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Post-fire mechanical and corrosion properties of duplex stainless steel: Comparison with ordinary reinforcing-bar steel

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HIGHLIGHTS

- Spinodal decomposition (SP) of duplex stainless steel (DSS) causes strengthening.
- After SP, DSS is still as ductile as the unannealed rebar steel (RS).
- After SP, DSS is still more corrosion resistant than the unannealed RS.
- Rebar corrosion problem is small for DSS after a short fire under 500 °C.

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ABSTRACT

This paper is a preliminary study on the merits of using duplex stainless steel (DSS) as concrete reinforcements. It looks into the post-fire mechanical and corrosion properties of the wrought DSS 2205 after annealing at 500 °C, and compare them with those of an ordinary rebar steel. Spinodal decomposition of the ferrite phase strengthens and embrittles the 2205 DSS. For the rebar steel, however, softening occurs. Even after the 2205 DSS is exposed to 500 °C for 1 week, its ductility as indicated by fracture strain is still comparable to that of the unannealed rebar steel. The present data show that after short-term exposure to temperatures under 500 °C, the ductility and retention of strength of the 2205 DSS are better than those of the the rebar steel. The corrosion performance of the 2205 DSS, both in 3.5% NaCl and in 3.5% NaCl + $Ca(OH)_2$, is also better than that of the unannealed rebar steel even if the former is exposed to 500 °C for 1 week.

1. Introduction

Concrete and steel rebars are considered a perfect match because the former provides an alkaline environment in which the latter can spontaneously passivate, while the latter will act as reinforcements under tensile loads [1]. However, steel rebars may still get corroded in the presence of aggressive species like chloride ions or when the alkalinity of the concrete is compromised because of carbonation [1]. Rebar corrosion may lead to cracking of the surrounding concrete [2], reduced bonding strength between the rebars and the concrete [3], and loss of ductility and strength of the rebars [4].

While extensive research efforts have been expended on rebar corrosion, a simple way out is to use stainless steels as concrete rebars, which has been demonstrated to be economically viable, as the higher initial investment will be offset by less maintenance work and repair [5], and longer services of structures [6]. Stainless steels have actually been specifically marketed as rebars, such as the Stainbars from Ancon®. While austenitic stainless steels (AusSSs) are popular choices as rebars, the ferritic grades and the duplex grades are also widely used. Besides being used as rebars, stainless steels have also been frequently adopted as structural components by the construction industry [7].

Besides corrosion, the influences of high-temperature exposure on rebars have received a great deal of attention. This is because the load-bearing capacity and corrosion resistance of stainless steels may be significantly altered after a fire. If the load-bearing capability of the stainless steel rebars/components is substantially reduced, then the integrity of the structure may be impacted. Also, if the corrosion resistance of the rebars is greatly degraded, then the long-term usability of the structure must be properly assessed.

There are mainly two branches of research on the effects of high-temperature exposure on steels and stainless steels. One

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branch of research looks at their mechanical behaviours *during* high-temperature exposure [8–12]. For stainless steels, Gardner et al. [8,9] have done systematic and extensive work, and the overall conclusion is that the durability of concrete structures and their fire resistance are better when they are reinforced with stainless steels. The other branch of research focuses on how the concrete reinforcements are affected mechanically *after* elevated-temperature exposure [13–21]. For the post-exposure studies, the majority of them are on structural steels and their welds [13–20], but not on stainless steels. This was one of the factors that prompted the present authors to look into the post-exposure mechanical and corrosion behaviours of the wrought duplex stainless steel (DSS), which is even less studied in this aspect than its austenitic and ferritic counterparts.

For the present paper, the discussion will be restricted to the temperature regime under 500 °C where DSSs undergo spinodal decomposition [22]. For higher temperatures, DSSs will go through another phase transformation route, i.e., formation of intermetallics (chiefly the sigma phase and the chi phase, with the former being dominant) [22]. The comparison between the DSS used in this paper with an ordinary rebar steel in the intermetallics-forming temperature range will be presented in a separate paper.

It must be emphasised that post-exposure studies of concrete reinforcements are important because they are an important part of the post-fire assessment of the integrity of concrete structures. Although many researchers have worked on post-exposure studies of structural steels in recent years, the attention to this topic is still far from enough, as stated by Atienza and Elices [17], let alone post-exposure studies on stainless steels. The present paper aims to address this issue and looks at the post-exposure mechanical and corrosion properties of a wrought DSS and how it compares with an ordinary steel rebar.

It has to be stressed that a complete understanding of the post-fire properties of a material can only be obtained when data of the material *before, during,* and *after* high-temperature exposure are available. Some of the post-exposure studies that have been cited in the present paper do not look at how the steels behave *during* thermal exposure, just like the present paper. Nonetheless, to be in line with the literature, the present authors have titled this paper using the term 'post-fire'.

Another issue that is worthy of mentioning is that the samples used in the present paper were annealed in a furnace without any concrete cover on them. In the case of concrete spalling, the reinforcing bars will be directly exposed to the fire. Thermal spalling of concrete can occur in the range of 170 °C and 280 °C due to moisture buildup and the resulting high pore pressure at a shallow depth below the fire-exposed surface [23]. Due to the more disconnected nature of the pores of high-performance concrete (HPC), this class of concrete is particularly vulnerable to explosive spalling, as the maximum pore pressure is higher and it exists at a shallower depth for HPC than for ordinary concrete. For HPC, explosive spalling may occur under the range of 300 °C–350 °C [24] (Ref. [25] states an even lower temperature limit, i.e., 200 °C).

2. Materials and experimental details

The designation of the wrought DSS used in this paper is 2205 whose nominal composition is shown in Table 1. The 2205 DSS samples were solution-treated at 1100 °C for 1 h and then quickly quenched into water. The compositions of the ferrite and austenite phases of the 2205 DSS were determined using the energy-dispersive spectroscopy (EDS) system of a Hitachi S-3400N, Type I scanning electron microscope (SEM) (Table. 2). For its carbon and nitrogen contents, they were determined using a carbon-sulphur anaylser and a nitrogen analyser, respectively. The total C and N contents were found to be 0.01 wt% and 0.16 wt%, respectively.

A few tensile tests were conducted on the 7MoPLUS DSS, with the aim of estimating how the 2205 DSS would behave after annealing at the low end of the spinodal temperature regime. The 7MoPLUS DSS was solution-treated as mentioned above. The nominal composition of 7MoPLUS and the compositions of its ferrite and austenite phases are shown Table 1 and Table 3, respectively. The C and N contents of 7MoPLUS were determined to be 0.04 wt% and 0.34 wt%, respectively.

Unlike the heavier elements like Cr and Mo, the contents of C and N of the ferrite and austenite phases of DSSs cannot be determined with certainty using SEM-EDS. Hence, the C and N contents of the ferrite and austenite phases of the two DSSs were only estimated.

For N, its partition coefficient is around 0.1 [22]. For the 2205 DSS, the content of N of its austenite phase is therefore estimated to be 0.144 wt% (=0.16% $\times$ 0.9), and that of its ferrite phase to be 0.016 wt%. For C, a *conservative* estimate is to assume that the austenite phase takes up all of it, as it is known that carbon partitions mainly to this phase [22]. So, the C content of the austenite of the 2205 DSS is estimated to be 0.01 wt%. For 7MoPLUS, the content of N of its austenite phase is estimated to be 0.306 wt%, and that of its ferrite phase to be 0.034 wt%. Again, C would be assumed to partition entirely to the austenite phase. Hence, the content of C of the austenite phase of 7MoPLUS would be 0.04 wt%.

Annealing treatments were done at 500 °C for 5 h and 1 week, with the view of assessing how thermal exposure would affect the tensile and corrosion properties of the 2205 DSS and the rebar steel. As will be presented below, when the rebar steel and the 2205 DSS are annealed at 500 °C, their changes in mechanical properties are monotonic with annealing time. Hence, for the more usual annealing times used in fire testing, i.e., 30, 60, 90, 120 and 180 min, the corresponding tensile curves of the 2205 DSS and the rebar steels are expected to fall between the 0 h and the 5 h curves. Because of the monotonicity of the tensile data and due to the limited availability of the 2205 DSS to the authors, it was decided to conduct annealing treatment at 5 h, so that the shorter time periods (i.e., t = 30, 60, 90, 120 and 180 min) would be well encompassed. If the 2205 DSS outperforms the rebar steel after an exposure time of 5 h, then the former would still be better for the afore-mentioned shorter times because of the monotonicity of their tensile behaviours with annealing time at a fixed temperature at and under 500 °C.

The tensile tests were conducted in duplicate or triplicate with an INSTRON 5567 tensile tester with a crosshead speed of 0.0009 mm/s. The size and dimensions of the cylindrical samples complied with the ASTM E 8 standard (for diameter: 0.25 in). It is pointed out here that the deformations of the samples were not measured with an extensometer. Mechanical properties such as yield strength and modulus of elasticity of the samples were determined from the engineering tensile curves that were obtained using the load-displacement data, and the consequences will be discussed in Section 3.2. Microhardness measurements were done with a Wilson VH3100 automated Vickers/Knoop hardness tester.

Potentiodynamic anodic polarisation tests were done with a VersaSTAT 3F potentiostat in 3.5% NaCl and 3.5% NaCl + $Ca(OH)_2$, respectively, with a sweep rate of 1 mV/s. For the latter solution, 2 g of $Ca(OH)_2$ were dissolved in one litre of 3.5% NaCl solution to study the effects of chloride ions in saturated concrete solution [26]. The former solution was used to assess the influence of chloride-induced corrosion, and the latter solution was used to check out how the corrosion properties of the steels would change in the presence of concrete pore solution. For each annealing condition, polarisation tests were repeated at least five times and the polarisation curves presented in this paper reflect the general trends of experimental results. Phase identification was done with a Rigaku MiniFlex 600 X-ray diffractometer (XRD) using CuK_{α} with a scan rate of 0.1°/s. Transmission electron microscopy (TEM) was used to reveal the microstructural changes caused by spinodal decomposition with a Jeol JEM-2100F TEM.

3. Results and discussions

3.1. Microstructural characterisation

Fig. 1a shows the microstructure of the 2205 DSS in its unannealed (as-solution-treated) state, whereas the microstructure of the rebar steel is shown in Fig. 1b. The unannealed 2205 DSS was composed of the austenite and ferrite phases only, as demonstrated by Fig. 1a and its XRD diffractogram (Fig. 2). In Fig. 2, it may be seen that the diffractogram of the 1-week-annealed sample

Table 1
Nominal compositions of the two DSSs (wt%). *: Max. value.

	Cr	Mo	Ni	Mn	Si	P	S	C	N
2205	21.0–23.0	2.5–3.5	4.5–6.5	2.00*	1.00*	0.030*	0.020*	0.030*	0.08–0.20
7MoPLUS	26.0–29.0	1.0–2.5	3.50–5.20	2.00*	0.60*	0.035*	0.010	0.030*	0.15–0.35