CYCLIC MATERIAL BEHAVIOUR OF WELDED ULTRA HIGH-STRENGTH STEELS

Benjamin Möller[1]*, Rainer Wagener[2] and Tobias Melz[3]

[1] Technische Universität Darmstadt, System Reliability and Machine Acoustics SzM,
Magdalenenstraße 4, 64289 Darmstadt, moeller@szm.tu-darmstadt.de, www.szm.tu-darmstadt.de
[2] Fraunhofer Institute for Structural Durability and System Reliability LBF,
Bartningstr. 47, 64289 Darmstadt, rainer.wagener@lbf.fraunhofer.de, www.lbf.fraunhofer.de
[3] Fraunhofer Institute for Structural Durability and System Reliability LBF,
Bartningstr. 47, 64289 Darmstadt, tobias.melz@lbf.fraunhofer.de, www.lbf.fraunhofer.de

Key Words: *Ultra High-Strength Steel, Butt Weld, Small-Scale Testing, Weld Zones, Cyclic Material Behaviour, Cyclic Stress-Strain Curve, Strain-Life.*

Introduction

A crucial issue within the field of crane structures is the fatigue life of welded ultra high-strength fine-grained steels, which are widely used in order to achieve increasing carrying capacities and to enable lightweight design. The typical fatigue behaviour of highly loaded truck and crawler cranes is related to the low cycle fatigue (LCF) regime and often focused on critical details of welded joints. Fatigue recommendations for the design and analysis of welded structures [1, 2] are based on fatigue resistance Wöhler curves irrespective of the steel grade and describe the LCF behaviour improperly. Latest stress-controlled experiments on large scale, butt-welded specimens describe the overall S-N relation of such structural elements in the LCF and HCF regime [3], but do not describe the mechanisms leading to fatigue of welded ultra high-strength steels accurately – especially in case of variable amplitude loading.

Material and methods

The present study has been carried out on MAG-welded butt joints of three ultra high-strength steels S960QL, S960M and S1100QL. Irrespective of a manually or automatized welding process of these steels the appearance and quality in terms of strength is influenced by several factors, such as weld preparation (e.g. opening angle of the weld), welding parameters (e.g. $t_{8/5}$ time) and accuracy of the welding process. All factors individually and in combination with each other can have a significant influence on the geometrical notch of the weld toe (or the weld root for other weld details) and on the interior metallurgical notch. Therefore the fatigue strength is evaluated by examinations on the geometrical and metallurgical notch effect in case of constant amplitude loading (CAL) and the ascertaining of the corresponding Wöhler curves by stress- as well as strain-controlled testing using servo-hydraulic and piezoelectric based test rigs. Specimens including the overall butt weld seam are machined across the weld (Figure 1a), while thin and small-scale specimens according to Figure 1b are extracted longitudinal to the weld in the base material (BM), heat affected zone (HAZ) and weld metal (WM). A similar procedure was introduced by [4] for laser welded joints of S355J2G3 steel.

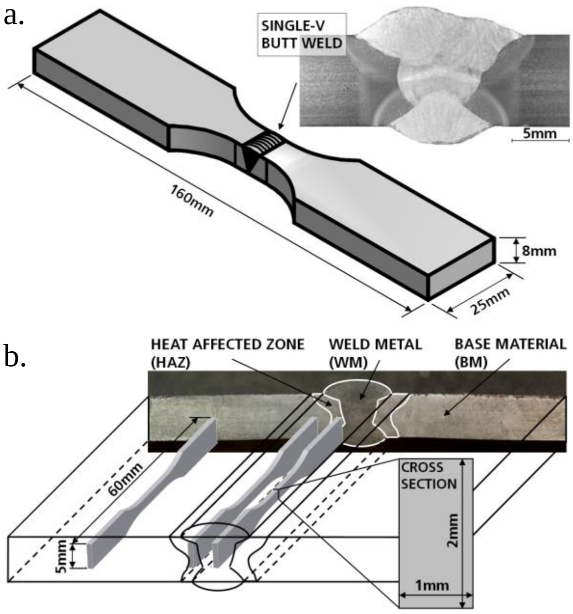

Figure 1: Schematic presentation of the

a. specimens for strain-controlled testing of the overall single-V butt weld (also specimens with flat milled surface and base material specimens)
b. specimens for strain-controlled small-scale testing of three weld zones (BM, HAZ, WM) using a piezoelectric based test rig

Results and discussion

The failure behaviour of the overall single-V butt weld shows crack initiation at the geometrical notch of the weld toe in about 95% of the experiments, while crack propagation proceeds either along the interface between heat affected zone (HAZ) and base metal (BM) or across the HAZ. However, for similar specimens with a flat milled surface crack initiation can be observed at the interface between WM and HAZ (no geometrical notch) for nearly 45%. The crack then propagates across the HAZ for about 42% of the experiments.

The comparison of the single-V butt weld specimens with the flat milled surface specimens and accordingly base material specimens show that the geometrical notch effect is the governing factor for fatigue and especially crack initiation (see also [5]). Anyways, the results show that the fatigue strength of welded sections is also affected by the metallurgical notch effect. The interior shape of the WM and HAZ as well as the interface from WM to HAZ and HAZ to BM (e.g. in terms of the gradient of the hardness decrease in the HAZ) in combination with weld defects furthermore limit the fatigue strength of a welded connection.

The investigation of the microstructural differences of the three weld zones (for S960QL) and their cyclic material behaviour is the key to a well-defined specification of a weld. Since the cyclic behaviour at the crack initiation point includes considerable large plastic strains [6], the region of a notch is subjected to (plastic) strain-dominated mechanisms, especially when the weld is exposed to LCF. Strain-controlled testing is able to characterize fatigue mechanisms in the regime of low-cycle fatigue by strain-life-curves, as shown in Figure 2, and cyclic stress-strain curves, Figure 3.

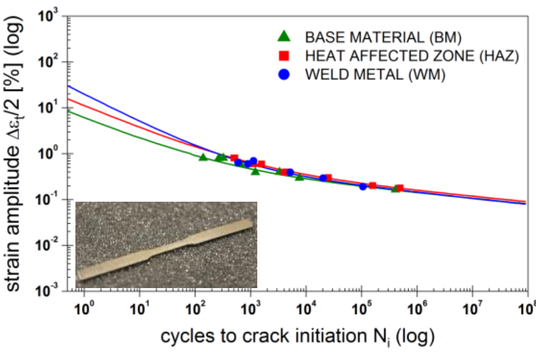

Figure 2: Strain-life of the three zones BM, HAZ and WM for a S960QL butt weld (preliminary results)

The strain-life curves of every single weld zone hardly differ from each other. Even though strain-life of the BM is comparably low, the stabilized stress-strain-curve comparable values to the WM and higher stresses than the HAZ.

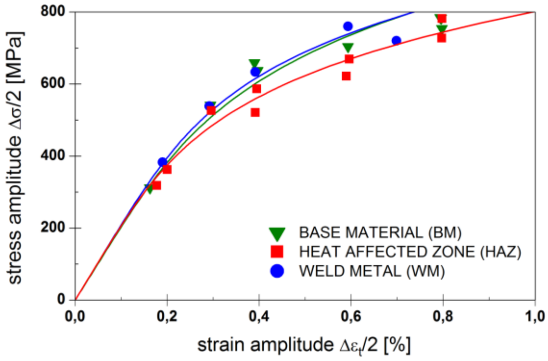

Figure 3: Cyclic stress-strain relation of the three zones BM, HAZ and WM for a S960QL butt weld (preliminary results)

Conclusions

Low-cycle fatigue of welded high-strength fine grained steels is limited by the geometrical and metallurgical notch effect. The weld geometry and shape of the notch, respectively, as well as the interior dimensions of the variant microstructures of the WM and HAZ are essentially defined by the weld preparation, the welding parameters and the choice or rather accuracy of the welding process. The grade of steel – S960QL, S960M or S1100QL – therefore is of minor significance for the fatigue of welded high strength steels.

Differences of the three weld zones (microstructure etc.) partly result in diversified cyclic material behaviour. For ultra high-strength steels a decrease of hardness in the HAZ and lower stresses of the stabilized stress-strain curve in combination with the observed crack initiation and propagation indicate that the HAZ is the weakest link.

Deeper knowledge about the cyclic material behaviour of welded joints in the low-cycle fatigue will help to develop fatigue life assessment methods, e.g. local strain concepts, presented in an overview for welded joints by [7].

References

[1] Hobbacher, *IIW Recommendations for Fatigue Design of Welded Joints and Components*, 2008.

[2] Eurocode 3, *Design of steel structures – Part 1-9: Fatigue*, 2009.

[3] Möller *et al*, *Seventh International Conference on Low Cycle Fatigue*, Conference Transcript: 507-512, 2013.

[4] Boroński, *Seventh International Conference on Low Cycle Fatigue*, Conference Transcript: 377-382, 2013.

[5] Bergers *et al*, *Stahlbau 75*, **11**:897-915, 2006.

[6] Haibach, *Betriebsfestigkeit*, 3rd Edition, 2006.

[7] Sonsino CM *et al*, Int J Fatigue, **34**:2-16, 2010