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A hierarchical multi-scale approach to mechanical characterization of heat affected zone in welded connections

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ABSTRACT

During the welding process, the microstructure of the base material changes locally that leads to altering mechanical properties in the weld and the neighboring areas, Heat Affected Zone (HAZ). The constitution of the HAZs also varies spatially as a result of different temperature gradients during heating and cooling cycles. Consequently, the macroscopic material behavior of the HAZ also varies spatially as well and therefore the determination of the mechanical behavior of the welded connection is very challenging. In this study, a hierarchical multiscale approach is presented and applied in order to characterize the material behavior of the Heat Affected Zone (HAZ) in welded connections. First, the metallurgical constituents in particular areas of HAZ have been identified experimentally. Next, several representative volume elements (RVEs) have been constructed using microscopic images.

Then employing the computational homogenization methods, the stress–strain curves representing the macroscopic material behavior in respective points of the HAZ have been calculated. Meanwhile, some miniature tensile tests have been performed to experimentally identify the stress–strain behavior in the HAZ. Finally, the numerically calculated stress–strain curves are compared with the measured experimental data and they show a good agreement. The comparison of the results depicts that the proposed multiscale approach is suitable for the characterization of the material properties in welded connections or in general for materials with specially varying microstructures.

1. Introduction

Welding is the most dominant fusion technique in fabrication of engineering steel structures. The welding process locally changes the microstructure of the base material and leads to altering the mechanical properties in the neighboring areas of the weld and the Heat Affected Zone (HAZ). The so called HAZ is the term used to call the weld surrounding regions that undergo thermal cycles above 500 °C that results in metallurgical transformation [1,2]. The solid transformation processes can also lead to the softening of certain regions of the HAZ or to the generation of brittle coarse-grained areas along the fusion line of the weld. Fig. 1 shows a butt welded joint (DHY) and the microstructure in particular regions of the HAZ.

The weld zone is characterized by solidification of microstructure caused by melting of the filler material and a part of the base material. The fusion zone is surrounded by the HAZ, where in the HAZ a solid state transformation occurs without the material being melted during the fabrication process. In the HAZ, there is a wide variety of microstructures due to the thermal history of the welding process [1,2] and can be divided into four different areas: (1) coarse-grained zone, (2) fine-grained zone, (3) partially astenitized zone and (4) tempered zone [3]. The major cause of the microsscale gradation in the HAZ is the local temperature gradient during heating and cooling process [4]. Therefore, the different areas in the microstructures of the HAZ exhibit different mechanical properties, i.e. strength, ductility and toughness [5]. As a result, the mechanical properties of the HAZ is first, scale and second position dependent.

The mentioned facts contribute to high complexity of predicting the mechanical properties of the welded connections. Especially in the context of structural engineering, the existing studies of the mechanical analysis of the welded connections is highly inefficient by the ignorance or insufficient consideration of the influence of the HAZ [2,6]. This is caused by inability of the standard testing methods to address the mesoscopic constitutive elements that mainly influence the macroscopic material properties in the HAZ [7,8]. This leads to the reason that the design rules of welded

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connections are very conservative [2,6] resulting in unnecessary costs in the building process.

Nevertheless, from the perspective of material science there are many possibilities to characterize the material properties from the lower spatial scales either using experimental or numerical methods [9–15]. In the area of experimental characterization, notable measurement techniques are high resolution imaging and diffraction, e.g. X-ray diffraction, convergent beam electron diffraction and electron backscatter diffraction. These methods enable us to identify constitutive elements from the lower scales, such as crystallite structures, grain orientations and metallurgical constituents that highly influence macroscopic material behavior [14,16,17,1]. One can use the resultant experimental characterization of the microstructure in a class of methods called the Multiscale methods that have gained a lot of popularity in the last decade.

Despite the complexity of microstructures in welded connections, the approaches for the assessment of structural integrity as well as the mechanical performance of welds are simplifying the mechanical behavior by neglecting the variation of material properties in the HAZ [6]. Examples of such simplified studies is by Khalfallah [18] to assess the mechanical properties of welded tubes, or the analysis of welded tensile plates with a surface notch performed in [19]. Only a small amount of numerical research studies exist where material properties of a HAZ have been assumed to be different to the weld and the base material [2,20].

Other recent methods to characterize the weld zone properties have been proposed based on the uni-axial tension test in accordance with the rule of mixture [21] or the uni-axial tension test using the sub-sized ASTM specimens [22]. However, applying the rule of mixture is rather questionable because the size of the area represented by the average measured properties is rather coarse. Moreover, the preparation of the small sub-sized specimens is not a straight forward task for some welding processes such as metal active gas (MAG) or tungsten inert gas (TIG). A more realistic approach to characterize the mechanical properties of the metal active gas weld zone and the HAZ were done utilizing the continuous indentation method together with its finite element (FEM) analysis by Chung et al. [23] or in recent contributions by Song et al. [24] and by Sun et al. [25].

For computational prediction of the structural integrity and load bearing capacity of welded connections, methods are needed

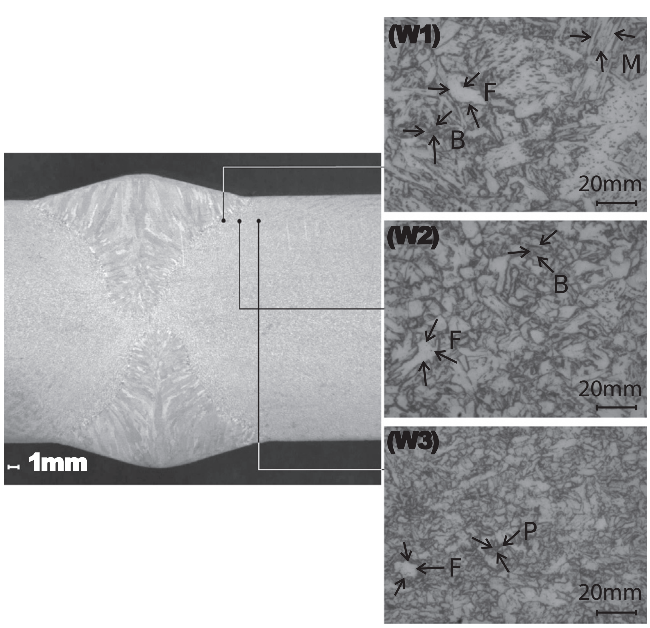

Fig. 1. Butt welded joint (DHY) and microstructure in particular regions of HAZ.

to characterize the material properties in different regions of the welded connection. Accordingly, multiscale modeling provides the possibility to characterize the macroscopic material behavior and recently it has been extensively used to characterize the material properties of different heterogeneous materials [9,15,26,27]. Multiscale methods can be categorized into hierarchical, semi-concurrent and concurrent methods [28]. Please refer to the manuscripts by Talebi et al. [29,30] for the detailed description of the methods. In hierarchical multiscale methods, information are passed from the lower scale to the higher scale only, usually using, the conventional method of computational homogenization. In the hierarchical methods, often a macroscopic constitutive material model is assumed and the variables of the model are calculated from the analysis of the microstructure. Please refer to the manuscripts in [31–33], extensions to composite materials in [34–36] and its application to steel structures in [26,27] among many others.

As mentioned before, the many studies on the investigation of the mechanical properties of the welded connections for different welding processes suffer from several shortcomings. Some of the major shortcomings are negligence of the inhomogeneities of HAZ, combined numerical studies with expensive experimental characterization of the materials or too specific solutions that are only appropriate for a small range of structures. In this study however, we are seeking a new approach based on the hierarchical multiscale methods that only uses material properties of the base constituents of the weld and the micro images of the weld and its surroundings to compute the mechanical properties. The rest of the methodology employs conventional software and finite element simulation tools that lead to a fast, cheap and yet accurate path to achieve the mechanical characteristics.

In other words, the purpose of the study presented here is to characterize the welded structure from mechanical point of view using a hierarchical multiscale approach. Our goal is then to compute stress–strain behavior in the HAZ, depending on the metallurgical phase constitution in discrete points of this region in comparison to the base material. For this purpose, the microscopic constituents have been identified using the microscopic images of the microstructure. The microstructure images, are then used to create the representative volume elements (RVEs). Using the mechanical properties of each constituent of the RVE from the available literature and computational homogenization, we have predicted the stress–strain behavior of many individual points of the macrostrucutre. This enables us to identify the mechanical properties of each point in the global structure which later can be used to numerically analyze the whole structure in a concise manner. To validate, the numerical results of the stress–strain relations in the HAZ and the base material have been compared with experimental results of the miniature tensile tests.

This study is of great importance from several aspects. First, it provides a straight forward approach to deal with materials which have position dependent physical properties. Second, analyzing welded connections, the method enables us to investigate and assess the influence of different regions of HAZ on the load bearing capacity of the structure. Thus results can be used to optimize welded process in order to provide desired properties in the HAZ. And finally, the accurate computed properties can be used to design safer yet lighter structures.

This paper is organized as follows. Section 2 shortly presents the theory of micromechanical modeling. Section 3 explains the experimental procedure to obtain the RVEs. In the Section 4 the numerical methodology is discussed in detail to obtain the finite element model and the material properties and finally applying the hierarchical multiscale approach. Section 5 presents the results of the numerical procedure and its comparison to the experimental tests. Finally, in Section 6 we draw some conclusions.