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Stress build-up in HSLA steel welds due to material behaviour

Dirk Schroepfer*, Thomas Kannengiesser

BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany

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ABSTRACT

For the performance of high-strength steel welds by means of load bearing capacity and safety, the information about stress level and distribution due to welding is needed. The interaction between the filler material grade (strength) and heat input on the reaction stresses in high-strength steels, welded under defined restraint conditions were analysed. Butt welds were joined by a multilayer GMAW process in the Instrumented Restraint Cracking test facility (IRC-test). This test facility allowed a defined restraint and, simultaneously, an in-situ analysis of the reaction stresses while welding and cooling. The reaction force build-up of the weld tests showed a significant influence of the used filler materials according to the heat input. Higher strength filler material grades cause a decrease of the welding stresses compared to lower strength grades, if a low heat input is used. The different stress build-up is described in detail for the root welds, filler layers and subsequent cooling to ambient temperature. Residual stresses in the weld, HAZ and base material were measured in loaded and unloaded condition using the incremental hole drilling method.

1. Introduction

High-strength fine-grained structural steels with yield strengths from 690 MPa upwards are applied in a growing amount of industrial applications. Specific design solutions and economic aspects of modern steel constructions, e.g. mobile cranes or hydro power plants, lead to an increasing trend in light weight design according to (Hara and Sato, 2009). Steel producers currently provide a diversified spectrum of high-strength base and filler materials as (Rauch et al., 2012) shows. Thus, an extensive reduction in weight and production costs can be achieved, referred to (Hulka et al., 2005), with increasing material strength. Recent competitions of increasing energy and resource efficiency emphasise this issue. For a sustainable and economic application, advanced requirements for the loading capacity and safety of welded components have to be achieved. The accomplishment of the needed mechanical properties in a weldment depends on the application of adequate filler materials. Several recent works discussed the advantages of low and high matching ratios, the strength ratio of base and filler material, respectively. Particularly, (Loureiro, 2002) analysed static mechanical properties like tensile strength and hardness. In cold cracking tests, (Umekuni and Masubuchi, 1997) found that an under-matching weld metal is beneficial, if applied in root welds of high-strength steels, since a lower preheating temperature could be used without decreasing mechanical properties of the weld. (Maltrud, 2009) recommends the use of slight over-matching filler materials for thermo-mechanically rolled high-strength steel. High-strength materials are mostly beneficial in quasi-static and low-cycle-fatigue regions, since the fatigue life of welded joints is more or less independent from the material strength. Considering the dynamic behaviour of high-strength steel welds, (Stoschka et al., 2012) investigated the fatigue of S960QL with slightly under-matched high-strength filler materials. According to (Heuser and Jochum, 2007) it is, basically, a matter of the manufacturers and economic aspects, which filler materials and matching ratios are applied. Any benefits from high-strength steel application have to be verified by the required safety of the weldment, like identified by (Zrilic et al., 2007).

However, the reliability of welded components during production and service is a subject to the interaction of load, material and design; see Fig. 1a. A defined working range considering heat control, e.g. $\Delta t_{8/5}$-cooling time, must be maintained in order to fulfil metallurgical requirements as well as a sufficient hydrogen effusion and crack resistance. Additionally to the metallurgical aspects, crack prevention could also be contributed by reduced residual stresses.

Particularly, in restrained structures, a superposition of local and global welding stresses may lead to high residual stress levels, which are able to diminish the components safety; see Fig. 1b. High restraints occur specifically in bulky components and in circumfer-

* Corresponding author.
E-mail address: dirk.schroepfer@bam.de (D. Schroepfer).

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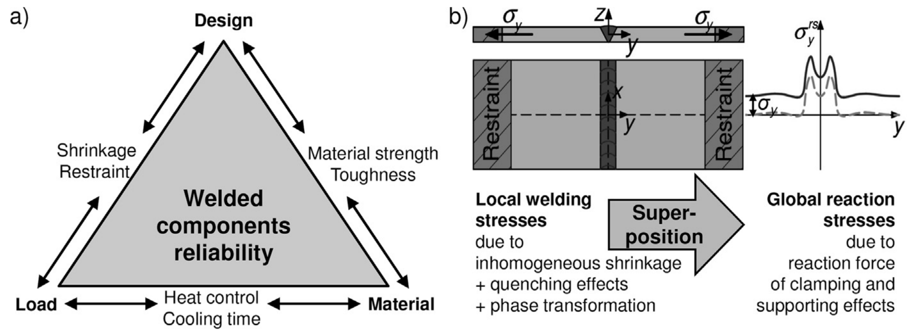

Fig. 1. Interaction of design, material and load (a) during component production and service according to (Lausch et al., 2013); welding stresses as a result of local and global restraint (b) according to (Schroepfer et al., 2015).

ential welds in pipes, as analysed by (Leggatt, 2008), as well as in repair welds, pointed out by (Dong et al., 2005). In contrary, recent important research activities mainly involved residual stress characteristics in welds of laboratory and free shrinking samples, like works of (Uwer and Hohne, 1992) and (Lachmann et al., 1997). But in order to determine adequate process conditions, an enhanced consideration of the interaction between heat control, material and restraint of the surrounding structure is required. Both the arising global and local welding stresses have to be limited to enhance the performance of high-strength steel welds by means of load bearing capacity and safety, which is the requirement for a complete utilisation of the high-strength potential. High reaction stresses should be avoided in component welds where high restraint intensities are present, since as a consequence a disproportionately high tensile residual stress increase could occur in the HAZ. Especially in the HAZ, high residual stresses may diminish the components safety.

Investigations of (Lausch et al., 2013) with a special designed component weld test under defined restraint showed that the interpass temperature has a significant influence on the reaction force after cooling to ambient temperature. Furthermore, (Kannengiesser et al., 2011) found a high effect of the preheating and interpass temperature on the reaction stresses during welding, especially for the root weld, and after subsequent cooling. Further influences for a welding stress optimization were already investigated by (Boellinghaus and Kannengiesser, 2003). These weld tests exhibited increased global reaction stresses for higher restraint intensities. Another major influence was found for the weld metal phase transformation behaviour during welding and cooling. The comparison of the reaction forces after cooling to ambient temperature of two welds with different weld metals exhibited reduced values for the over-matched weld. Therefore, the reaction stress build-up has to be analysed in detail for the different welding and cooling phases of the multilayer welds taking into account the transformation-specific changes in volume. Note that it is important to apply a proper heat control, basically to meet the recommendations of the steel producers. An advanced minimization of welding stresses in high-strength steels by an improvement of the concepts given in technical guidelines and standards by a proper filler material selection is desirable.

Hence, this present study is concerned with the influence of the filler material on the stress build-up due to welding and cooling under hindered shrinkage. Therefore, externally restrained high-strength steel welds by means of IRC (Instrumented Restraint Cracking)-tests, already described in detail by (Kannengiesser et al., 2011), with three different filler materials were implemented. The additional variation of heat input shows the intensity of the described effects in connection with the heat control and cooling times, respectively.

2. Experimental

20 mm thick plates of high-strength quenched and tempered fine-grained structural steel S690Q (EN 10,025-6) were welded; see Tables 1 and 2, . The high-strength solid filler wires G 69 6 M21 Mn4Ni1.5CrMo and G 89 5 M21 Mn4Ni2.5CrMo (EN ISO 16,834-A) were applied in order to realize different matching ratios. In addition, two specimens were welded with a high-alloyed duplex filler wire G 22 9 3 NL (EN ISO 14,343-A), which primarily solidifies into ferrite. This allows a detailed analysis of effects due to phase transformation and the involved restrained volume expansion of the microstructure while welding and cooling, by a direct comparison with the low alloyed steel grades.

For reasons of comparison considering resulting global restraints in different weld constructions, the restraint intensity R_{Fy} was established. The restraint intensity in weld transverse direction R_{Fy} is the components stiffness towards the weld seam based on the seam length. It can be estimated for simple butt joints according to (Satoh et al., 1977). An implementation of a defined restraint intensity in weld transverse direction of $R_{Fy} = 3$ kN (mm mm)$^{-1}$ during welding and cooling was accomplished with an IRC-test facility. Six multilayer MAG-weld tests at single-V butt joints were performed in the IRC-test facility. In each weld test a specimen is centrically fixed into the IRC-test facility using clamping adapters, where an online registration of the reaction force is provided by

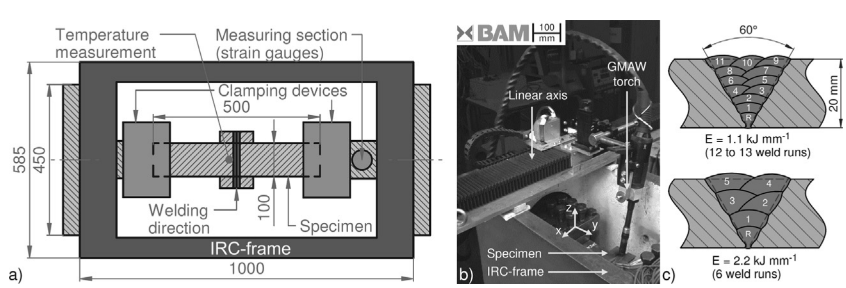

Fig. 2. Experimental setup: Schematic of the IRC-test (a), weld setup in the test facility (b) and build-up sequence (c).