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Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure

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HIGHLIGHTS

- Test on Stainless steels S30408 and S31608 after exposure to elevated temperature.
- The influences of high temperature on yielding strength were remarkable.
- Cooling mode and exposure duration had slight effects on post-fire mechanical properties.
- Proposed predictive equations to estimate the post-heating mechanical properties.

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ABSTRACT

With excellent corrosion resistance and appearance, stainless steels have been widely used in building structures. Although fire accidents in steel buildings have happened occasionally in recent years, only few steel structures have collapsed entirely and most can still be used after reasonable assessment, repair, and reinforcement, thus reducing economic losses of fire accidents. The post-fire mechanical properties of stainless steels are the key parameters in the process of structural assessment after a fire. In this paper, the effects of exposure temperature, exposure duration, and cooling mode on mechanical properties of common stainless steels S30408 and S31608 were studied through experiments. The following conclusions were obtained: 1) when the exposure temperature is lower than 1000 °C, the post-fire ultimate tensile strength, rupture stress, and post-fracture elongation of S30408 and S31608 have little weakening; 2) When the temperature is lower than 1000 °C, the post-fire elasticity modulus of S30408 and S31608 increased to some extent, initially increasing then decreasing with exposure temperature increase, reaching the peak at 800 °C with an increase coefficient of about 50%. 3) The post-fire nominal yield strength of S30408 and S31608 decreased significantly, and when exposure temperature reached 1100 °C, the post-fire nominal yield strength of S30408 and S31608 decreased by about 30% and 20%, respectively. 4) Cooling mode (natural cooling in air and water cooling) and high temperature exposure duration (30 min and 180 min) had slight effects on the post-fire elasticity modulus, nominal yield strength, ultimate tensile strength, rupture stress, and post-fracture elongation of stainless steels.

1. Introduction

With a beautiful appearance, high corrosion resistance, easy maintenance, and a low maintenance cost throughout service life, stainless steel structures are widely used in civil engineering [1–2]. Stainless steel has been used in architectural structures since the early 20th century. In the beginning, it was mainly used in decoration engineering, building envelopes, and roof structures. With the development of design and construction technologies, stainless steel structures have become increasingly popular in the past two decades. Stainless steel is highly appreciated in landmark buildings for its excellent performance in structure, aesthetics, corrosion resistance, and durability [1–2].

Many studies have been conducted on the structural behavior and design methods of stainless steel structures at elevated temperature [3–6], but only a few studies have referred to their post-fire residual structural properties. Gardner presented the revised values for the heat transfer coefficient and emissivity of

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structural stainless steel members exposed to fire [3], and presented an overview and reappraisal of previous pertinent research on material properties of stainless steels at elevated temperature [4]. Uppfeldt [5], Tondini [6]. and Lopes [7] have studied the structural behavior and design method of stainless steel columns at elevated temperature. Although fire accidents of steel structures happened occasionally in recent years, only few steel structures have collapsed entirely, and most are still used after reasonable assessment, repair, and reinforcement, thus reducing economic losses of fire accidents. Therefore, the studies on the post-fire residual structural behavior of steel structures has become one of the research focuses in civil engineering.

In the early stages, extensive studies were conducted on the high-temperature behavior of structural steels of varying types and grades [8–16]. Design guides, such as British Standard (BS) 5950-8 [17] and EC3 [18], also provided recommendations. At present, increasing attention has been given to the post-fire mechanical properties of various structural steels such as hot-rolled mild steel [19–20], cold-formed steels [20–22], and high-strength structural steels [23–26]. Other studies have also focused on high-strength steel tie rods [27], reinforcing steel bars [28–29], pre-stressing steel wires [30], and concrete-filled steel hollow sections [31–32]. However, studies specifically focusing on the mechanical properties of stainless steels after fire exposure are not available in the existing literature. Given the considerable differences in the chemical compositions and manufacturing processes of common steels and stainless steels, directly applying conclusions regarding common steels to stainless steels is obviously inappropriate.

In this paper, residual mechanical properties of S30408 and S31608 after exposure to different high temperatures were discussed through experiments. Prediction formulas of elasticity modulus, ultimate strength, and elongation of S30408 and S31608 after exposure to different high temperatures were proposed. Research results will provide several theoretical references for reasonable assessment, repair, and reinforcement of stainless steels after fire accidents.

2. Experimental study

2.1. Specimens design

Stainless steels are divided into five types according to metallographic structure: austenite, austenite–ferrite (biphase), ferrite, martensite, and precipitation-hardening. Austenite stainless steel is usually used in building structures. Therefore, this paper studied the post-fire mechanical properties of two austenite stainless steels (S30408 and S31608). The stainless steels S30408 is similar to the 1.4301 in EN 10088-2; the stainless steels S31608 is similar to the 1.4401 in EN 10088-2 [33]. Based on standard tensile tests and chemical composition tests of three specimens without high temperature exposure, the mechanical properties of the studied materials were given in Tables 1 and 2.

Standard stainless steel specimens for static tension tests after high temperatures exposure were designed according to GB/T228-2002 [35]. A total of 93 specimens was conducted to study the influence of exposure temperature, exposure duration, and cooling mode. Each data in the following tables and figures was the mean value from three same specimen tests. Stainless steel specimens were cut from hot-rolled stainless steel sheets through cold working way.

2.2. Thermal treatment

Thermal treatments were conducted using a high-temperature heating box (Fig. 1). To study the effect of high temperatures, thermal treatment duration, and cooling mode on residual mechanical properties of stainless steels after exposure to high temperature, thirty thermal treatment cases as listed in Table 3 were designed Temperature–time curves are shown in Fig. 2, where *T* is the designed thermal treatment temperature of specimens; *t1* is the time for temperature to increase to T-50 °C; *t2* is the time for temperature to increase to T-10 °C; and *t3* is the time for temperature to increase to *T*.

The thermal treatment process is as follows: Specimens were first put into the high-temperature heating box; then these were heated at 50 °C lower than the target temperature at a rate of 20 °C/min for 15 min. Next, specimens were further heated at 10 °C lower than the target temperature for 10 min. Then the specimens were heated to the target temperature for 30 min or 180 min. Finally, specimens were taken out and cooled to room temperature by natural cooling in air or water cooling. In water cooling, spray flow and time were controlled (spray with a watering can, 200 ml for each group, stop spraying after no smog is produced). In each thermal treatment scheme, 10 temperatures (200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 °C) were considered.

2.3. Tensile test

According to GB/T228-2002 [27], static tension tests of stainless steel specimens after exposure to high temperature was conducted by the electronic universal material testing machine. In the initial stage, stress control was adopted and the loading rate was 5 MPa/s. In the late stage, displacement-speed controlled loading was used, and the speed was 2 mm/min.

3. Test phenomena

3.1. High temperature exposure phenomena

Surface states of S30408 specimens after high temperature exposure are shown in Fig. 3. With the increase of exposure temperature, the post-fire color of specimens deepened, especially higher than 400 °C. Specimens were dark cyan after high temperature exposure. Ash began to be produced on the specimen surface when reaching 1000 °C. By comparing surface states of high temperature exposure Case-1 to Case-10 (Fig. 3(a)) and high temperature exposure Case-11 to Case-20 (Fig. 3(b)), specimens with longer high temperature exposure duration were darker and produced more ashes after reaching 1000 °C. By comparing surface states of high temperature exposure Case-1 to Case-10 (Fig. 3(a)) and high temperature exposure Case-21 to Case-30 (Fig. 3(c)),

Table 1
Mechanical properties of the studied materials.

	Tested values		Standard values [34]	
	S30408	S31608	S30408	S31608
Elasticity modulus (GPa)	195.7	189.7	193	193
Ultimate tensile strength (MPa)	658.7	574.0	515	515
Nominal yield strength (MPa)	277.0	258.3	205	205