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The effect of manufacturing process on the post-fire mechanical response of thin-walled ultra-high strength steel (Grade 1200) tubes

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ABSTRACT

This study aims to investigate the effect of manufacturing process on the post-fire mechanical response of Grade 1200 ultra-high strength steel (UHSS) tubes. To this end, the post-fire mechanical properties of “direct-quenched” UHSS (UHSS-DQ) standard tensile coupons are compared to those made of “quenched and tempered” UHSS material (UHSS-QT) with similar original room temperature stress-strain responses. Thus, to compare the post-fire compression behaviour of UHSS-DQ tubular stub columns with those made of UHSS-QT material, a finite element (FE) model is developed in ABAQUS FE software with precise material properties extracted from the results of the post-fire tensile coupon tests. Quasi-static compression tests are then conducted on UHSS-QT tubular stub columns cooled from different fire temperatures to room temperature to validate the FE analysis. Using the results of the tensile coupon tests and the FE analysis on UHSS stub columns, it is shown that the manufacturing process substantially affects the mechanical properties of UHSS stub columns under cooling phase of a fire.

1. Introduction

In recent years, due to the high strength to weight ratio of ultra-high strength structural steels (UHSS), researchers have attempted to investigate the potential of utilising this material in civil engineering construction [1–9]. As an example of the first practical applications of UHSS in the world, it can be referred to Nippon Steel & Sumitomo Metal Corporation, which applied these materials with 880 MPa yield strength for the circular steel pipe columns, welded built-up H beams used as columns, and four-side-welded-box-type columns [8]. In addition, during the past decade, innovative fabricated columns composed of ultra-high strength steel (UHSS) tubes with nominal yield strength of 1200 MPa have been proposed [4–6]. The superior performance of these innovative columns indicates the great potential of UHSS to be introduced as a structural material in production of sustainable structural members. However, there is lack of sufficient research addressing the behaviour of this type of steel under extreme structural loadings. Fire is one of the extreme hazards which can significantly damage the structure during its service life. After a structure is cooled from fire, the residual strength of the structural members should be accurately evaluated to decide whether or not it is possible to reuse them. To date, a number of researchers have addressed this issue by investigating the in-fire and post-fire mechanical behaviour of structural steels [10–24]. In recent years, the authors performed an extensive experimental study to investigate the post-fire tensile mechanical behaviour of Grade 1200 UHSS under fire [17–20]. The results showed a considerable reduction in residual strength of this material after being cooled from certain fire temperatures.

It has been reported in the literature that the mechanical behaviour of steel materials under fire conditions can be significantly affected by their manufacturing process technique [10,25]. The ultra-high strength of UHSS materials is basically obtained by fast quenching techniques either in water or oil. If the cooling rate of the quenching process is sufficiently high, with a proper chemical composition of the steel, “martensite” phase might be formed which is very strong but also brittle [26]. Considering the great ductility these steels lose after the quenching process, different methods are used by manufacturing companies to compensate for this loss. The most applied method used for manufacturing the UHSS materials is the traditional quenching and tempering technique (QT). During this process, the material is quenched rapidly in several stages either in water or oil. Thus, through a final heat treatment, the steel is reheated to moderate temperatures for a short time [27]. This process is called tempering, by which a certain level of the ductility of steel is recovered. In Ref. [27], Heidarpour et al. investigated the mechanical response of the quenched and tempered UHSS (i.e. UHSS-QT) at different elevated temperatures. They showed that the deterioration of the in-fire strength of UHSS-QT is greater than mild steel or high strength steel, which is due to the QT manufacturing

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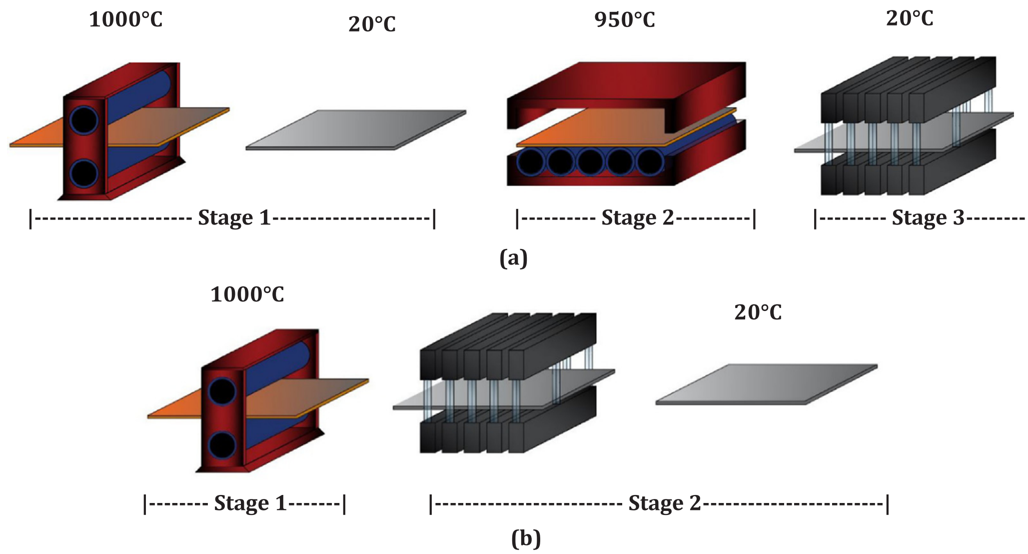

Fig. 1. Schematic illustration of the a) traditional quenching and tempering manufacturing process of plates compared to the b) direct quenching one.

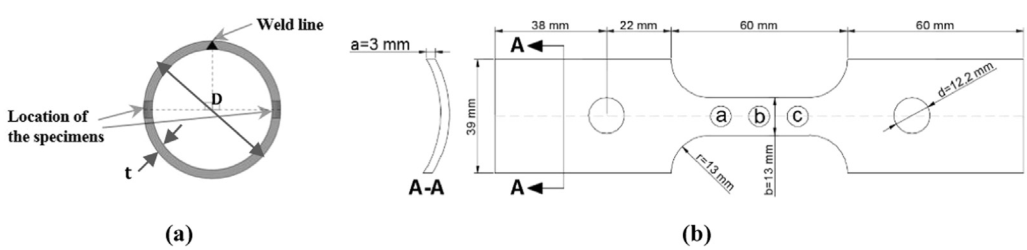

Fig. 2. a) Tube section and b) dimensions of test specimens.

process leading to a fundamentally different microstructure, with a different thermal stability. In recent years, a unique manufacturing process called the direct quenching technique (DQ) has been proposed by steel manufacturers [28]. Unlike the traditional QT technique where the material is quenched in several stages, in direct quenching method the material is quenched only in one stage. In Fig. 1, the two techniques are compared by schematic diagrams. It is important to note that the UHSS material tested in Refs. [17–20] by the authors was also manufactured by using the DQ technique.

In this study, it is aimed to understand the effect of manufacturing process on the post-fire compressive behaviour of the UHSS tubular stub columns. To achieve this, standard tensile coupon tests are first conducted on direct-quenched, and quenched and tempered UHSS specimens (labelled as UHSS-DQ and UHSS-QT, respectively) after cooling from elevated temperatures of up to 800 °C to room temperature. Comparing the results of these tests on UHSS-DQ and UHSS-QT tensile coupons, the effect of manufacturing process on the tensile stress-strain curves, and also the residual post-fire tensile strength and ductility of UHSS material is evaluated. Afterwards, using the precise material properties inputs obtained from the post-fire tensile tests, a finite element (FE) model is developed using the ABAQUS FE software [29] to compare the post-fire compressive behaviour of tubular stub columns made of UHSS-DQ and UHSS-QT materials. In order to validate the results of the FE model, quasi-static compression tests are conducted on UHSS-QT tubular stub columns cooled from different fire temperatures to the ambient state. After validation of the FE analysis, the effect of manufacturing process on the post-fire compressive behaviour of UHSS tubular stub columns is examined in which the load-displacement curves, and the strength and slenderness values of the two simulated stub columns are compared.

2. The effect of manufacturing process on the post-fire tensile behaviour of UHSS materials

2.1. Tensile coupon tests

The post-fire material properties of the UHSS-QT and UHSS-DQ materials studied in this paper, are measured by the results of tensile coupon tests. Using the waterjet cutting facility, the dog-bone specimens are extracted from two strips located at right angles (90°) to the tube weld line of the UHSS-QT (with $D = 38.1mm$ and $t = 1.8mm$) and UHSS-DQ tubes (with $D = 76.1mm$ and $t = 3.2mm$). The shape and dimensions of the coupons as well as their location in the UHSS tubes are indicated in Fig. 2. In addition, the chemical compositions of the two UHSS materials are shown in Table 1. It can be seen that despite the different manufacturing techniques of these UHSS materials, except for a slight difference between their carbon (C) contents, their chemical compositions are quite similar.

The tensile coupons taken from UHSS tubes had an outward curvature representing the residual stresses developed due to cold-forming process. In order to conduct the tensile coupon test, first, the specimens are mechanically flattened to be gripped inside the tensile loading machine. Then, they are heated up to elevated temperatures ranging from 470 °C to 800 °C inside a split furnace (model SF-16). Once the temperatures at the three thermocouples attached to points a, b and c on the specimen's gauge length (see Fig. 2) are stabilized (after

Table 1
The chemical composition of test materials (wt%).

Material	C	Si	Mn	P	S	Cr	Ni	Mo	B
UHSS-QT	0.20	0.8	1.7	0.025	0.015	1.5	1.0	0.5	0.005
UHSS-DQ	0.23	0.8	1.7	0.025	0.015	1.5	1.0	0.5	0.005