Engineering Structures 118 (2016) 16–27

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of weld on the mechanical properties of high strength and ultra-high strength steel tubes in fabricated hybrid sections

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ARTICLE INFO

Article history:
Received 26 August 2015
Revised 17 March 2016
Accepted 17 March 2016
Available online 1 April 2016

Keywords:
Ultra-high strength tube
Fabricated hybrid section
Heat affected zone
Mechanical properties
Strain hardening rate
Microstructure

ABSTRACT

The effect of welding on the mechanical properties of high and ultra-high strength tubes in hybrid sections is a critical factor which influences the global performance of fabricated members and should be considered in the design and incorporation of these materials. To investigate and quantify these effects on the material of welded steel, a specific type of hybrid section composed of plates and tubes is considered in which two scales of experimental analysis are conducted at different positions from weld. In the macro scale, standard tensile tests are performed at various distances from weld to obtain the mechanical properties of heat affected steel in the axial direction parallel to the weld. Comparisons are made among three different welded materials: mild steel, high strength steel and ultra-high strength steel. The original and after-weld alteration in the ultimate tensile strength (UTS) and the strain corresponding to the UTS are investigated giving particular attention to the effect of yield strength and strain hardening rate. At the micro level, the microstructure of three above-mentioned materials in addition to microhardness profiles have been examined providing extensive data of the material behavior after welding. It is shown that the welding and post welding process, such as heat input and cooling rate affect the local material properties at different distances from weld leading to an overall heterogeneity in the material influencing the mechanical behavior.

1. Introduction

High strength steel (HSS) and ultra-high strength steel (UHSS) materials are widely used in industry (e.g. automotive, pressure vessels, etc.) [1–3] due to their unique characteristics such as strength, energy absorption, and weight saving. In structural engineering, taking advantage of the strength capacity of these materials can be beneficial especially in structures with high load-bearing demands. High strength steel tubes are utilized in structures for their superior load bearing capacities and therefore their performance has been studied under various loading conditions [4–6]. Innovative sections fabricated from high and ultra-high strength steel tubes have recently been proposed due to their convenient structural application providing high performance and sustainable construction [7–11].

During the design and incorporation of these high strength materials in fabricated sections, the defects and material modifications due to welding need to be considered. Depending on the applied loads such as axial [12] or bending [13], the behavior of high strength material is enhanced by welding and the heat induced by that. Welding results in the formation of material softening at the Heat Affected Zone (HAZ) which is of decisive influence on the response of the structure. Various analytical and experimental analyses have been conducted on high strength steel plates to find the governing phenomenon in the behavior of high strength material affected by welding from a metallurgical point of view [14–19]. The HAZ microstructure depends on the steel material, type of weld, heat input during welding, and the post welding conditions.

Steel production procedures such as quenching and tempering, thermomechanical rolling and techniques like direct quenching affect the properties of the heat affected zone (HAZ) after welding. This is because High strength steels made through different methods differ in chemical composition and carbon equivalences and therefore exhibit various weldabilities. Indeed it has been shown that a quenched and tempered high strength steel compared to a thermomechanically processed high strength steel with same strengths and under similar arc welding conditions, possess

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http://dx.doi.org/10.1016/j.engstruct.2016.03.046
0141-0296/

different HAZ widths and microstructures [17]. Depending on the steel chemical composition, heat input in welding should be limited to a specific amount so the presence of carbides in the heat affected zone (HAZ) can be removed which increases the impact toughness of microstructure in this region [18]. In case of low heat input welding of quenched and tempered high strength steels, a very high tensile material will develop within the HAZ area whereas, in high heat input welding, the yield and tensile strength of base material may be reduced [20]. The amount of heat input varies in different welding types. In types such as laser welding (LW) [21] and Electron Beam Welding (EBW) [22] heat input is quite low which results in a smaller HAZ width in these types of welding. However, these are not currently popular types of welding for mass fabrications.

Post-welding cooling conditions also strongly influence the HAZ properties. Welding can lead to excessive hardening for short cooling times in ultra-high strength quenched and tempered steel, which can increase the risk of cold cracking in the HAZ [23]. The cold cracking in ultra-high strength steels, which are known as steels with ultimate stresses of more than 900 MPa [24], can be prevented by preheating [25]. Several studies are available specifically on the performance of HAZ areas of high strength steel in the form of tubes. Steel strengths of less than 500 MPa have been experimentally and numerically studied for different tube geometries, in which effect of welds results in various residual stress distributions produced in circular tubes [26]. On ultra-high strength steel, studies have been conducted on cold formed circular tubes in the axial direction of tube [12] and obtaining the ductility of each material and making comparisons with standards [27].

Following the previous works on ultra-high strength steel tubes, the present study examines the behavior of the heat affected material extracted directly from a fabricated hybrid section and presents analysis on the effect of weld on the properties of high and ultra-high strength tube. In this study, the axial material properties in the direction parallel to weld are examined, comparisons are performed and conclusions are presented based on the observations from three types of steels: Mild Steel (MS), High Strength Steel (HSS) and Ultra-High Strength Steel (UHSS) tubes welded to Mild steel plate material. Particular attention is placed on the ultimate tensile strength (UTS) and the strain corresponding to the UTS with regards to the effects of yield strength and strain hardening rate. Micro-scale observations are made on various locations of the affected steel and based on the microstructure and material type, welding procedures and post-welding conditions, the mechanical properties are rationalized. Microhardness profiles have also been obtained to justify the microstructure at various distances from weld.

2. Test specimens

2.1. Fabrication and welding

A fabricated hybrid sample section is prepared consisting of different tube materials welded to plates (Fig. 1). Such section configuration has previously been proposed for high load bearing capacity structural performance [7–9]. The proposed fabricated section consists of square-shaped Mild steel plates strengthened by steel tubes at corners. From a practical point of view, depending on the expected load bearing capacity and ductility of the section, different strengths of tube materials can be adopted. The structural role of Mild steel plates is to increase the overall ductility and postpone the displacement corresponding to peak load, while the high strength tubes bear the applied load until failure. For the purposes of the current study, a 500 mm-long hybrid sample section is fabricated consisting of different tube materials at each corner.

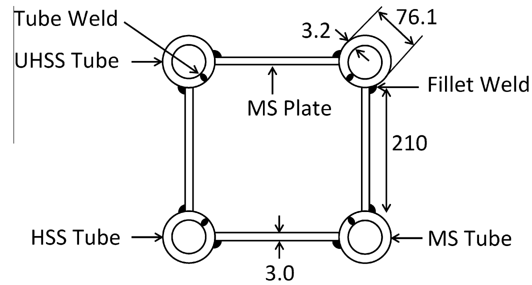

Fig. 1. Configuration of the 500 mm hybrid fabricated section (nominal dimensions in mm).

The configurations and dimensions are shown in Fig. 1. To connect the tubes and plates, fillet weld is used on the outer surface [28]. Gas tungsten arc welding (G.T.A.W.) is used which helps to maintain a consistent weld thickness throughout the length of section. The welding wire is 2.4 mm of the category AWS A5.9 ER2209 with a 0.2% proof stress and tensile strength equal to 560–620 MPa and 800–835 MPa, respectively. Weld metal elongation is around 30%. The speed of welding for all fabrications is in a range of 75–95 mm/min and the gas used is 99.9% argon gas. Using a welding amperage of 80 A and voltage of 10 V the heat input of welding is calculated and equal to 0.6 kJ/mm [29] which is considered to be a relatively low range of heat input. Throughout the welding process, argon gas was purged through welded tubes. All welding methods used are in compliance with AS/NZS1554.7:2006 [30].

2.2. Original tensile specimens

Three types of materials are chosen for tube specimens welded to one type of plate specimen. The tube materials consist of Mild steel, high strength steel (HSS) and ultra-high strength steel (UHSS) welded to a Mild steel plate. HSS material is manufactured through thermomechanical rolling (TM). The strength and toughness of the steel in this procedure is improved by combined hot rolling and accelerated cooling. This leads to a very fine grain structure which results in the toughening effect. The UHSS, however, is produced by direct quenching. In this process, the steel is quenched directly after controlled rolling and subsequently reaches ambient temperature. This results in a fine sub-structure of bainite which helps improve the strength of steel [31].

Conventional tension tests are conducted for each steel type following the guidelines of ASTM-E8M-04 [32] and AS1391 [33]. Water jet technique was chosen to cut coupons with the aim of having minimal effect on the mechanical properties of specimens throughout the cutting procedure. The coupon geometries sectioned from the plates and tubes are shown in Fig. 2a. The longitudinal specimens are extracted from tube samples with 90° angle from the tube weld as outlined in above standards. All quasi-static tests were performed in a Shimadzu tensile test machine with a load capacity of 300 kN applying a constant grip displacement rate of 0.3 mm/min. Data acquisition is followed using both strain-gauges and non-contact MTS laser extensometer (model LX500). Due to the occasional early failure in strain gauges, the laser extensometer provides the material results until failure. Average stress versus strain curves read from the laser extensometer data for the Mild steel plate and three different steel tubes are shown in Fig. 2b. Along with the strength increase in HSS and UHSS materials, the ductility exhibits a significant decrease. The average mechanical properties of three repeat tests for each kind of Mild steel plate, Mild steel tube, high strength steel tube and ultra-high strength steel tube are summarized in Table 1 along with the error values which is the percentage of the difference of each