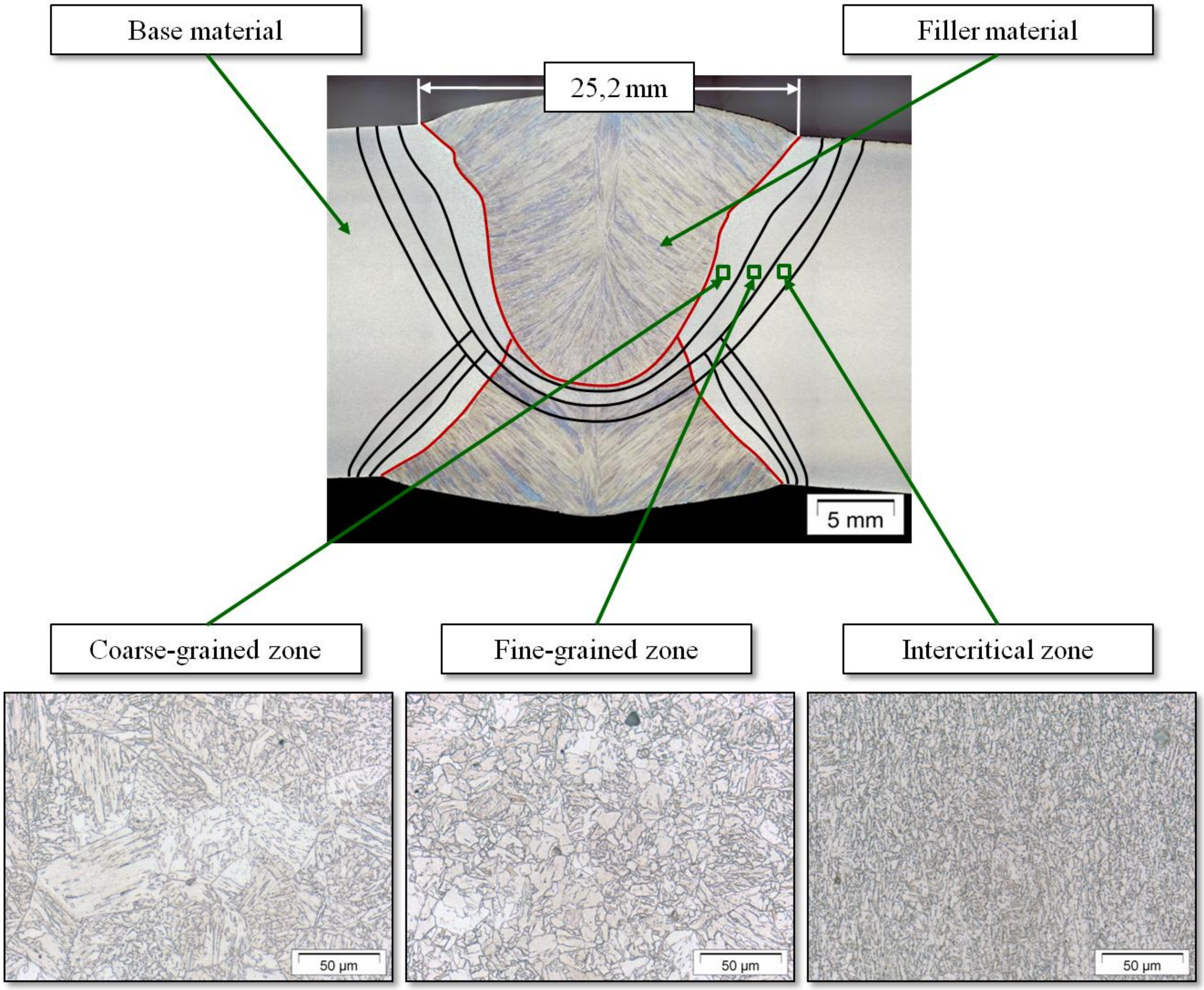

Fig. 1: Different zones of a welded joint

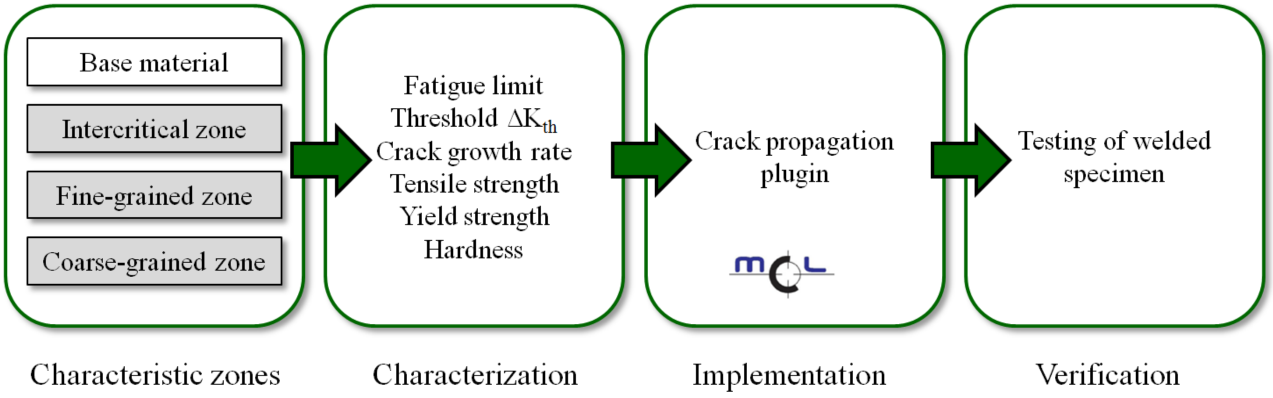

Fig. 2: Closed characterization chain of the fatigue life evaluation

Fig. 2 shows the closed chain of material characterization, simulation and verification of the results and the developed fatigue life evaluation assessment. The mechanical properties such as fatigue limit, fatigue threshold, crack growth rate, tensile strength, yield strength and hardness of the base material as well as of the material states in the IZ, CZ and FZ are characterized using SENB and flat test specimen. The test results are the base for the following simulation. Further developed Abaqus™-Plugins for determination of crack growth [2] and crack direction in inhomogeneous materials based on the configurational forces concept [3,4] are coupled to calculate the crack growth in common double submerged welded structures. The verification of the simulation is performed with welded specimens.

Manufacturing of specimens with defined microstructures

To gather the necessary information about the local heat treatment of the characteristic zones within the HAZ the temperature evolution during laboratory welding tests for different positions within the HAZ are measured. The temperature curves are shown in Fig. 3. The parameters for the welding tests are similar to the parameters in pipeline manufacturing. Nevertheless it should be mentioned that the flux from the double submerged welding process was not removed after an appointed clearance from the welding head but persists until the weld is cooled down sufficiently for manipulating the plates manually for welding the final pass on the other side. In the present case two of the temperature curves representing IZ and FZ were measured directly, the third curve representing CZ was calculated by a two- and three-dimensional analytical approach according to SEW 088 [5]. A two-dimensional approach shows a good agreement with the measured data and therefore the missing temperature curve could be extracted out of the simulation. These curves, especially the cooling rates and peak temperatures, are the input for the heat treatment process using a gleeble thermal simulator so that blanks with similar microstructures as in the IZ, CZ and FZ are produced. For evaluation of the homogeneity of the resulting microstructures metallographic investigations such as optical microscopy and EBSD are performed. After grinding, polishing and etching the microsections of the three distinctive zones are investigated at different positions across the specimen and the results are compared with the finding of the HAZ of a welded pipe. As a preliminary result, the microsections differ marginal in grain size, but show a good correlation along the width of the specimen. Additional information from hardness measurements with the Vickers method strengthen the picture, that the microstructure is homogeneous in the areas of interest and no deviation of crack propagation and fatigue endurance limit because of different microstructures should occur.

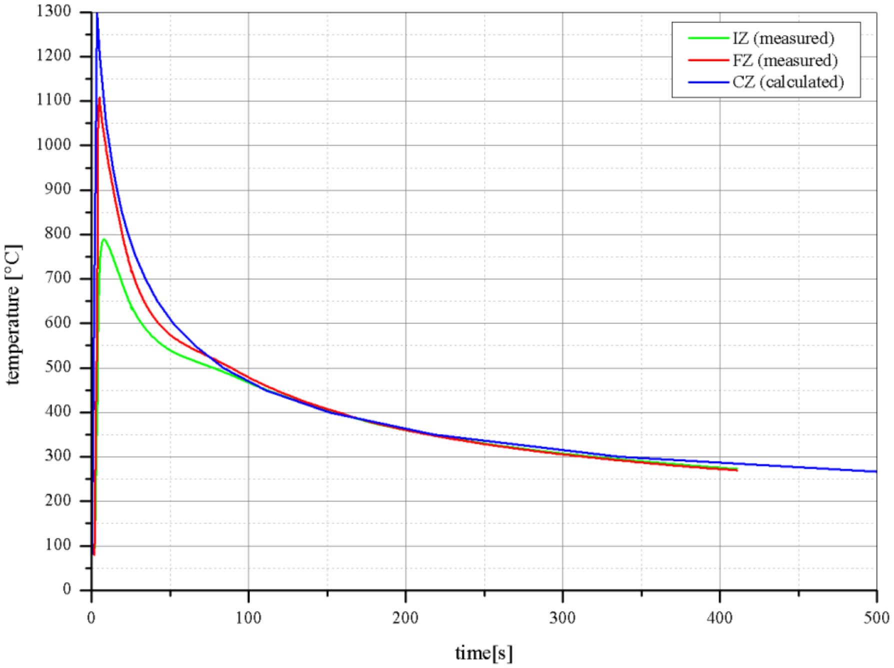

Fig. 3: Temperature evolution during laboratory test welding at different positions in the HAZ. The curve representing the CZ is calculated based on the measurements.

Crack propagation testing

Tensile pre-cracking and test execution in accordance to ASTM is not suitable because of the influence of the plastic zone emerging at the threshold of ductile materials. Instead of this procedure, the so called CPCA-method (compression pre-cracking, constant amplitude) was used to perform crack propagation testing. The tests are operated on a resonance testing machine, the crack growth is measured by the direct-current potential-drop method (DCPD). The SENB-specimen is pre-cracked under cyclic compression with a stress ratio R=10. After pre-cracking an appropriate load increase is performed until the crack starts to grow. The aim of this procedure is to minimize plasticity-induced closure effects and load interaction effects [6].

Verification of the simulation model by modelling and testing welded specimen

For the verification of the simulation model welded specimens with geometry shown in Fig. 4 which are manufactured out of welded plates from the laboratory welding tests, are used. Fig. 5 shows the cycle of verification of the simulation model. First of all a welding simulation with Sysweld™ for determination of the residual stresses due to the welding process is performed. The resulting stress state is mapped into Abaqus™.

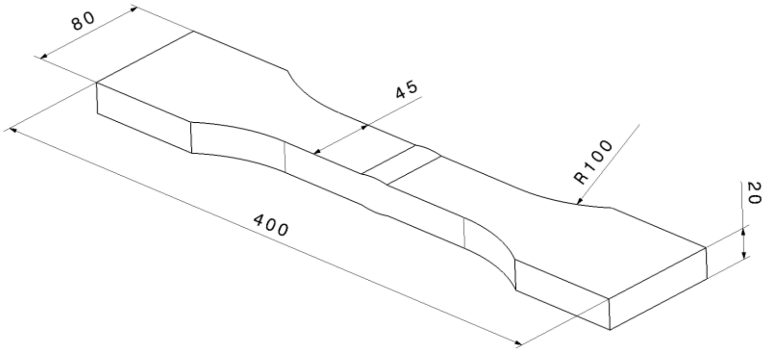

Fig. 4: Specimen geometry

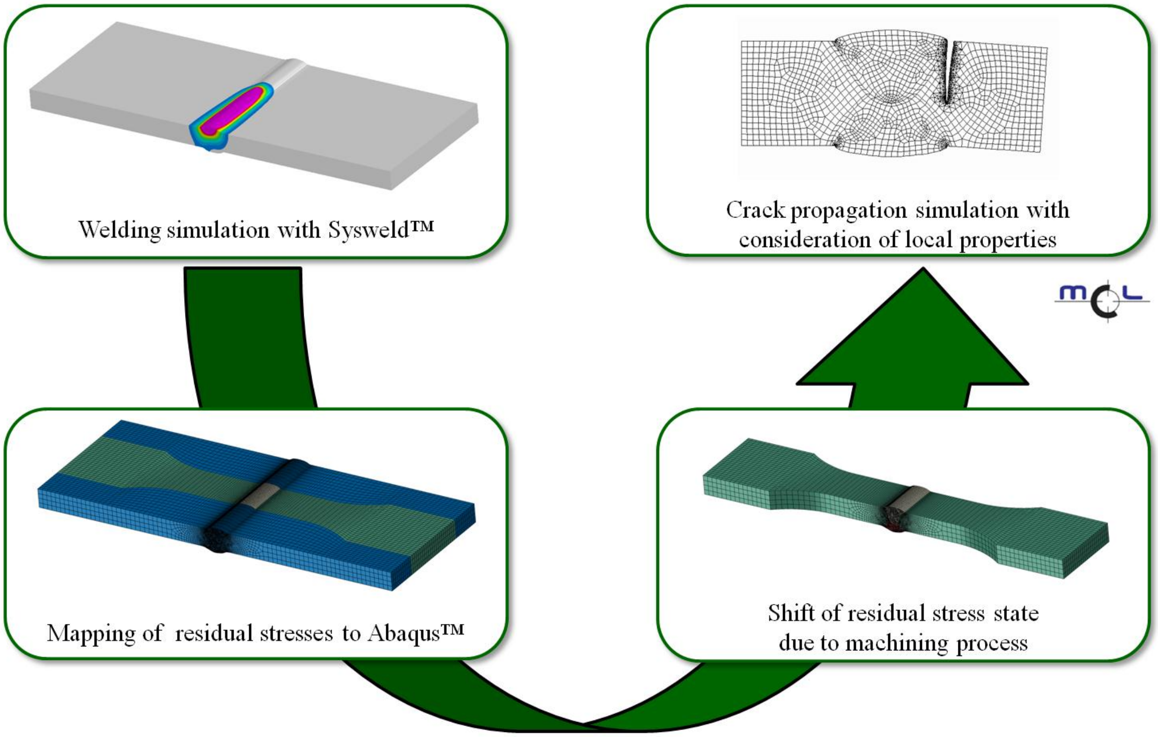

Fig. 5: Simulation cycle of the welded specimen as a verification of the developed fatigue life evaluation

From the welded structure specimen are manufactured. The manufacturing process of a specimen causes a shift in the residual state. To gain an equivalent stress state in the simulation the manufacturing process of the welded specimen is reproduced with a deletion of elements, which would be removed when manufacturing the specimen. With this initial residual stress state the crack propagation simulation is performed. In the crack propagation simulation the crack rates in the HAZ are locally different due to dependence of the crack growth rates on the local microstructure. The locally inhomogeneous crack growth resistance influences not only the crack growth rate but also the crack growth direction. The results of the fracture mechanical based fatigue simulation considering residual stresses due to the welding and manufacturing process of the specimen as well as the effect of locally different crack propagation rates in the HAZ will be validated by the fatigue tests of welded specimens.

Summary

A FE based fracture mechanical approach for fatigue life evaluation was presented. This approach takes into account residual stresses and local mechanical and fracture mechanical properties of the different zones of the HAZ of a double submerged welded joint. To get the required information test specimen blanks were set to the different microstructures of three characteristic zones of the HAZ by a gleeble thermal simulator. Out of this blanks specimen for crack propagation tests and fatigue tests were manufactured. Further developed crack propagation post-processing routines for Abaqus™ were used to take different material properties of the inhomogeneous material of a welded joint into account. The simulation results were emphasized with test results of welded specimen. The Achievement of this should be a more accurate fatigue life evaluation to increase the reliability of the dimensioning process of welded structures, especially welded pipelines.

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