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Mechanical response of ultra-high strength (Grade 1200) steel under extreme cooling conditions

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HIGHLIGHTS

- The behaviour of ultra high strength steel (UHSS) cooled from fire is investigated.
- Mechanical properties of UHSS cooled with different cooling methods are studied.
- Cooling rate has a major effect on behaviour of UHSS cooled from high temperatures.
- Micrographs of UHSS cooled with different methods are consistent with the results.
- Mechanical behaviour of UHSS cooled to very low temperatures is studied.

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ABSTRACT

Ultra-high strength steels (UHSS) with nominal yield strength of up to 1200 MPa have many potential applications in engineering fields. However, due to inadequate knowledge on the mechanical behaviour of these materials under extreme loading conditions (e.g. severe temperature changes), their extent of application in civil construction has remained restricted. This paper characterises the mechanical properties of Grade 1200 UHSS under extreme cooling conditions, which is defined as cooling from fire temperatures with an extreme cooling rate or cooling from ambient state to sub-zero temperatures. In order to simulate the extreme cooling rate, UHSS standard dog-bone specimens are heated up to different fire temperatures and cooled to room temperature using water-quenching (WQ) technique. To evaluate the effect of extreme cooling rate on the post-fire mechanical response of the tested materials, the residual mechanical properties of water-quenched specimens are compared to the air-cooled (AC) ones for different fire temperature exposures. For simulation of extreme cooling temperatures, the test specimens are cooled to sub-zero temperatures using Liquid Nitrogen (LN) injection. The changes in the mechanical properties of the tested specimens are then quantified and discussed. In both set of experiments, the mechanical behaviour of UHSS under extreme cooling conditions is compared to the common structural steels. Microstructural evaluation of UHSS tested specimens are also presented using optical and scanning electron microscopy (SEM) techniques.

1. Introduction

In order to minimise the weight of the structures and optimise the labour and transportation costs, ultra-high strength structural steels (UHSS) have recently been introduced as a promising construction material for energy efficient structural members [1–4]. In order to safely use these materials in civil engineering applications, their mechanical behaviour under different loading scenarios must be accurately known [5–13]. Considering fire as a common extreme loading scenario that can significantly damage the structure, understanding the behaviour of any construction material during this hazard is necessary.

In recent years, to investigate the effect of different parameters including maximum fire temperature, creep strain, steel grade, etc., on the mechanical properties of Grade 1200 UHSS material during fire and after cooling to room temperature, extensive experimental tests have been performed [3,14–17]. With the main focus of these tests being on the residual mechanical properties of UHSS after

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cooling from fire to room temperature, it was concluded that the primary models proposed for the post-fire mechanical behaviour of mild steel [18,19] are not applicable for all grades of steel and for all temperature ranges. It was also shown that there is a considerable reduction in the residual strength of UHSS cooled from fire temperatures of above 450 °C [3,14,16]. In these studies, based on the thermodynamic stability of the phases present in UHSS, it was discussed that the mechanical behaviour of this material is very different in the two temperature regimes: the low temperature regime (up to ~700 °C), and the high temperature regime (above 700 °C). Based on the obtained results, it was observed that in low temperatures, while the changes in the post-fire residual strength of UHSS mostly depends on the maximum temperature reached, they are almost insensitive to the cooling rate. However, in the high temperature regime, it was predicted that the UHSS residual strength will be highly dependent on the cooling rate from elevated temperatures. The reason behind these conclusions were explained based on the phase diagrams, where in low temperatures, the identities of the phases present in the microstructures of the UHSS reached fire are not changed, and only the configuration and size of the microstructural grains are changed. However, due to formation of a new phase at high fire temperatures, depending on how fast the UHSS cools from fire, the residual strength of the material can significantly change. Some researchers in the field of civil engineering have so far investigated the effect of cooling rate on the residual mechanical properties of steel materials after being cooled form different temperature regimes [20,21]. Wang et al. [21] investigated the post-fire mechanical properties of high strength Q460 steel (HSS-Q460), including the yield strength, ultimate strength, uniform elongation and the elastic modulus, after exposure to fire temperatures of up to 900 °C. In their study, two cooling methods of natural air-cooling and water-quenching were considered. They concluded that while the cooling method does not have a considerable effect on the yield strength and elastic modulus of the HSS-Q460 specimens cooled from fire to room temperature, it has a major effect on the ultimate tensile strength and uniform elongation of the HSS-Q460. According to their results, the ultimate tensile strength of the HSS-Q460 specimen water-quenched from 900 °C to room temperature, is ~34% higher than the air-cooled one. However, the uniform elongation of the same water-quenched specimen is ~51% lower than the air-cooled one, meaning that the material becomes less ductile when cooled from fire with an extreme cooling rate. It was finally concluded that the effects of cooling method and even the maximum fire temperature on the residual mechanical properties of HSS-Q460 are only significant for temperatures above 700 °C. In 2016, Aziz et al. [20] performed a similar study and evaluated the effect of fire temperature and cooling method on residual mechanical properties of ASTM A572 steel (high strength low alloy steel with original yield strength of 450 MPa) after exposure to fire temperatures of up to 1000 °C. According to their results, regardless of the method of cooling, the A572 steel cooled from fire temperatures of up to 600 °C, recovers almost 100% of its original room temperature yield strength and ultimate tensile strength. However, this material loses ~40% of its yield strength when air-cooled from 800 °C to room temperature and ~25% when water-quenched. In addition, the ultimate strength of A572 steel, only reduces when air-cooled from temperatures above 600 °C and does not change when water-quenched from these temperatures. Similar to the results obtained in Ref. [21], the elastic modulus of A572 is fully reversible for all temperatures and both cooling methods. This result was quite expected as the elastic modulus of steel only depends on the temperature at which the material is tested [22].

From the literature, it is understood that the effect of cooling rate on residual mechanical behaviour of steel materials (especially high-strength steels) becomes significant after exposure to a certain temperature, which is the start of the high fire temperatures range. This paper mainly aims to investigate the effect of extreme cooling rate on post-fire mechanical behaviour of Grade 1200 ultra-high strength steel (UHSS) cooled from high fire temperatures. To this end, the UHSS standard dog-bone coupons extracted from cold-formed welded UHSS tubes are heated up to different fire temperatures and cooled to room temperature using water-quenching and their residual mechanical properties including stress-strain curves, strength and ductility are compared to those of naturally air-cooled samples obtained in Ref. [16]. Similar tests are carried out on Grade 800 high strength steel (HSS) and Grade 350 mild steel (MS) and the effect of steel grade is discussed. For a more clear justification of the obtained results, a microstructural evaluation is performed on the bulk microstructure of some air-cooled and water-quenched materials.

In line with the purpose of simulating the extreme cooling conditions, this paper also investigates the mechanical behaviour of UHSS (as the main purpose), HSS and MS (for comparison purposes) cooled from room temperature to harsh low temperatures, i.e. sub-zero temperatures. As a common application of this goal of the study, it can be referred to the safety of critical offshore structures such as oil platforms, which require steel capable of exhibiting high load capacity while maintain structural integrity at very low temperatures [23]. Although the general qualitative behaviour of these materials at sub-zero temperatures are quite predictable without performing experimental tests, quantifying the exact mechanical properties of them under harsh low temperatures is necessary for the design of offshore structures. It is noted that the design codes such as NORSOK standards only provide limited guidance on the requirements for steels at temperatures of down to −14 °C [24].

In this paper standard dog-bone UHSS, HSS and MS steels are cooled to sub-zero temperatures of as low as −80 °C and after conducting quasi-static tensile tests on them, their mechanical properties are measured and compared to the original room temperature values.

2. Experimental tests

2.1. Test specimens

The chemical compositions of the three grades of steel studied in this paper, i.e. Grade 1200 UHSS, Grade 800 HSS and Grade 350 MS, are presented in Table 1. To conduct quasi-static tensile

Table 1
The chemical compositions of tested materials (wt%).

Material	C	Si	Mn	P	S	Cr	Ni	Mo	B	Al
UHSS	0.230	0.800	1.700	0.025	0.015	1.500	1.000	0.500	0.005	
HSS	0.100	0.250	2.100	0.020	0.010					0.015
MS	0.230	0.400	1.350	0.040	0.050					