Mechanical properties of lean duplex stainless steel at post-fire condition

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Title Mechanical properties of lean duplex stainless steel at post-fire condition

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Abstract

This paper reports an experimental investigation of the mechanical properties of cold-formed lean duplex stainless steel after exposure to high temperatures up to 1000°C. The test specimens were extracted from rectangular and square hollow sections that were cold-rolled from flat plates of lean duplex stainless steel. The mechanical properties, Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter and strain at ultimate strength of lean duplex stainless steel, are reported. The residual mechanical properties of steel materials are compared with the predicted values calculated by the existing equations. It is shown that the existing equations cannot provide accurate predictions for the post-fire mechanical properties of lean duplex stainless steel materials. Thus, a unified equation is proposed to predict residual mechanical properties for lean duplex stainless steel specimens in post-fire conditions. A constitutive model is also proposed to predict the stress-strain relationship of the test specimens after exposure to high temperatures up to 1000°C. A reliability analysis was conducted for the proposed equation. The proposed equation compared favourably with the experimental results, and was found to be reliable for predicting lean duplex stainless steel mechanical properties after exposure to high temperatures.

Keywords Lean duplex; stainless steel; mechanical properties; post-fire; stress-strain curve.

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25 October 2017

Dear Professor Silvestre,

I wish to submit a revised paper entitled "Mechanical Properties of Lean Duplex Stainless Steel at Post-fire Condition" to be considered for publication in *Thin-Walled Structures*. All the reviewers' comments have been considered and addressed.

This paper presents a comprehensive experimental and theoretical study on lean duplex stainless steel material after exposed to high temperatures. The test specimens were extracted from cold-formed lean duplex stainless steel rectangular hollow sections (RHS). Lean duplex stainless steel is a relatively new material to be used as structural elements in construction industry. But it has gained increasing attention, as it has a high strength-to-cost ratio compared with other stainless steel material and better fire resistant properties compared with carbon steel. The investigation on their post-fire mechanical properties provides evidence in repair and reinforcement of stainless steel structures after fire hazards, and thus reduce economic losses of fire and improve sustainability of the built environment. We believe that this manuscript is appropriate for publication by *Thin-Walled Structures*, because it investigates mechanical properties of cold-formed thin-walled hollow sections after exposed to high temperatures. I believe it will be of great interest of the readers of *Thin-Walled Structures*.

I have no conflicts of interest to disclose. Please address all correspondence concerning this manuscript to me at Yuner.huang@ed.ac.uk.

Thank you for your consideration of this manuscript.

Sincerely,

Yuner Huang

Written explanation and changes (TWST_2017_587)

Journal: Thin-Walled Structures

Title of Paper: Mechanical properties of lean duplex stainless steel at post-fire condition

Authors: Yuner Huang and Ben Young

Ms. Ref. No.: TWST_2017_587

The authors appreciate the reviewers' useful comments. The reviewers' comments have been considered seriously and addressed accordingly below:

Reviewer #1

This paper describes an experimental study on the residual mechanical properties of lean duplex stainless steels following exposure to fire conditions. It includes the details of test specimens, test procedures and test results, followed by comparisons with available predictive equations for the residual mechanical properties. Finally it proposes new predictive equations. As stated by the authors post-fire mechanical properties are not available for lean duplex stainless steels, and thus this experimental study and its results are quite useful. This reviewer recommends acceptance of this paper for publication in TWS. However, it needs major revision before it can be accepted.

Authors' reply: Thank you very much for the recommendation for publication in *Thin-Walled Structures*. Major revisions have been made according to the reviewer's comments.

1. This paper has so many English mistakes throughout the paper. Authors must revise the paper by correcting all the English mistakes. Examples of mistakes are: hollow sections that cold-formed, equation compare well, eminent need, there is no available research, are remain unknown, steel at post-fire condition, after exposed to fire, increased in a constant rate, were took out, mainly base steel, past tense versus present tense, plural versus singular. These mistakes should not have been in the paper submitted to a Q1 journal

Authors' reply: The authors agree with the reviewer's comment. The paper has been checked carefully, and English mistakes have been corrected. The paper has also been proofread by a professional native speaker. Therefore, the English of the paper has been improved.

2. Page 4: what is external thermal coupon?

Authors' reply: This is a typo error. The word "external thermal coupon" has been changed to *"external thermal couple"*.

3. Only two hollow sections were considered. Why only 3 temperatures were considered for L2 section? Are these limited test results adequate to develop a single equation for the residual mechanical properties of all the RHS and SHS sections?

Authors' reply: The reviewer has a very good point in querying why only 3 temperatures (300, 500 and 700 C) were considered for the L2 section. In fact, 9 temperatures (200, 300, 400, 500, 600, 700, 800, 900 and 1000 C) were considered for the L1 section, and it was found that there was a sudden change in energy absorption (Fig. 10), 0.2% proof stress (Fig. 13) and elongation at fracture (Fig. 15) at 600 C, whereas there was no significant change in Young's modulus (Fig. 12) and ultimate strength (Fig. 14). Therefore, it was decided to focus on 3 temperatures (300, 500 and 700 C) for the L2 section.
Furthermore, the main objective of this study was to investigate the post-fire behaviour of lean duplex stainless steel material instead of looking into the cold-forming effect of hollow sections. Therefore, lean duplex stainless steel coupons of two different thicknesses of 1.5mm and 2.5mm were used in the investigation. The coupon test specimens were extracted in the flat portions and away from the corners cold-work effects. Therefore, the two different hollow sections used in the investigation were not the major concern, hence the proposed single equation for the residual mechanical properties of lean duplex stainless steel material instead of the RHS and SHS sections.

4. Page 6: 0.5% proof stress, 1.5% proof stress, 2.0% proof stress - there are problems with these definitions

Authors' reply: The definition of these three proof stresses has been changed to the following sentence, in order to make the definition clear:
"The 0.5%, 1.5% and 2.0% proof stresses are defined as 0.5%, 1.5% and 2.0% strains with non-proportional vertical lines intersected with the stress-strain curves".
This definition is the same as in the British Standard (BS 5950: Part 8, 1998) and Chen and Young (2006).

[12] Chen J. and Young B. (2006). "Stress–strain curves for stainless steel at elevated temperatures." *Engineering Structure*, 28(2), pp. 229–39.

5. The use of "residual factors" does not look good. It should be residual mechanical property factor, isn't it?

Authors' reply: The authors agree with the reviewer. The words "residual factors" in the paper have been changed to *"residual mechanical property factor"*.

6. The paper includes a series of topics: the use of SEM, hardness tests, energy absorption, residual mechanical properties, effects of soak time, etc. The paper simply outlines the relevant procedures and the results as if a standardized procedure was used to get some results without much critical analyses/evaluations.

Authors' reply: The authors agree with the reviewer that more critical analyses and evaluations of the test procedures and the results should be included in the paper. The following sentences have been added in the revised paper, to explain the reasons of using SEM, and to correlate the post-fire mechanical properties with the change of microstructure in post-fire condition. There is relatively little research investigating the relationship between the post-fire mechanical properties and microstructure of steel materials, thus the paper involves critical analyses/evaluations:

Section 2.2.3: *"The change of microstructure and grain evolution in the lean duplex stainless steel material at different temperatures leads to the change of residual mechanical properties. Therefore, it is necessary to evaluate the microstructures of the specimens after fire exposure, in order to understand the characteristics of the tested stainless steel specimens after exposure to elevated temperatures."*

Section 2.3.1: *"The energy absorption of the tested specimens is subjected to a sudden increase by 33.5% from 600 ℃ to 700 ℃. It may be due to the change of microstructure, where ferrite start to transfer to austenite, as detailed in Section 2.3.3."*

Section 2.3.1: "The *hardness (HV30) of the specimens generally maintain the same, ranging from 235.5 to 280.0 kgf/mm^2, after exposure to elevated temperatures up to 1000°C. Martensite is a hard material that generally leadd to the change of hardness of steel materials. Martensite was not observed in the microstructure of the test specimens, as detailed in Section 2.3.3, thus the hardness of the test specimens after exposure to different temperatures generally remained the same."*

7. Why do the residual ultimate strength and elasticity modulus factors remain at 1 even after being exposed to 1000 deg C? Yield strength decreases noticeably with exposure temperature, why?

Authors' reply: The reviewer has a very good point in asking why the residual ultimate strength and elastic modulus factors remain at 1. The Young's modulus, yield strength and ultimate strength of carbon steel materials decreased significantly after being exposed to high temperatures beyond 500°C, as shown in previous studies [1-4] and Figures 12 – 14 of the paper. However, the same phenomenon, that the residual ultimate strength and elasticity modulus factors remained at 1 even after being exposed to 1000 °C, was also observed and reported in the reference [5] for austenitic stainless steel. Unfortunately, the paper [5] does not explain this phenomenon.

The authors believe that the phenomenon for austenitic stainless steel and lean duplex stainless steel is related to the change in microstructure at different temperature exposures to fire conditions. Figure 4 in the paper shows that the grain size and grain pattern of lean duplex stainless steel generally remained the same after the material was exposed to elevated temperature, and martensite was not generated during the cooling stage, which may have lead to the residual Young's modulus and ultimate strength being the same. It suggests that future study should be conducted with dedicated test methods in mineralogy to explain the change of post-fire mechanical properties.

[1] Qiang, X., Bijlaard, F., and Kolstein, H. (2012). "Post-fire mechanical properties of high strength structural steels S460 and S690." *Engineering Structures*, 35, 1-10.

[2] Qiang, X., Bijlaard, F., and Kolstein, H. (2013). "Post-fire performance of very high strength steel S960." *Journal of Constructional Steel Research*, 80, 235-242.

[3] Tao, Z., Wang, X-Q., and Uy, B. (2013). "Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures." *Journal of Materials in Civil Engineering*, ASCE, 25(9), 1306-1316.

[4] Gunalan, S. and Mahendran, M. (2014). "Experimental investigation of post-fire mechanical properties of cold-formed steels." *Thin-Walled Structures*, 84, 241-254.

[5] Wang, X. -Q., Tao, Z., Song, T. -Y., and Han, L. -H. (2013). "Mechanical properties of austenitic stainless steel after exposure to fire." *Research and Applications in Structural Engineering, Mechanics and Computation: Proceedings of the Fifth International Conference on Structural Engineering, Mechanics and Computation*, Cape Town, South Africa, 1483-1488.

8. Do we need a reliability analysis here?

Authors' reply: The authors think that a reliability analysis is needed in this study, in order to assess the reliability of the proposed design equations. The reliability index of the proposed design equation is larger than the target value of 2.50, which shows that the proposed design equation is reliable.

Reviewer #2

The present paper describes an experimental study of the post-fire material behaviour of lean duplex stainless steel, followed by the development of new strength reduction factors. This work fills the gap in the research area of post-fire behaviour of stainless steels. The paper is well structured and written. The paper can be accepted upon addressing the following comments:

Authors' reply: Thank you very much for the recommendation for publication. The reviewer's comments have been considered seriously and addressed accordingly.

1. How is the specimen expansion measured during heating phase? Is it measured in the furnace or outside the furnace?

Authors' reply: The specimen expansion is measured with a high temperature extensometer, and it is measured in the furnace. The following sentence has been modified to explain the measurement of thermal expansion in Section 2.2.1:
"... a calibrated high temperature extensometer of 25 mm gauge length with the range limitation of ± 2.5 mm was mounted onto the specimens to measure their thermal expansion (longitudinal strain) in the furnace."

2. Why the thermal expansion at higher temperature is sometimes even smaller than that at lower temperature, as shown in Table 1 and Fig. 11? For example, the thermal expansion is 0.71% when the specimen is heated to 200°C, while it's only 0.29% when the specimen is heated to 300°C.

Authors' reply: The reviewer has a good point. First, as described in Section 2.2.1, "the air temperatures in the furnace increased in a constant rate of 20 °C/min". The specimen temperature may not be fully stabilized and become homogeneously throughout the section when the heating time is relatively short, in particular for a lower temperature range at 200°C and 300°C. Second, it is observed from Figure 11 that the thermal elongation of the test specimens at different temperature generally follow the same trend. Third, we conducted the test carefully and obtained these results, and the authors reported the measured values in the paper.

3. The strain at ultimate strength and energy absorption increase with temperature greater than 600°C, but a sudden drop is then observed at 1000 °C. Any reason for this phenomenon?

Authors' reply: The authors believe that this phenomenon is due to the change of microstructure at different temperatures. But the detailed explanation on this phenomenon is still an open question. Currently, there is a knowledge gap in understanding the reasons for the change of strain at ultimate strength and energy absorption of steel materials in the post-fire condition. This study provides the first set of test results in lean duplex stainless steel, but future interdisciplinary study is needed with dedicated test methods in mineralogy to explain the change of post-fire mechanical properties.

4. The stress-strain curves for soak time of 0, 20, 60 mins generally coincide with each other, while the ductility of the specimen for soak time of 180 mins is larger than the other three specimens. Any reason for this phenomenon? How does the soak time affect the material behaviour?

Authors' reply: The effect of soak time in post-fire mechanical properties is similar to the effect of annealing in steel manufacturing. Annealing is a heat treatment procedure wherein a material is heated to an elevated temperature for a specific period of time and then slowly cooled down. Such process involves change in microstructure and recrystallization, and it is carried out to relieve stresses and improve ductility. Therefore, the authors believe that the ductility of the test specimen for soak time of 180 mins is larger than the other three specimens due to the change of microstructure and recrystallization. The following sentence is added in Section 2.3.2 of the paper:
"The effect of soak time is similar to the annealing procedure, which is normally carried out to relieve stresses and improve ductility in steel manufacturing."

5. As indicated in Section 2.3.3, there is a transition from ferrite to austenite when the specimen is exposed to a high temperature (greater than 800°C). Does it mean that the lean duplex stainless steel may behave similarly to austenitic stainless steel after fire?

Authors' reply: The authors agree with the reviewer that the lean duplex stainless steel may behave similarly to austenitic stainless steel after fire. But the material was not completely transformed to austenitic stainless steel in this study, thus this remains an open question that requires further study.

Mechanical properties of lean duplex stainless steel at post-fire condition

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ABSTRACT

~~Experimental~~ This paper reports an experimental investigation ~~on~~ of the mechanical properties of cold-formed lean duplex stainless steel after ~~exposed~~ exposure to high temperatures up to 1000°C ~~is presented in this paper~~. The test specimens were extracted from rectangular and square hollow sections that were cold-rolled from flat plates of lean duplex stainless steel. The mechanical properties, ~~such as~~ Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter and strain at ultimate strength of lean duplex stainless steel, are ~~obtained~~reported. The residual mechanical properties of steel materials are compared with the predicted values calculated by the existing equations. It is shown that the existing equations cannot provide accurate predictions for the post-fire mechanical properties of lean duplex stainless steel materials. Thus, a unified ~~design~~ equation is proposed to predict residual mechanical properties for lean duplex stainless steel specimens ~~at~~ in post-fire conditions. A constitutive model is also proposed to predict the stress-strain relationship of the test specimens after ~~exposed~~ exposure to high temperatures up to 1000°C. ~~Reliability~~ A reliability analysis was conducted for the proposed ~~design~~ equation. ~~It is shown that the~~The proposed equation compared ~~well~~ favourably with the experimental results, and ~~it is~~was found to be reliable ~~to be used~~ for ~~prediction~~ predicting ~~of~~ lean duplex stainless steel mechanical properties after ~~exposed~~ exposure to high temperatures.

KEYWORDS: Lean duplex stainless steel, mechanical properties, post-fire, stress-strain curve

1. INTRODUCTION

Lean duplex stainless steel (EN 1.4162), which is a relatively new type of steel material, has been ~~increasingly~~ used increasingly in construction in recent years. It has a high strength-to-cost ratio compared with ~~the~~ other types of stainless steel materials, due to a low nickel (Ni) content of 1.5%, compared with over 5% in other duplex and austenitic stainless steel materials. It has an excellent corrosion resistance, which leads to ~~its~~ an aesthetic appearance, ease in future maintenance, and ~~a~~ long life cycle. Fire hazards are normally destructive for steel structures, as both stiffness and strength of steel materials decrease dramatically at elevated temperatures. Generally, stainless steel materials have a better fire resistance than carbon steel materials. The investigation ~~on~~ of their post-fire mechanical properties provides evidence ~~in~~ about the repair and reinforcement of stainless steel structures after exposure to fire hazards, ~~and thus~~which can reduce economic loss~~es~~ ~~of~~ due to fire and improve sustainability of the built environment. The post-fire mechanical properties of lean duplex stainless steel have not been reported in literature. Hence, there ~~is~~ was an eminent need to investigate the deterioration and residual mechanical properties of lean duplex stainless steel after ~~exposed~~ exposure to high temperatures.

Previous researchers have investigated residual mechanical property factors of steel materials after fire, including high strength structural steel of grade S460, S690 [1] and S960 [2], structural steel and reinforcing steel [3], cold-formed steel of grades G300, G500 and G550 [4], and austenitic stainless steel of grade EN 1.4301 [5]. However, there is no available research on post-fire mechanical properties of lean duplex stainless steel. Therefore, the effect of the high temperatures on the mechanical properties of lean duplex stainless steel materials ~~are~~ remain unknown to ~~the~~ engineers and researchers. On the other hand, numerous stress-strain models to predict the full stress-strain behavior for stainless steel material at room temperature have been proposed by previous researchers. The Ramberg-osgood equation [6] has been ~~widely~~ used widely for a rounded stress-strain curve, and several 2-stage models have been modified from the Ramberg-osgood equation [7 – 9] for a more accurate prediction for stainless steel materials. The two-stage model was ~~further~~ modified further to three-stage models [10 – 11]. Stress-strain models for austenitic and duplex stainless steel materials at elevated temperatures ~~were also~~have also been proposed by Chen and Young [12] and Huang and Young [13]. It should be noted that there is no ~~design~~ equation to predict stress-strain relationship of lean duplex stainless steel ~~at~~ in post-fire conditions.

~~Experimental~~ An experimental investigation ~~on~~ of the post-fire mechanical properties of lean duplex stainless steel ~~has been~~was conducted and is presented in this paper. A total of 17 lean duplex stainless steel specimens~~, have been~~ was tested. The residual mechanical property factors of the Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter, strain at the ultimate strength, hardness, and energy absorption ~~have been~~were obtained and are reported here. The lean duplex stainless steel specimens ~~are~~ were cooled down in the furnace from the specified elevated temperature to room temperature. The microstructure of the lean duplex stainless steel specimens before and after exposed to fire ~~has been~~was investigated using a scanning electron microscope (SEM). The residual mechanical properties of lean duplex stainless steel after ~~exposed~~ exposure to high temperatures ~~are~~ were compared with the predicted values calculated by the existing equations for other types of steel materials. It should be noted that lean duplex stainless steel ~~is~~ was not covered in the existing equations. It ~~is shown~~was found that the existing ~~design~~ equations generally are not capable of providing accurate predictions for lean duplex stainless steel. A set of new ~~design~~ equations ~~are~~ is proposed, therefore, to predict the post-fire mechanical properties. ~~Reliability~~ A reliability analysis ~~also~~ was performed to assess the reliability of the proposed equations.

2. EXPERIMENTAL INVESTIGATION

2.1 Test Specimen

The test specimens were extracted from a cold-formed lean duplex stainless steel rectangular hollow section (RHS) and square hollow section (SHS) with nominal dimensions (D×B×t) of 150×50×2.5 and 50×50×1.5, where D, B, t are respectively the depth, width and thickness, in millimeters, of the cross-sections~~, respectively~~. The coupons were taken from the center of the face at a 90° angle from the weld for all specimens;~~,~~ ~~and the~~this coupon dimension agrees with the Australian Standard (AS 1979) [14] and American Standard (ASTM 2002) [15] using a 6 mm wide coupon and a gauge length of 25 mm. The specimens were labeled such that the steel section, the temperatures to which ~~that~~ the specimens were exposed ~~to~~, and the soak time could be identified, as shown in Table 1. The first letter and the number indicates the steel section, where "L1" and "L2" represent~~s~~ sections 150×50×2.5 and 50×50×1.5, respectively. The number after "T" is the temperature that the specimen ~~is~~ was exposed to in degrees Celsius. The third letter "s" represents soak time. The number after "s" is the time for which the specimen ~~is~~ was exposed to a specified temperature in minutes. For example, the label "L1T600s20" represents a lean duplex stainless steel coupon specimen extracted from section 150×50×2.5 being exposed to 600 °C for 20 minutes. Specimens L1T24 and L2T24 ~~do~~ did not ~~have~~ undergo the heating and cooling process, but ~~be~~ were tested in tensile loading at ambient temperatures after being extracted from the sections.

2.2 Test Procedure

2.2.1 Heating and cooling

The specimens were first heated ~~up~~ to ~~a~~ specified elevated temperatures, and cooled down to room temperature. Tensile coupon tests are then conducted at room temperature, in order to obtain their post-fire mechanical properties. An MTS tensile testing machine equipped with an MTS high temperature furnace and Flex Test SE controller were used for the heating and cooling, as shown in Fig 1. The furnace ~~is~~ was able to generate elevated temperatures up to 1400 °C with an accuracy of 1 °C. There ~~are~~ were three heating elements located at the upper, middle and lower parts on each of the two sides of the furnace. Three internal thermal couples were installed to measure the air temperature, while an~~other~~ external thermal couple was attached at the mid-length of the coupon specimen to measure the specimen temperature, as shown in Fig 1(b). First~~ly~~, the upper end of the coupon specimens was gripped, and the lower end ~~of the specimens~~ was free to expand during the "heating and cooling" stage. Second~~ly~~, a calibrated high temperature extensometer of 25 mm gauge length with the ranged limitation of ± 2.5 mm was mounted onto the specimens to measure their thermal expansion (longitudinal strain) in the furnace. Third~~ly~~, the air temperatures in the furnace increased ~~in~~ at a constant rate of 20 °C/min, until the corresponding specimen temperature reached the target temperature. Fourth~~ly~~, the specimens were heated under the target temperatures for a period of time (soak time). The average specimen temperature during the soak time is summarized in Table 1 for each specimen. The soak time ~~is~~ was generally 20 mins, except that specimens L1T600s0, L1T600s60 and L1T600s180 were heated for 0 min, 60 mins and 180 mins, respectively, to investigate the influence of soak time for post-fire mechanical properties. After the soak time, the heating elements stopped generating heat. The specimens were left inside the chamber for cooling down until the specimen temperature ~~is~~ was below 150 °C, and then they ~~specimens~~ were ~~took~~ taken out from the chamber for further cooling down to a room temperature of around 24 °C.

2.2.2 Tensile coupon test

Tensile coupon tests for the specimens exposed to elevated temperature were conducted at ambient temperature (24°C). Strain gauges and an extensometer were used to measure the longitudinal tensile strain of the coupon specimens in the initial part and plastic range, respectively. Two linear strain gauges were attached at mid-length to the center of both faces of each coupon, while an extensometer of 25 mm gauge length was mounted onto the specimen with three-point contact knife edges, as shown in Fig 2. The loading machine was driven by displacement control of stroke during the tensile coupon tests. The loading process follows Huang and Young [16] for lean duplex stainless steel flat coupons. Tensile loading was applied to the specimens until fracture, so that the whole stress-strain curve ~~can~~ could be obtained. Static stress strain curves were used to determine the post-fire mechanical properties.

2.2.3 Scanning electron microscope

The change of microstructure and grain evolution in the lean duplex stainless steel material at different temperatures lead~~s~~ to ~~the~~ a change of residual mechanical properties. Therefore, it ~~is~~ was necessary to evaluate the microstructures of the specimens after fire exposure, in order to understand the characteristics of the tested stainless steel specimens after exposed to elevated temperatures. The HITACHI S-3400N scanning electron microscope in the Electron Microscope Unit of The University of Hong Kong was used, as shown in Fig 3. A sample of 6 mm width and 10 mm length was taken from the gauge length of each coupon specimen~~s~~ after ~~exposed~~ exposure to elevated temperatures. The samples were grounded with silicon carbide grinding papers from 240 to 1200 grit, and then polished with 1.0 µm and 0.5 µm diamond compounds. Then, the samples were electrolytically etched with a solution of perchloric acid (70%) and ethanol (100%) by 1:4. The samples were placed on the sample holders of the SEM for examination. The microstructure of lean duplex stainless steel of the scale of 20 µm are shown in Fig 4. The chemical compositions of several specimens after ~~exposed~~ exposure to different elevated temperatures ~~are~~ were obtained from the energy-dispersive X-ray (SEM EDX) spectrum, as shown in Table 2.

2.2.4 Hardness test

~~Hardness~~ The hardness test was also conducted at the ambient temperature (24°C) after tensile testing for the test specimens that ~~are~~ were cooled in the furnace, in order to investigate the hardness of lean duplex stainless steel after ~~exposed~~ exposure to different temperatures. The test method and procedure conformed to BS EN ISO 6507-1 [17] and ASTM E384-11[18]. The ESE WAY Hardness Tester was used for the Vickers hardness test (Fig 5). A square-based diamond pyramid indenter, with the angle between the opposite faces at the vertex equal~~s~~ to 136°, was used to apply an impact loading in this study. The location of the hardness measurement ~~is~~ was away from the necking region of each specimen, in order to avoid the influence of tensile stress in the plastic range. The loading-unloading procedure in the plastic range may have lead to an increased hardness value. A force equal to 30 kgf (294.2 N) was applied to the specimens for 10 seconds. Then the lengths of the two diagonals were measured under a microscope. The arithmetical mean of the two lengths was taken to determine the Vickers hardness value for each specimen, according to BS EN ISO 6507-4 [19]. The hardness values of the test specimens ~~were~~ are summarized in Table 1 and Fig 6 for lean duplex stainless steel.

2.3 Test Results

2.3.1 Effect of elevated temperatures

The post-fire static stress-strain relationships of the lean duplex stainless steel specimens are shown in Figs 7 – 9. ~~Post~~The post-fire mechanical properties of specimens exposed to temperature T, including Young's modulus (E_T), 0.2% proof stress (yield strength) ($f_{0.2,T}$), 0.5% proof stress ($f_{0.5,T}$), 1.5% proof stress ($f_{1.5,T}$), 2.0% proof stress ($f_{2.0,T}$), ultimate strength ($f_{u,T}$), strain at ultimate strength ($\varepsilon_{u,T}$), strain at fracture ($\varepsilon_{f,T}$) and Ramberg-Osgood parameter (n_T), ~~are~~ were obtained from the static stress-strain curves as summarized in Table 1. The post-fire Ramberg-Osgood parameter (n_T) ~~is~~ was calculated using $n_T = ln\ (0.01/0.2)\ /\ ln\ (f_{0.01,T}/f_{0.2,T})$, where $f_{0.01,T}$ is the 0.01% proof stress obtained from post-fire static stress-strain curve. The 0.2% proof stress ($f_{0.2,T}$) and 0.01% proof stress ($f_{0.01,T}$) are intersect points of the stress-strain curve and the proportional lines off-set by 0.2% and 0.01% strains, respectively. The 0.5% ($f_{0.5,T}$), 1.5% ($f_{1.5,T}$), and 2.0% ($f_{2.0,T}$) proof stresses are defined as 0.5%, 1.5% and 2.0% strains with non-proportional vertical lines intersected with the stress-strain curves. The energy absorptions for post-fire specimens were calculated by Eq. (1):

$$U_T = \int_0^{\varepsilon} f\, d\varepsilon \qquad (1)$$

where U_T is the total mechanical energy per unit volume absorbed by the material during the tensile testing after exposed to temperature T, f is stress and ε is strain. The energy absorption for each specimen is summarized in Table 1, and the relationship between energy absorption and specimen temperature is shown in Fig 10 for lean duplex stainless steel. The energy absorption of the tested specimens was~~is~~ subjected to a sudden increase by 33.5% from 600 °C to 700 °C. ~~It may be~~This may have been due to the change of microstructure, where ferrite started to transfer to austenite, as detailed in Section 2.3.3. The total thermal expansion during the heating process for the test specimens ~~was~~ is summarized in Table 1. The relationship between thermal expansion and specimen temperature of the specimens with thickness = 2.5 mm are plotted in Fig 11.

The r~~R~~esidual mechanical property factors of the test specimens, which are ratios of post-fire mechanical properties after ~~exposed~~ exposure to elevated temperature T over the mechanical properties at ambient temperature (E_T/E_o, $f_{0.2,T}/f_{0.2,o}$, $f_{u,T}/f_{u,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o), were plotted against the specimen temperatures, as shown in Figs 12 – 16. It ~~is shown~~can be seen that the Young's modulus (E_T) and ultimate strength ($f_{u,T}$) generally remained the same with different temperatures, while the other mechanical properties ~~vary~~ varied~~with temperatures~~. The 0.2% proof stress ($f_{0.2,T}$), 0.5% proof stress ($f_{0.5,T}$), 1.5% proof stress ($f_{1.5,T}$), 2.0% proof stress ($f_{2.0,T}$) generally decreased beyond 600°C with increasing specimen temperatures. The strain at ultimate strength ($\varepsilon_{u,T}$) ~~increases~~ increased with temperature when the specimen temperature ~~is~~ was higher than 600°C, but a sudden drop ~~is~~ was observed at 1000 °C. The hardness (HV30) of the specimens generally ~~maintain~~ remained the same, ranging from 235.5 to 280.0 kgf/mm^2, after ~~exposed~~ exposure to elevated temperatures up to 1000°C. Martensite is a hard material that generally leads to the change of hardness of steel materials. Martensite ~~is~~ was not observed in the microstructure of the test specimens, as detailed in Section 2.3.3, thus the hardness of the test specimens after ~~exposed~~ exposure to different temperatures generally ~~maintain~~ remained the same.

2.3.2 Effect of soak time

The research project also investigated the influence of soak time (heating time) on the post-fire mechanical properties. The stress-strain curves for lean duplex stainless steel coupon specimens with thickness of 2.5 mm exposed to 600°C for 0, 20, 60 and 180 mins are shown in Fig 9, and the mechanical properties are summarized in Table 1. Previous research~~es~~ [5, 20] ~~have~~ has shown that the soak time has negligible effect on post-fire mechanical properties for carbon steel and austenitic stainless steel. However, ~~it is shown~~ in this study it was found that the stress-strain curves for soak time of 0, 20, 60 mins generally coincided with each other, while the ductility of specimens for soak times of 180 ~~mins~~ minutes ~~is~~ were larger than for the other three specimens. The strain at ultimate strength ($\varepsilon_{u,T}$) and strain at fracture ($\varepsilon_{f,T}$) ~~increases~~ increased by 28% and 15% respectively for a soak time of 180 mins, ~~respectively,~~ as shown in Table 1. The effect of soak time is similar to the annealing procedure, which is normally carried out to relieve stresses and improve ductility in steel manufacturing.

2.3.3 Microstructure and chemical composition

The microstructure and chemical composition of lean duplex stainless steel specimens after ~~exposed~~ exposure to high temperatures ~~are~~ were examined using scanning electron microscopy analysis. The microstructure and chemical composition generally remained the same for specimens after ~~exposed~~ exposure to elevated temperatures up to 800°C, as shown in Fig 4 and Table 2. The specimens exhibited similar grain sizes and generally rounded grain shapes for various temperatures. The grains of darker colour are ferrite, and the grains of lighter colour are austenite. The content of ferrite (alpha-phase iron) and austenite (gamma-phase iron) ~~are~~ were roughly the same in the lean duplex stainless steel specimens after ~~exposed~~ exposure to high temperatures up to 800°C. The ferrite transited to austenite at high temperatures of around 900°C, and it ~~undergoes~~ underwent a phase transition from body-centred cubic (BCC) to face-centred cubic (FCC) [21]. The content of austenite ~~increases~~ increased beyond 800°C, as shown in Fig. 4.

3. EVALUATION OF EXISTING EQUATIONS

The ~~design~~ values predicted by design rules in the EC3 Part 1.2 [22] and previous research~~es~~ on post-fire mechanical properties ~~are~~ were compared with the test results. The thermal expansion predicted by the EC3 Part 1.2 [22] for austenitic stainless steel ~~is~~ was compared with the lean duplex stainless steel specimens in Fig 11. It should be noted that the design rule for the lean duplex stainless steel ~~is~~ was not available in EC3 Part 1.2 [22]. It ~~is~~ was shown that the equation is not suitable to be used for lean duplex stainless steel. The design rule generally provides a lower value of thermal expansion than the experimental results for lean duplex stainless steel.

The test results of residual mechanical property factors (E_T/E_o, $f_{0.2,T}/f_{0.2,o}$, $f_{u,T}/f_{u,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o) for lean duplex stainless steel were compared with the ~~design~~ values calculated by the existing equations [1-5], as shown in Figs 12 – 16. For lean duplex stainless steel, it ~~is shown~~was found that the equations proposed by Wang et al. [5] are generally capable of predicting residual mechanical property factors of Young's modulus (E_T/E_o) and ultimate strength ($f_{u,T}/f_{u,o}$) by taking residual mechanical property factor equals to 1. However, the other existing equations are not applicable for lean duplex stainless steel post-fire mechanical properties. Therefore, it is necessary to propose new ~~design~~ equations for lean duplex stainless steel residual mechanical property factors of $f_{0.2,T}/f_{0.2,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o.

4. PROPOSED DESIGN RULES

4.1 Residual Mechanical Property Factors

The design proposal consists of two parts, residual mechanical property factor (χ) and stress-strain model. It ~~is~~ can be observed from Fig 12 and Fig 14 that the residual mechanical property factors of Young's modulus (E_T/E_o) and ultimate strength ($f_{u,T}/f_{u,o}$) for lean duplex stainless steel can be taken as unity ($\chi = 1$). Existing equations have been reviewed to propose a suitable design rule for residual mechanical property factors in this study. Chen and Young [12] proposed a unifying equation as showed in Eq. (2) to predict the residual mechanical property factors at elevated temperatures. An equation, as shown in Eq. (3), that modified from Eq. (2) [12], is proposed to predict residual factors of different post-fire mechanical properties for both lean duplex stainless steel materials by changing the parameters of a, b, c and d. Compared with Eq. (2), the Eq. (3) used in this study is more flexible in predicting the value of residual mechanical property factors with temperature.

The proposed parameters for Eq. (3) to calculate residual mechanical property factors of lean duplex stainless steel are summarized in Table 3. The comparison of residual mechanical property factors obtained from the tests and those calculated from the proposed design rule are shown in Figs 12 – 16. It is shown that the proposed design rules are generally capable of providing accurate predictions for residual mechanical property factors of lean duplex stainless steel after ~~exposed~~ exposure to fire. Therefore, the ~~design~~ post fire mechanical properties can be obtained by multiplying the ~~design~~ residual factor (χ) with the mechanical properties obtained at room temperature.

$$\chi = a - \frac{(T-b)^n}{c} \tag{2}$$

$$\chi = a + \frac{c}{T}(T-d)^b \tag{3}$$

4.2 Reliability Analysis

The reliability of the proposed design rules to predict the residual mechanical property factors of lean duplex stainless steel after ~~exposed~~ exposure to fire was evaluated using reliability analysis, which is detailed in the Commentary of the ASCE [23]. However, the target reliability index (β) and the resistance factor (ϕ) for stainless steel material ~~property~~ properties under post-fire conditions are not specified by the design specifications. Therefore, the target reliability index of 2.50 for stainless steel members ~~is~~ was adopted in this study. If the reliability index is greater than or equal to 2.50, then the design rules are considered to be reliable. The resistance factors of the design rules were determined using Eq. 6.2-2 of the ASCE Specification [23]. The load combination of 1.2DL+1.6LL was used in calculating the resistance factors (ϕ) for the proposed equation for the residual mechanical property factor (χ), where DL is the dead load and LL is the live load. The statistical parameters M_m = 1.10, F_{ym} = 1.00, V_{ym} = 0.10 and V_F = 0.05, which are the mean values and coefficients of variation for material properties and fabrication factors for yield strength and Young's modulus in the Commentary of the ASCE Specification [23] were adopted for post-fire Young's modulus (E_T) and 0.2% proof stress ($f_{0.2,T}$). The statistical parameters M_m = 1.10, F_{um} = 1.00, V_{um} =

0.05 and V_F = 0.05 for ultimate strength in the commentary were adopted for post-fire ultimate strength, strain at ultimate strength ($\varepsilon_{u,T}$) and Ramberg-osgood parameter (n_T). The mean value (P_m) and coefficient of variation of tested-to-predicted load ratio (V_p) are shown in Table 4 for lean duplex stainless steel. The correction factor Eq. F1.1-3 in the North American Cold-formed Steel Specification AISI S100 [24] was used to account for the influence ~~by~~ of the ~~number~~ amount of data.

In this study, two sets of resistance factor (ϕ_0 and ϕ_1) and reliability index (β_0 and β_1) ~~are~~ were determined, as shown in Table 4. The resistance factor (ϕ_0) is calculated based on the reliability index (β_0) of 2.50. In other words, the value of ϕ_0 is the maximum resistance factor required to achieve the target reliability index (β_0). However, a slightly smaller resistance factor (ϕ_1) that rounded to integer or a decimal of 0.5 is recommended for practical use by engineers, as reported in Table 4. It is shown that the proposed design rules provide accurate predictions for post-fire mechanical properties of lean duplex stainless steel. The mean values of χ_t / χ_d range from 0.99 to 1.03 for various post-fire mechanical properties with the coefficient of variation (COV) of 0.026 to 0.179 for lean duplex stainless steel. The χ_t and χ_d are residual mechanical property factors obtained from the test results and those calculated from the proposed design rule, respectively. The resistance factors (ϕ_1) are recommended for lean duplex stainless steel Young's modulus, 0.2% proof stress, ultimate strength, strain at ultimate strength and Ramberg-osgood parameter, as shown in Table 4. The reliability indexes (β_1) corresponding to the recommended resistance factors (ϕ_1) are all larger than or equal to the target reliability of 2.50. Therefore, the proposed design rules are considered to be reliable with the recommended resistance factors. It is recommended that the resistance factor of Young's modulus, yield strength, ultimate strength, strain at ultimate strength and Ramberg-osgood parameter equal to 0.95, 0.90, 0.95, 0.90 and 0.80 for lean duplex stainless steel, respectively, in order to achieve the reliability index higher than the target value of 2.5.

4.3 Stress-strain Model

The~~ design~~ post~~-~~-fire mechanical properties, including Young's modulus (E_T), 0.2% proof stress ($f_{0.2,T}$), ultimate strength ($f_{u,T}$), Ramberg-Osgood parameter (n_T) and strain at ultimate strength ($\varepsilon_{u,T}$), are used to obtain the stress-strain relationship. The stress-strain curves of lean duplex stainless steel after exposed to fire have a round-house type non-linear behaviour without a plateau. Various existing stress-strain models for rounded stress-strain curves are reviewed and compared with the test results. Considering the accuracy and convenience in calculation procedure, the two-stage model [8] is adopted, except that the post fire mechanical properties (E_T, $f_{0.2,T}$, $f_{u,T}$, n_T, $\varepsilon_{u,T}$) calculated from the proposed design rule are used, as expressed by the stress-strain relationship in Table 3. Generally, the Rasmussen's model that used for ~~with design ~~post-fire mechanical properties are capable of providing accurate prediction for the full stress-strain curve. The comparison of stress-strain curves obtained from tests and calculated from~~ design~~ equations for the test specimens are shown in Figs 17 - 18. Therefore, it is recommended that the 2-stage stress-strain curve model [8] together with the proposed~~ design~~ equations for post-fire mechanical properties can be used for lean duplex stainless steel.

4.4 Relationship of Hardness Value and Ultimate Strength

Compared with the tensile coupon tests, the hardness test is much cheaper and easier to ~~be~~ conduct~~ed~~. It is a non-destructive testing technique, thus the structure does not need to be damaged to obtain the mechanical properties. The hardness value can be obtained quickly on-site after a structure is exposed to a fire hazard. The previous investigations [25, 26] have shown that the ultimate strength of a steel material~~s~~ is generally equal to three times ~~of ~~its Vickers hardness value (f_u = 3×HV). However, the previous research~~es~~ ~~are ~~has been based on carbon steel specimens, and the relationship between hardness value and ultimate strength for stainless steel after ~~exposed ~~exposure to elevated temperatures is not available. Therefore, the relationship between ultimate strength and hardness values of the lean duplex and ferritic stainless steel specimens after ~~exposed ~~exposure to 24 – 1000 °C is plotted in Fig 19. The test data of ferritic stainless steel material ~~is ~~were obtained by

Huang and Young [27]. It ~~is shown~~can be seen that the ultimate strength and hardness values exhibits a linear relationship, which can be expressed as Eq. (4) with the least square root value equal~~s~~ to 0.97, where $f_{u,d}$ is the predicted value of ultimate strength, and HV is the Vickers hardness value. The mean values of the test-to-design ratio ($f_{u,d}/f_{u,T}$) for lean duplex stainless steel are equal to 0.99 with a coefficient of variation (COV) of 0.040. Therefore, the equation is accurate and convergent for lean duplex stainless steel specimens after ~~exposed~~ exposure to 24 – 1000 °C. The test results and predicted values of ultimate strengths of lean duplex stainless steel materials are plotted in Fig 20. The Eq. (4) can be used to predict the ultimate strength of lean duplex and ferritic stainless steel structures after ~~exposed~~ exposure to elevated temperatures using the non-destructive hardness tests.

$$f_{u,d} = 3.4 \times \mathrm{HV} - 91.9 \tag{4}$$

5. CONCLUSIONS

An experimental investigation of post-fire mechanical properties of lean duplex stainless steel has been presented in this paper. The test specimens ~~are~~ were extracted from square and rectangular hollow sections of lean duplex stainless steel. The coupon specimens were heated and maintained at specified elevated temperatures up to 1000 °C for a certain soak time, and then cooled down to room temperature. Tensile coupon tests were conducted on the specimens after ~~exposed~~ exposure to high temperatures. Various post-fire mechanical properties, including the thermal expansion, Young's modulus, 0.2% proof stress (yield strength), ultimate strength, strain at ultimate strength, strain at fracture, Ramberg-osgood parameter, and energy absorption were obtained. Vickers hardness tests were conducted for post-fire specimens, and the linear relationship between Vickers hardness value and ultimate strength was obtained and reported. The Young's modulus, ultimate strength and hardness of lean duplex stainless steel specimens generally remained the same after ~~exposed~~ exposure to elevated temperatures. It ~~is~~ was shown that the soak time ~~has~~ had negligible effect on the material strength of the stainless steel specimens in this study. The test results were compared with

~~design~~ the predictions obtained from ~~in~~ previous investigations~~researches~~. It ~~is shown~~is~~was~~ found that the existing design rules ~~equations are~~ are ~~were~~ generally not applicable for lean duplex stainless steel post-fire mechanical properties, as the existing design rules were developed mainly base on carbon steel. New~~Design~~ equations are proposed for residual mechanical property factors and stress-strain relationships ~~at~~ in post-fire conditions ~~are proposed~~. The ~~design~~ values predicted from the new equations ~~are~~ were compared with the test results.~~, and i~~It is ~~is shown~~was found that the proposed design rules are capable of providing accurate predictions for the test specimens. Therefore, it is recommended that the proposed equations for ~~design proposal of~~ residual mechanical property factors and post-fire stress-strain relationship can be used for cold-formed lean duplex stainless steel after ~~exposed~~ exposure to high temperatures.

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NOTATION

The following symbols are used in this paper:

B = width of cross-section;

D = depth of cross-section;

E_o = initial Young's modulus at room temperature;

E_T = initial Young's modulus at temperature T ºC;

f = stress

$f_{0.2,o}$ = yield strength at room temperature;

$f_{0.2,T}$ = yield strength at temperature T ºC;

$f_{u,o}$ = ultimate strength at room temperature;

$f_{u,T}$ = ultimate strength at temperature T ºC;

$f_{0.01,T}$ = strength at 0.01% strain at temperature T ºC;

$f_{0.5,T}$ = strength at 0.5% strain at temperature T ºC;

$f_{1.5,T}$ = strength at 1.5% strain at temperature T ºC;

$f_{2.0,T}$ = strength at 2.0% strain at temperature T ºC;

n_o = Ramberg-Osgood parameter at room temperature;

n_T = Ramberg-Osgood parameter at elevated temperature T ºC;

T = temperature in ºC;

t = thickness;

U_T = total mechanical energy per unit volume absorbed by the material during tensile testing;

ε = strain;

$\varepsilon_{f,T}$ = tensile strain at fracture at temperature T ºC;

$\varepsilon_{u,o}$ = tensile strain at ultimate strength at room temperature; and

$\varepsilon_{u,T}$ = tensile strain at ultimate strength at temperature T ºC.

a = coefficient used in modified equations;

b = coefficient used in modified equations;

COV = coefficient of variation;

c = coefficient used in modified equations;

d = coefficient used in modified equations;

$E_{p,T}$ = initial modulus of elasticity at the onset of strain hardening

F_{um} = mean value of fabrication factor for ultimate strength;

F_{ym} = mean value of fabrication factor for yield strength and Young's modulus;

f_u = ultimate strength;

$f_{u,d}$ = ultimate strength predicted by Vickers hardness value;

HV = Vickers hardness value;

M_m = mean value of material factor;

m_T = parameter in stress-strain model;

N = coefficient used in Chen and Young (2006) equations;

P = parameter in the proposed stress-strain model;

P_m = mean value of tested-to-predicted load ratio;

V_F = coefficient of variation of fabrication factor;

V_p = coefficient of variation of tested-to-predicted load ratio;

V_{um} = coefficient of variation of material factor for ultimate strength;

V_{ym} = coefficient of variation of material factor for yield strength and Young's modulus;

β = reliability index;

β_0 = reliability index;

β_1 = reliability index;

χ = residual mechanical property factor;

χ_d = residual mechanical property factor calculated from proposed design rule;

χ_t = residual mechanical property factor obtained from test results;

$\varepsilon_{p,T}$ =strain at the onset of strain hardening;

ϕ = resistance factor;

ϕ_0 = resistance factor; and

ϕ_1 = resistance factor.

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TABLE 1. Post-fire mechanical properties of lean duplex stainless steel

Specimen	T (°C)	Thermal expansion (%)	E_T (GPa)	$f_{0.2,T}$ (MPa)	$f_{0.5,T}$ (MPa)	$f_{1.5,T}$ (MPa)	$f_{2.0,T}$ (MPa)	$f_{u,T}$ (MPa)	$\varepsilon_{u,T}$ (%)	$\varepsilon_{f,T}$ (%)	n_T	U_T (MPa)	HV30 (kgf/mm^2)
L1T24	24.0	---	208.8	648.1	676.2	748.1	753.0	805.4	21.7	33.4	7.1	251.3	260.0
L1T200s20	202.5	0.71	212.3	634.5	634.4	673.8	683.6	791.9	23.8	34.7	10.9	260.2	269.0
L1T300s20	304.1	0.29	216.3	632.4	632.2	668.7	679.1	781.1	20.5	34.1	11.8	252.8	277.0
L1T400s20	404.8	1.89	212.7	629.7	630.0	666.9	676.6	782.8	19.4	29.3	15.7	217.2	270.0
L1T500s20	505.9	2.50	214.5	638.2	637.4	659.9	673.3	802.3	18.7	33.5	11.5	253.1	271.0
L1T600s0	624.1	1.66	215.1	607.4	608.6	652.7	667.9	800.6	19.6	33.0	13.9	249.0	260.0
L1T600s20	604.6	5.3	209.8	616.2	616.8	668.3	681.3	800.2	19.9	33.2	12.7	251.7	275.0
L1T600s60	599.7	1.73	214.8	561.2	560.9	635.6	655.2	803.0	19.7	32.0	6.4	244.2	271.0
L1T600s180	594.1	0.90	215.2	538.9	549.5	640.8	658.2	793.3	28.4	39.1	4.7	299.4	264.0
L1T700s20	697.0	3.93	209.5	517.0	531.2	610.4	630.5	814.2	39.5	43.9	4.5	335.0	268.0
L1T800s20	795.0	4.06	217.3	509.6	526.1	613.9	633.7	851.2	39.5	44.6	3.7	346.4	265.0
L1T900s20	889.8	8.76	218.2	462.8	486.2	567.0	586.5	818.1	41.7	49.1	3.7	366.6	264.0
L1T1000s20	990.7	8.45	211.8	467.9	488.3	568.5	586.5	758.1	27.9	43.6	4.3	310.9	235.5
L2T24	24.0	---	198.7	682.4	666.5	748.8	753.7	828.1	20.2	30.6	6.4	243.2	280.0
L2T300s20	307.4	0.35	209.2	697.62	693.4	726.9	738.1	817.6	18.8	30.4	12.6	238.3	279.0
L2T500s20	509.1	0.70	212.8	703.84	694.5	731.7	742.7	855.9	19.0	30.9	9.4	251.6	274.0
L2T700s20	701.0	1.12	215.8	524.3	542.8	659.9	679.6	853.5	39.5	47.1	3.8	378.8	274.0

Note: L1 and L2 are extracted from sections 150×50×2.5 and 50×50×1.5, respectively.

TABLE 2. Chemical composition of lean duplex stainless steel specimens

Element	L200	L500	L900
C	1.89	2.30	4.57
Si	0.65	0.53	0.64
Cr	21.13	20.20	21.79
Mn	5.90	5.89	5.21
Fe	69.16	69.41	66.17
Ni	1.27	1.66	1.62

TABLE 3. Proposed post-fire mechanical properties for lean duplex stainless steel

Residual mechanical property factor $\chi = a + \frac{c}{T}(T-d)^b$	a	b	c	d	Temperature, T (°C)
$\frac{E_T}{E_o}$	1	0	0	0	$24 \le T \le 1000$
$\frac{f_{0.2,T}}{f_{0.2,o}}$	1	0	0	0	$24 \le T \le 500$
	1	1	-0.63	500	$500 < T \le 1000$
$\frac{f_{u,T}}{f_{u,o}}$	1	0	0	0	$24 \le T \le 1000$
$\frac{\varepsilon_{u,T}}{\varepsilon_{u,o}}$	1	2.5	-7.54E-06	24	$24 \le T \le 600$
	-4.1	2	8.50E-03	0	$600 < T \le 700$
	1.85	0	0	0	$700 < T \le 900$
	6.98	2	-5.70E-03	0	$900 < T \le 1000$
$\frac{n_T}{n_o}$	1	2.5	1.75E-04	24	$24 \le T \le 400$
	2.2	1.2	-1.03	400	$400 < T \le 800$
	0.5	2	2.86E-03	800	$800 < T \le 1000$

Stress-strain relationship ($24 \le T \le 1000$):

$$\varepsilon = \frac{f}{E_T} + 0.002\left(\frac{f}{f_{0.2,T}}\right)^{n_T} \quad \text{for} \quad f \le f_{0.2,T}$$

$$= \frac{f - f_{0.2,T}}{E_{0.2,T}} + \varepsilon_{u,T}\left(\frac{f - f_{0.2,T}}{f_{u,T} - f_{0.2,T}}\right)^{m_T} + 0.002 + \frac{f_{0.2,T}}{E_T} \quad \text{for} \quad f_{0.2,T} < f \le f_{u,T}$$

where $E_{0.2,T} = \frac{E_T}{1 + 0.002 n_T E_T / f_{0.2,T}}$, $m_T = 1 + 3.5 f_{0.2,T}/f_{u,T}$

TABLE 4. Comparison of residual factors obtained from test results with design values for lean duplex stainless steel

Specimen	T (°C)	χ_t					χ_d					$\frac{\chi_t}{\chi_d}$				
		E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T	E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T	E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T
L1T24	23.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
L1T200s20	202.5	1.02	0.98	0.98	1.09	1.54	1.00	1.00	1.00	0.98	1.37	1.02	0.98	0.98	1.11	1.13
L1T300s20	304.1	1.04	0.98	0.97	0.94	1.68	1.00	1.00	1.00	0.97	1.76	1.04	0.98	0.97	0.98	0.95
L1T400s20	404.8	1.02	0.97	0.97	0.89	2.22	1.00	1.00	1.00	0.95	2.18	1.02	0.97	0.97	0.94	1.02
L1T500s20	505.9	1.03	0.98	1.00	0.86	1.63	1.00	0.99	1.00	0.92	1.65	1.03	0.99	1.00	0.93	0.98
L1T600s0	624.1	1.03	0.94	0.99	---	---	1.00	0.88	1.00	---	---	1.03	1.07	0.99	---	---
L1T600s20	604.6	1.00	0.95	0.99	0.92	1.80	1.00	0.89	1.00	1.04	1.19	1.00	1.07	0.99	0.88	1.51
L1T600s60	599.7	1.03	0.87	1.00	---	---	1.00	0.90	1.00	---	---	1.03	0.97	1.00	---	---
L1T600s180	594.1	1.03	0.83	0.98	---	---	1.00	0.90	1.00	---	---	1.03	0.92	0.98	---	---
L1T700s20	697.0	1.00	0.80	1.01	1.82	0.64	1.00	0.82	1.00	1.82	0.83	1.00	0.97	1.01	1.00	0.77
L1T800s20	795.0	1.04	0.79	1.06	1.82	0.53	1.00	0.77	1.00	1.85	0.51	1.04	1.02	1.06	0.98	1.02
L1T900s20	889.8	1.04	0.71	1.02	1.92	0.52	1.00	0.73	1.00	1.85	0.53	1.04	0.98	1.02	1.04	0.99
L1T1000s20	990.7	1.01	0.72	0.94	1.28	0.61	1.00	0.69	1.00	1.33	0.60	1.01	1.05	0.94	0.96	1.00
L2T24	23.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
L2T300s20	307.4	1.05	1.02	0.99	0.93	1.98	1.00	1.00	1.00	0.97	1.77	1.05	1.02	0.99	0.96	1.12
L2T500s20	509.1	1.07	1.03	1.03	0.94	1.48	1.00	0.99	1.00	0.92	1.64	1.07	1.04	1.03	1.02	0.90
L2T700s20	701.0	1.09	0.77	1.03	1.96	0.60	1.00	0.82	1.00	1.85	0.82	1.09	0.94	1.03	1.06	0.74
											# of data	17	17	17	14	14
											Mean	1.03	1.00	1.00	0.99	1.01
											COV	0.024	0.042	0.027	0.058	0.179
											Resistance factor (ϕ_0)	0.95	0.91	0.96	0.93	0.81
											Reliability index (β_0)	2.50	2.50	2.50	2.50	2.50
											Resistance factor (ϕ_1)	0.95	0.90	0.95	0.90	0.80
											Reliability index (β_1)	2.50	2.56	2.51	2.63	2.52

Note: L1 and L2 are extracted from sections 150×50×2.5 and 50×50×1.5, respectively.

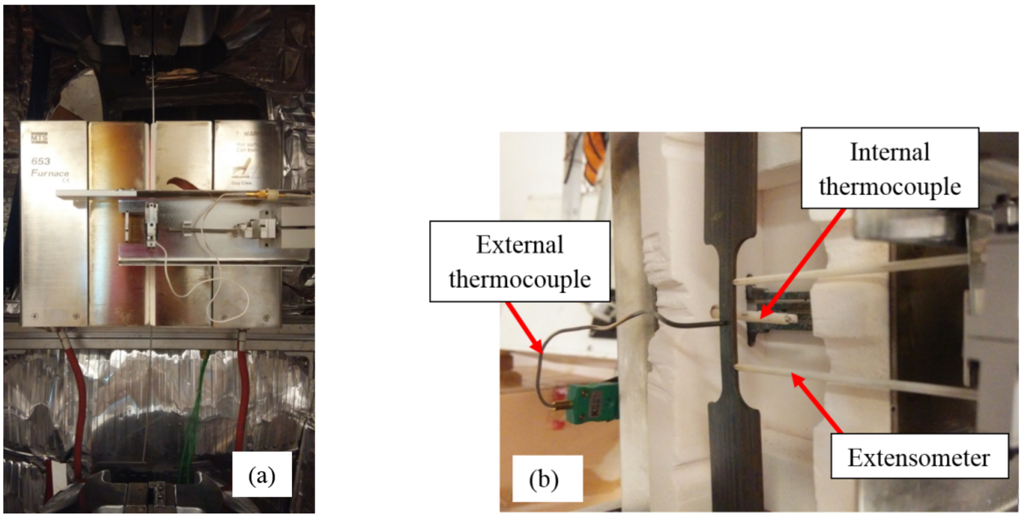


Fig. 1. (a) MTS high temperature furnace. (b) Test specimen in furnace.

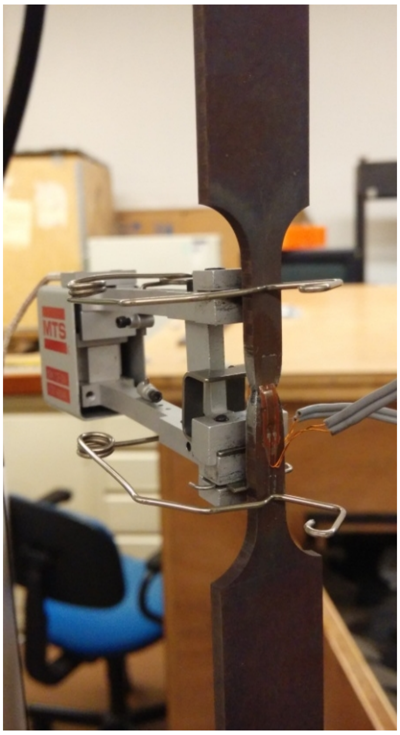


Fig. 2. Tensile coupon test

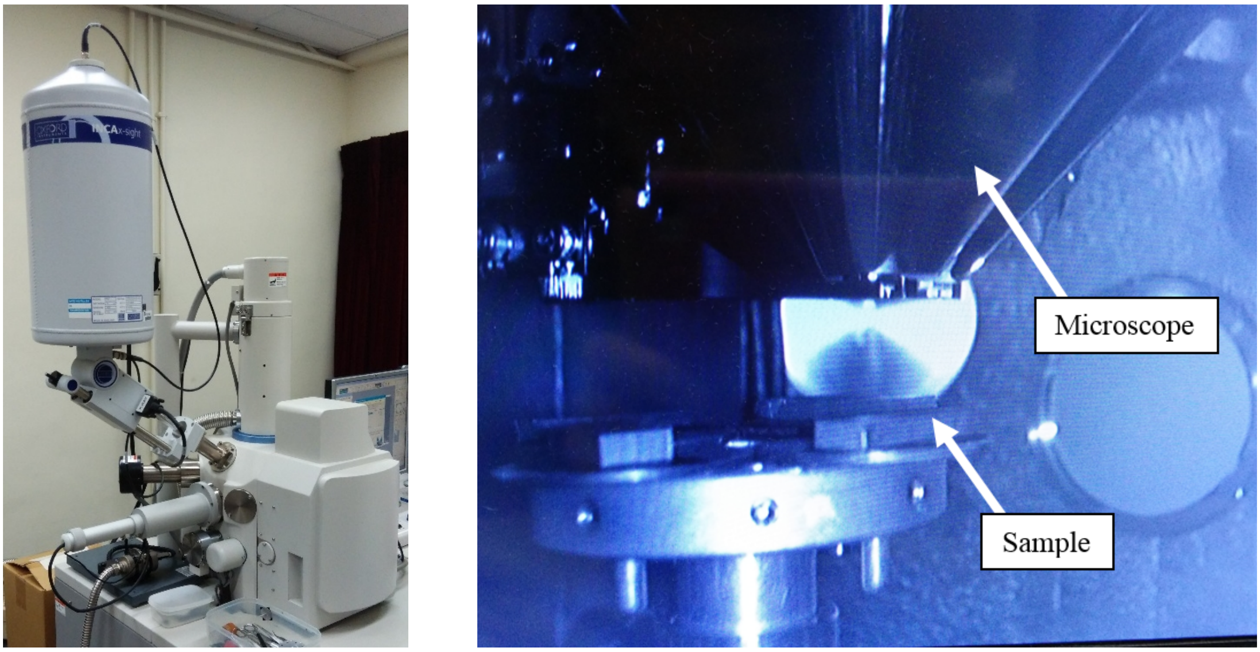


Fig. 3. Test setup for scanning electron microscopy analysis.

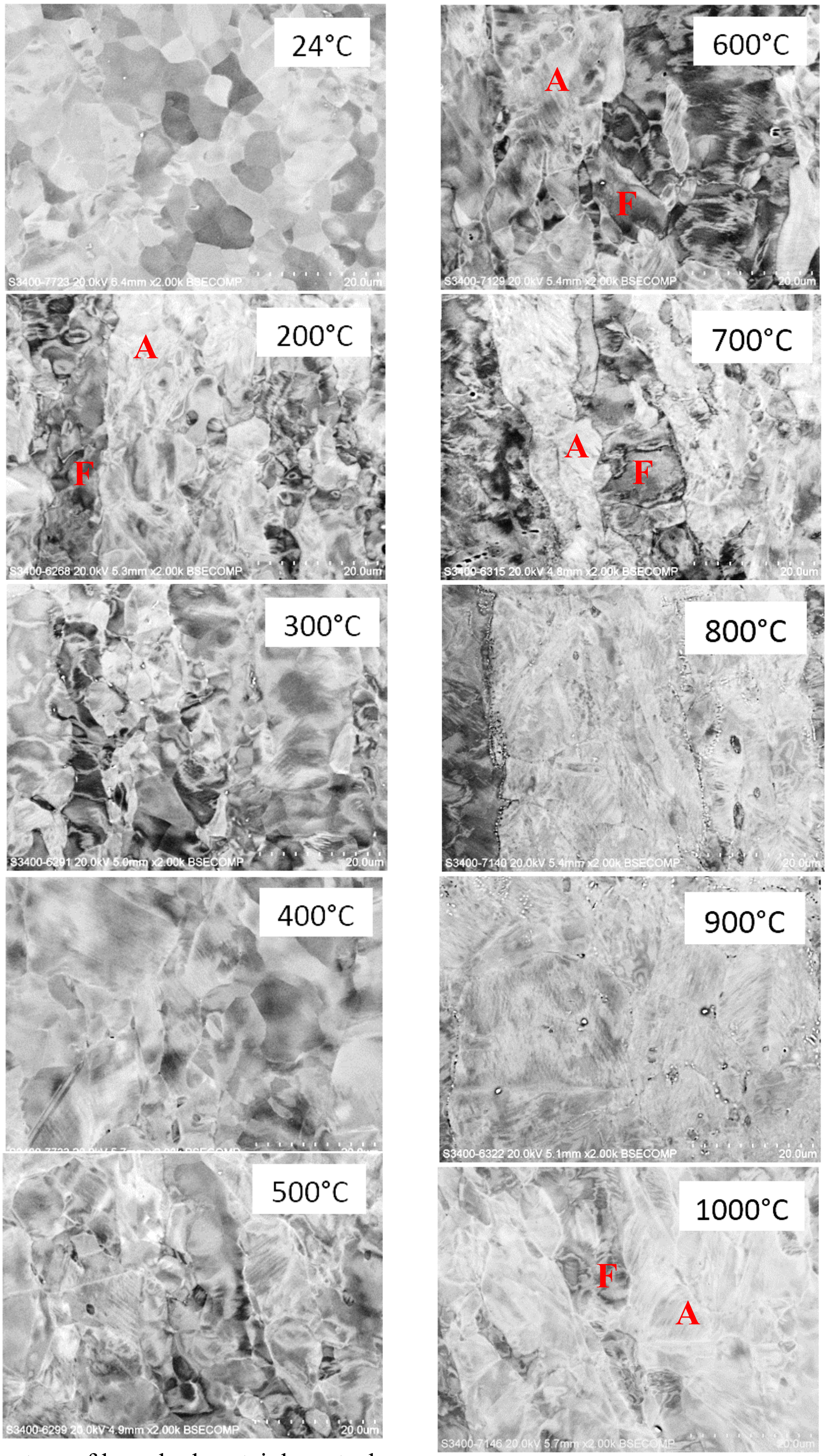
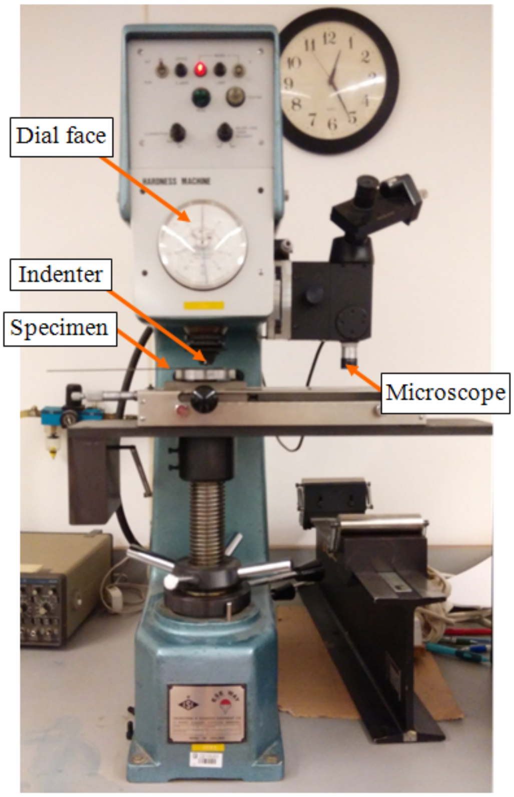
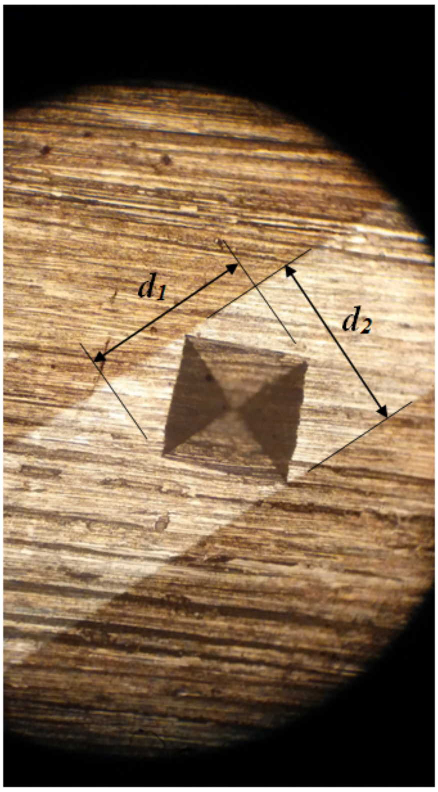


Fig. 4.
Microstructure of lean duplex stainless steel specimens after exposed to elevated temperature (A = Austenite, F = Ferrite).



(a)



(b)

Fig. 5. (a) Test setup of hardness test. (b) Indentation of test specimen in microscope.

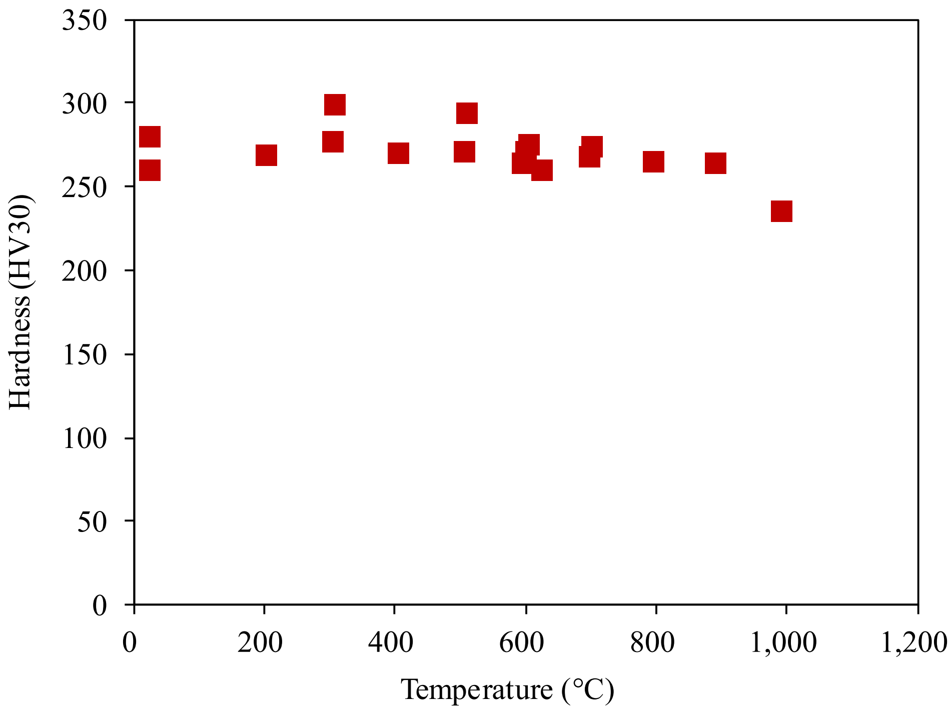


Fig. 6. Hardness of lean duplex stainless steel at different temperatures.

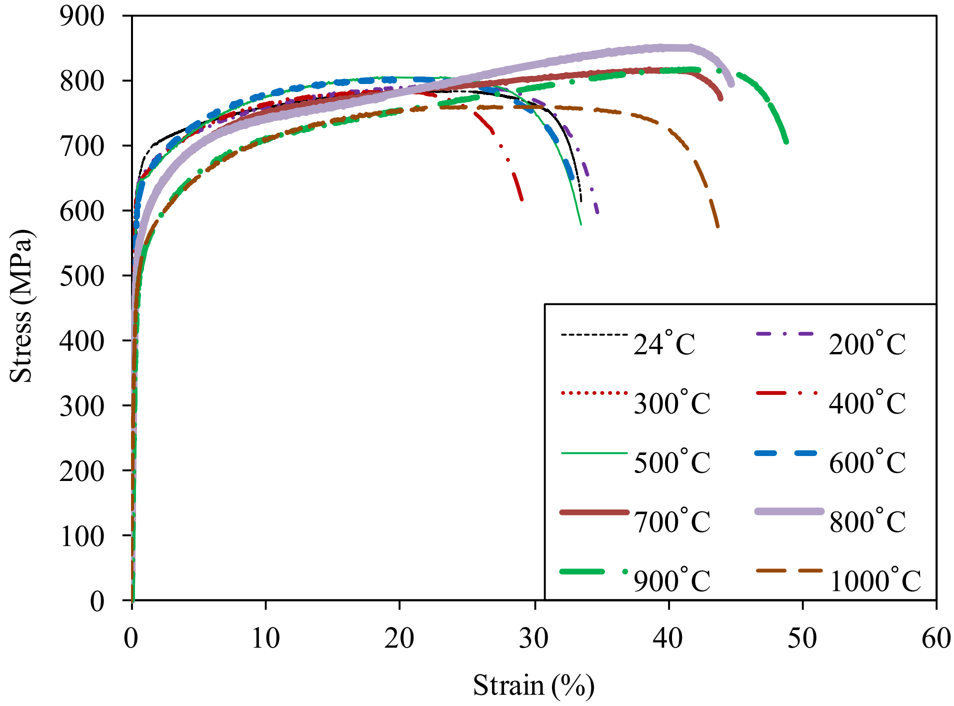


Fig. 7. Stress-strain curves of lean duplex stainless steel type “L1” at different temperatures.

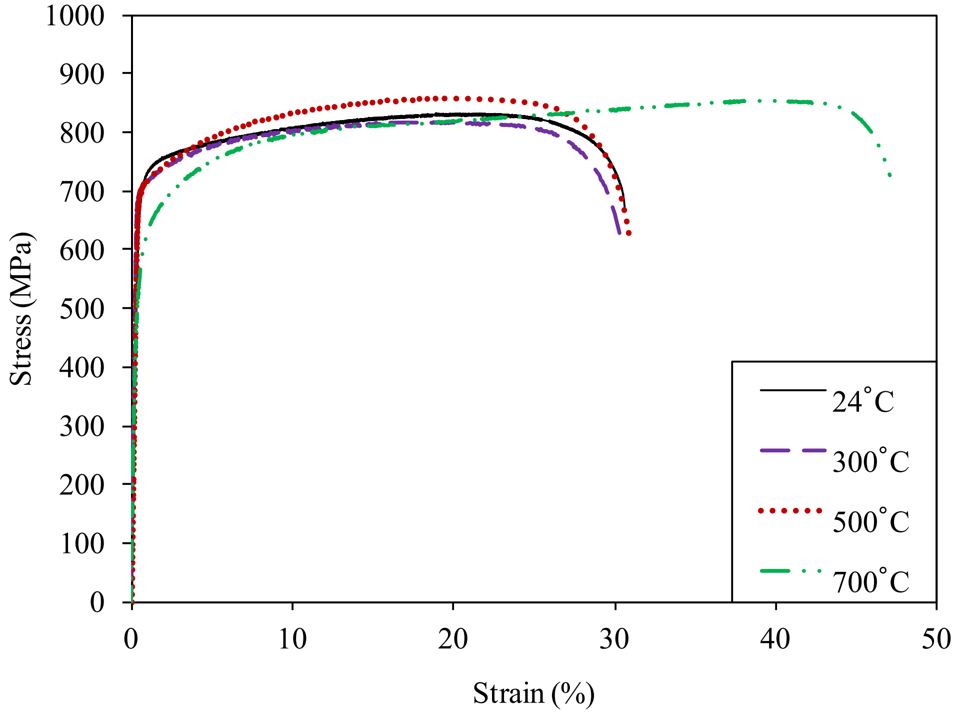


Fig. 8. Stress-strain curve of lean duplex stainless steel type “L2” at different temperatures.

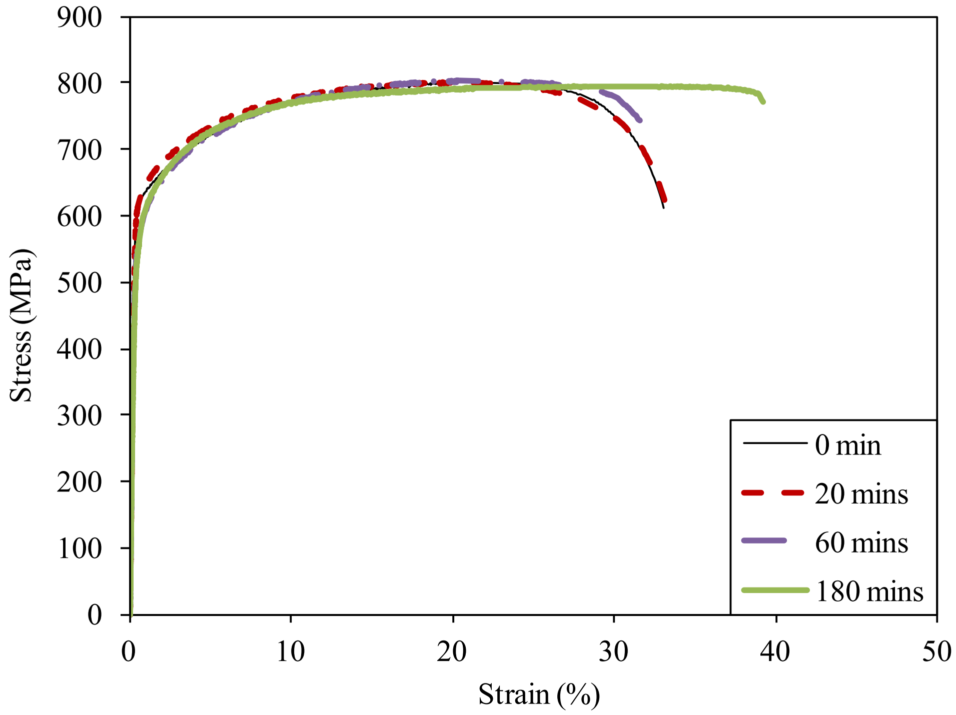


Fig. 9. Stress-strain curves of lean duplex stainless steel at 600 °C with different soak time.

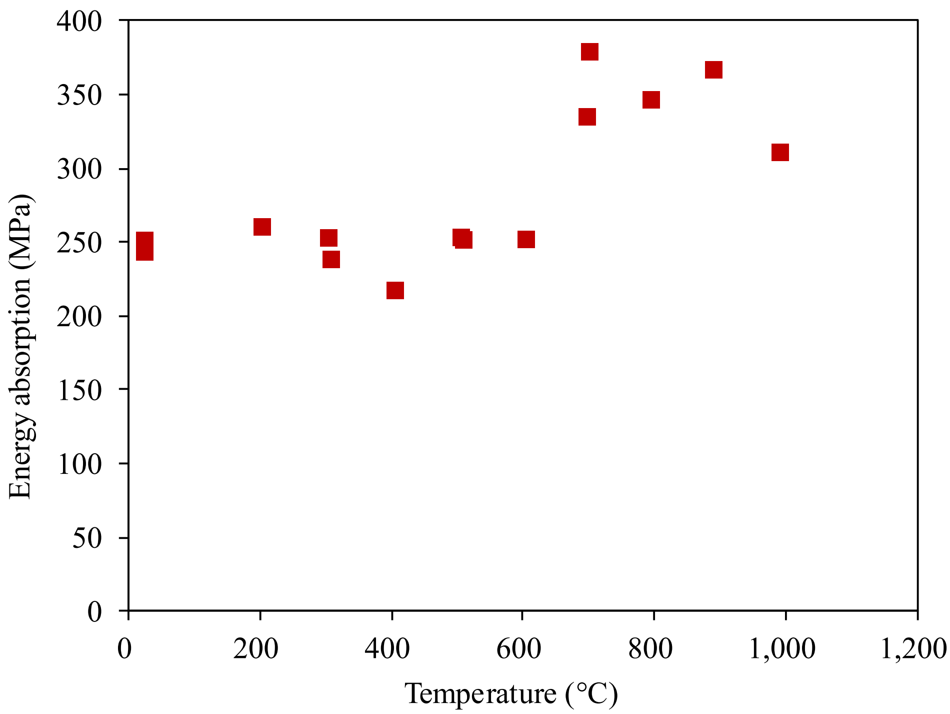


Fig. 10. Energy absorption of lean duplex stainless steel at different temperatures.

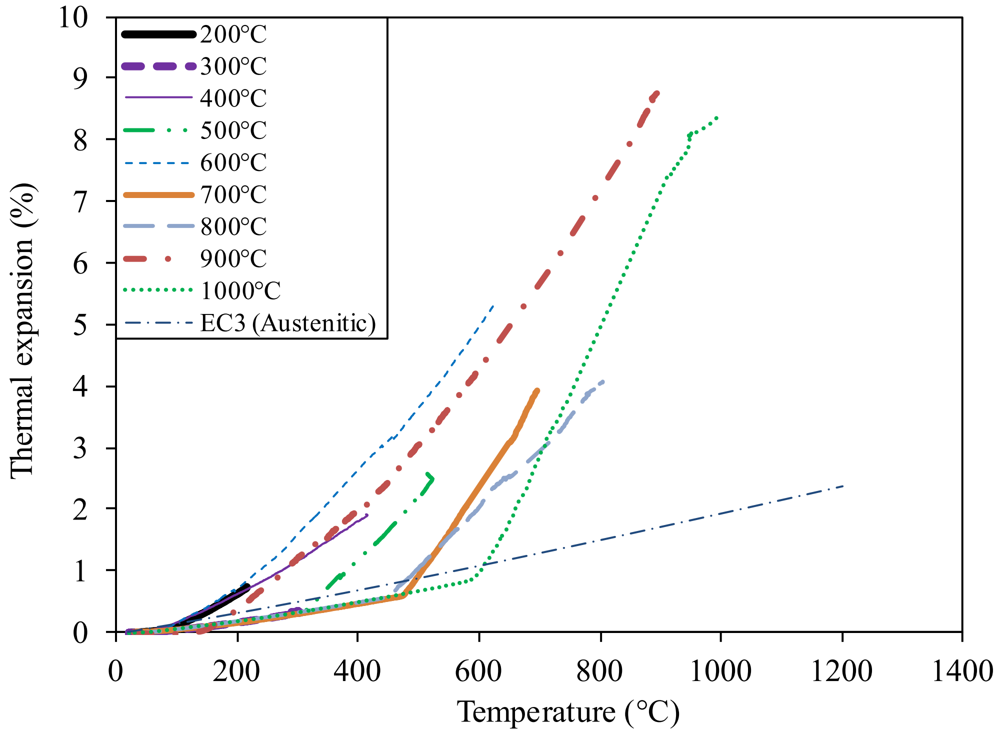


Fig. 11. Thermal elongation predicted by EC3 with lean duplex stainless steel test results.

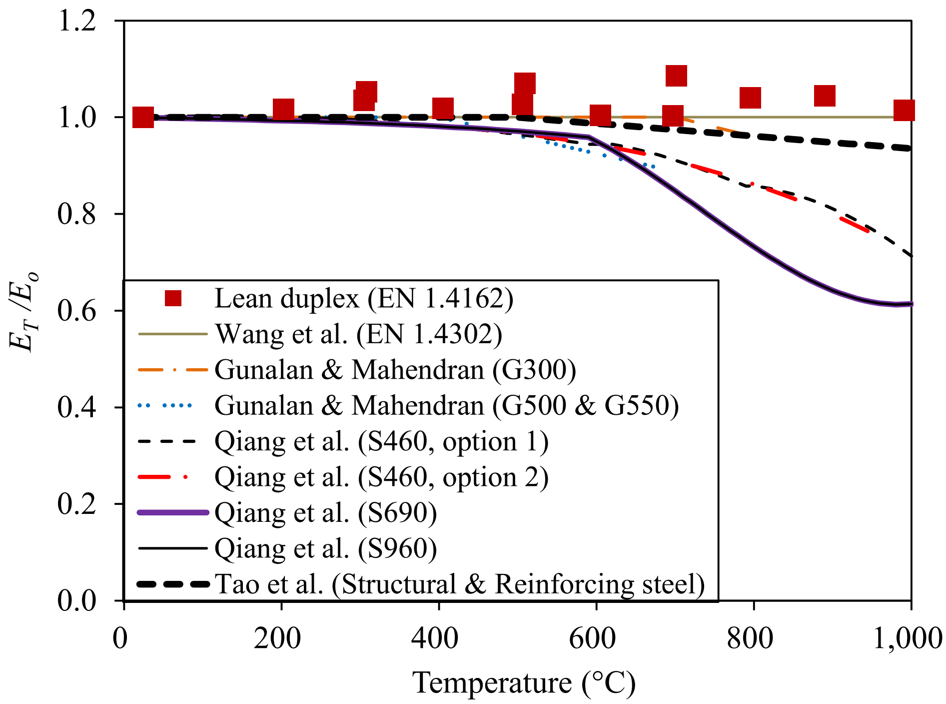


Fig 12: Residual factor of Young's modulus

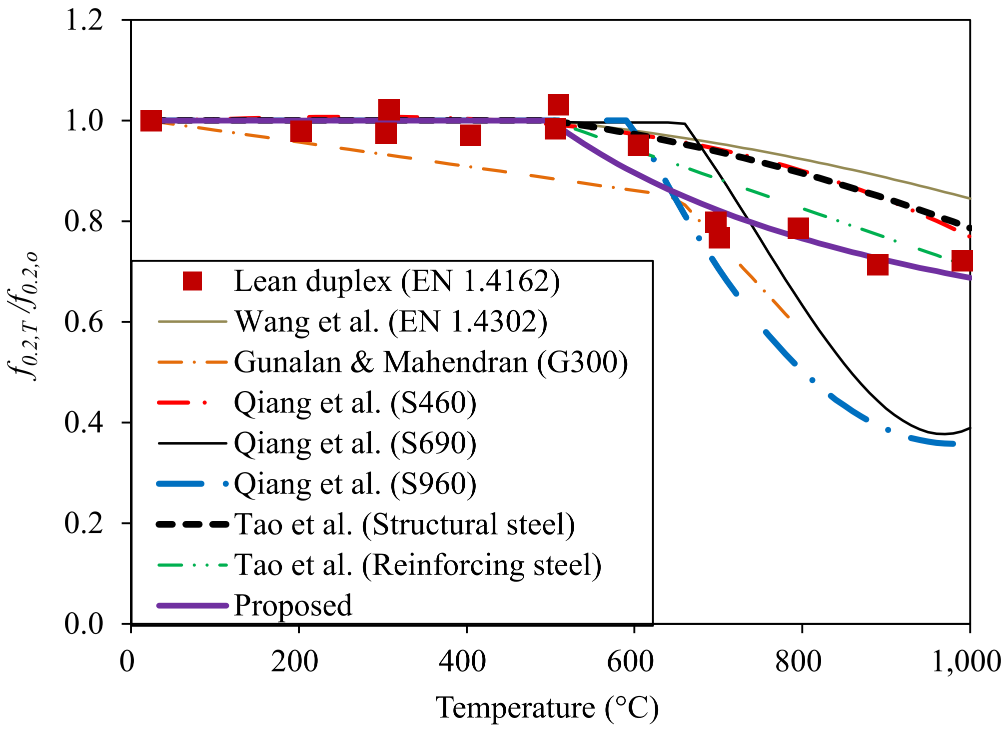


Fig 13: Residual factor of yield strength

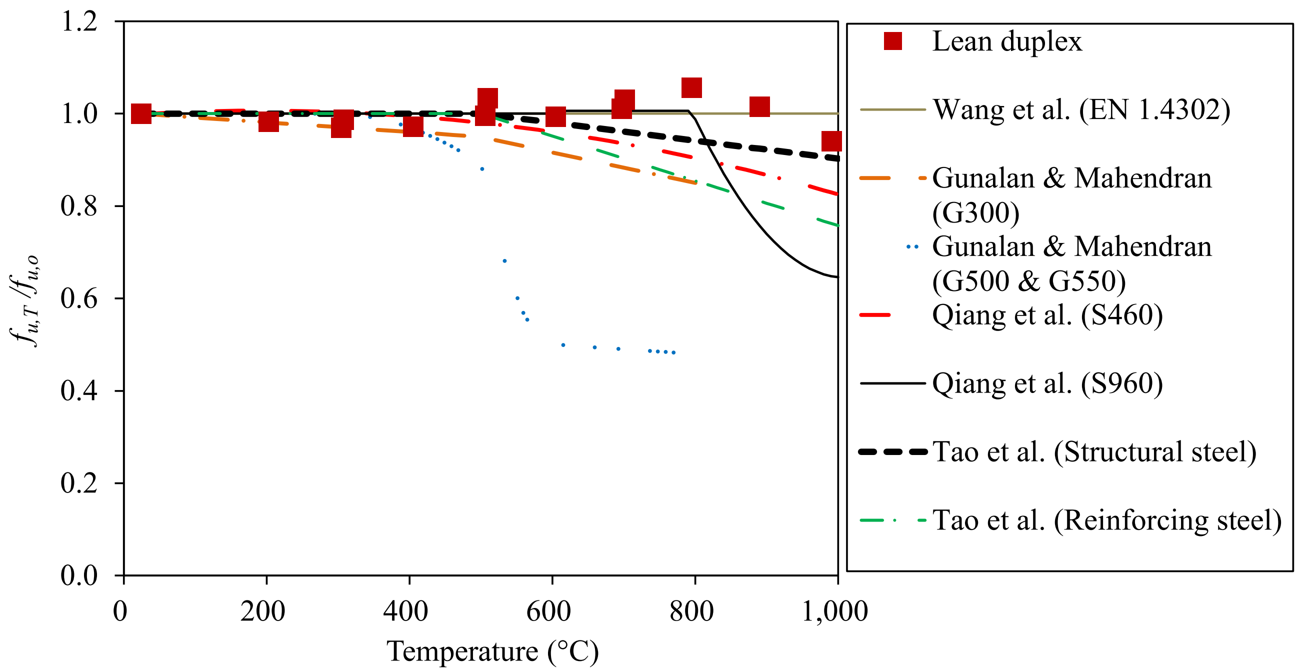


Fig 14: Residual factor of ultimate strength

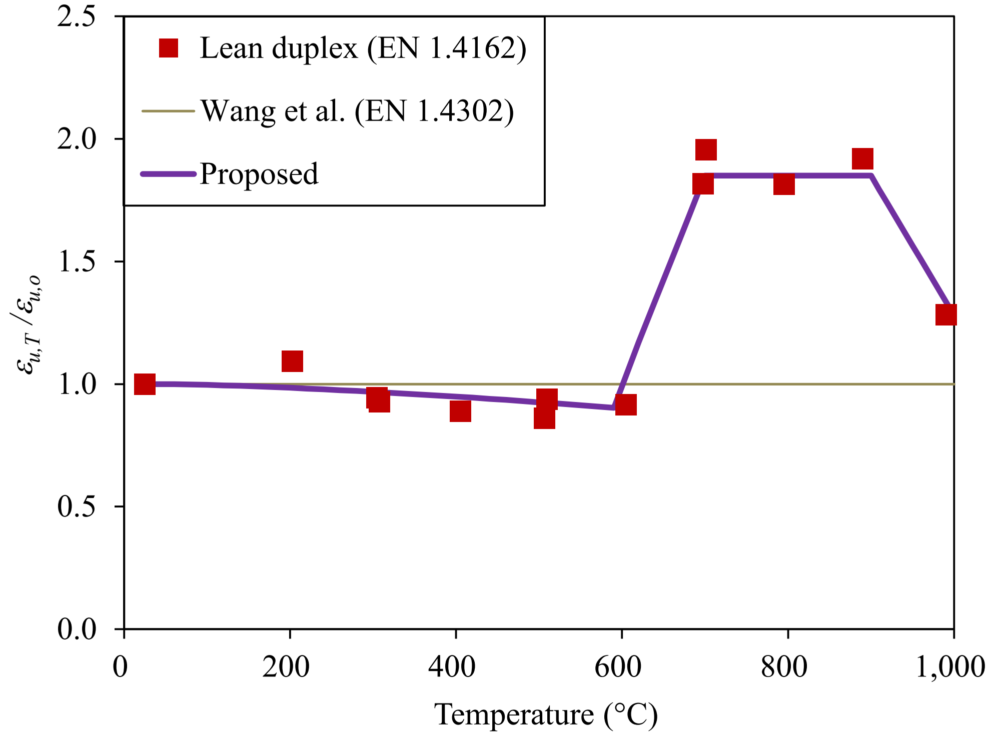


Fig 15: Residual factor of ultimate strain

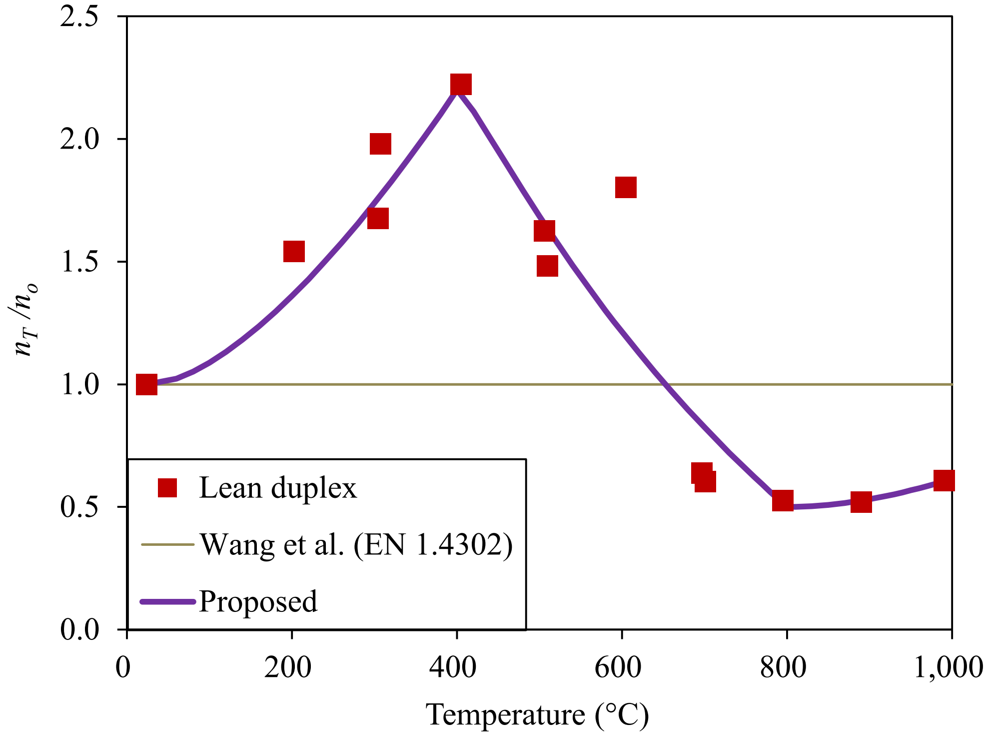
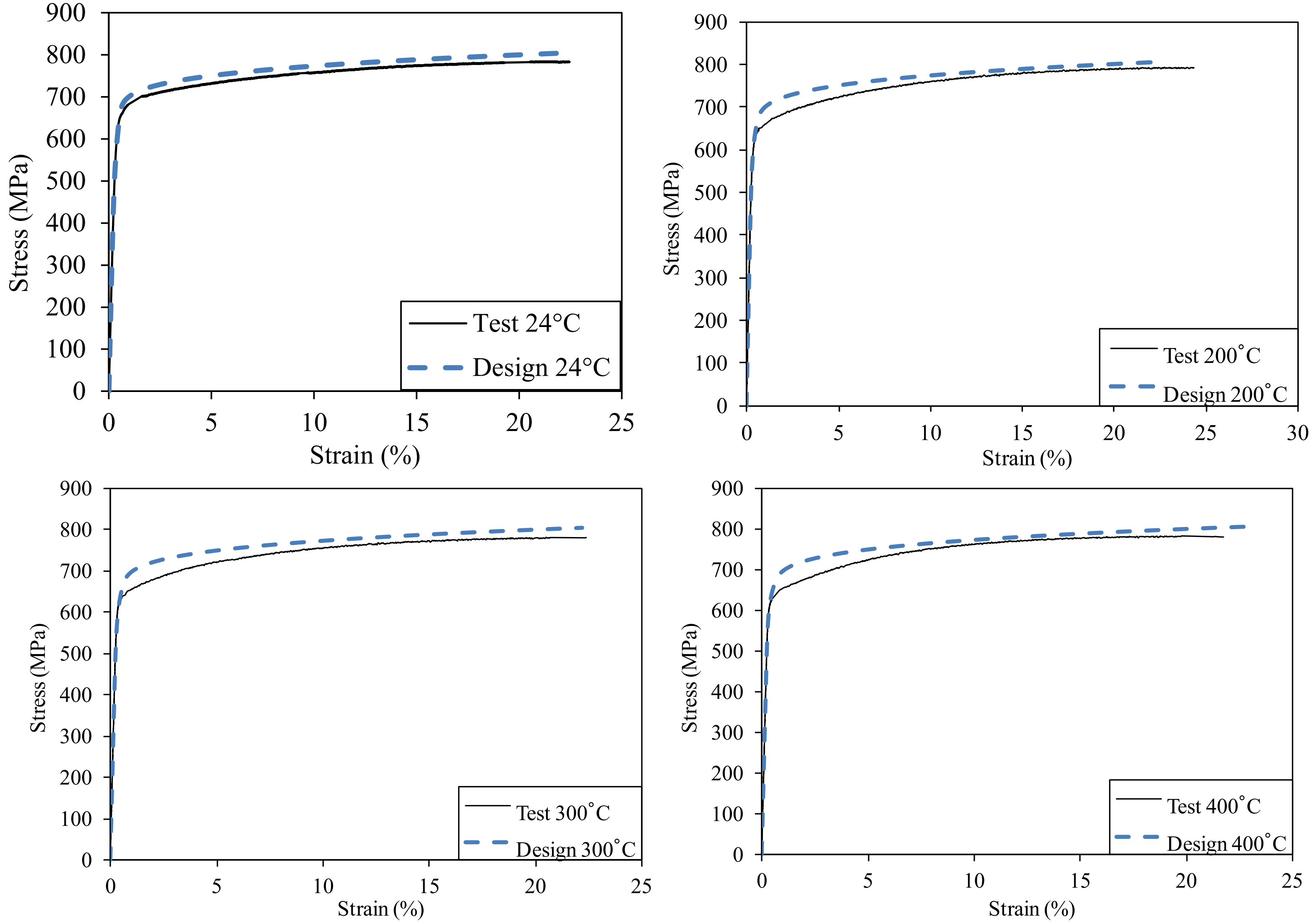


Fig 16: Residual factor of Ramberg-Osgood parameter


Stress (MPa)
Strain (%)
Test 24°C
Design 24°C
Test 200˚C
Design 200˚C
Test 300˚C
Design 300˚C
Test 400˚C
Design 400˚C

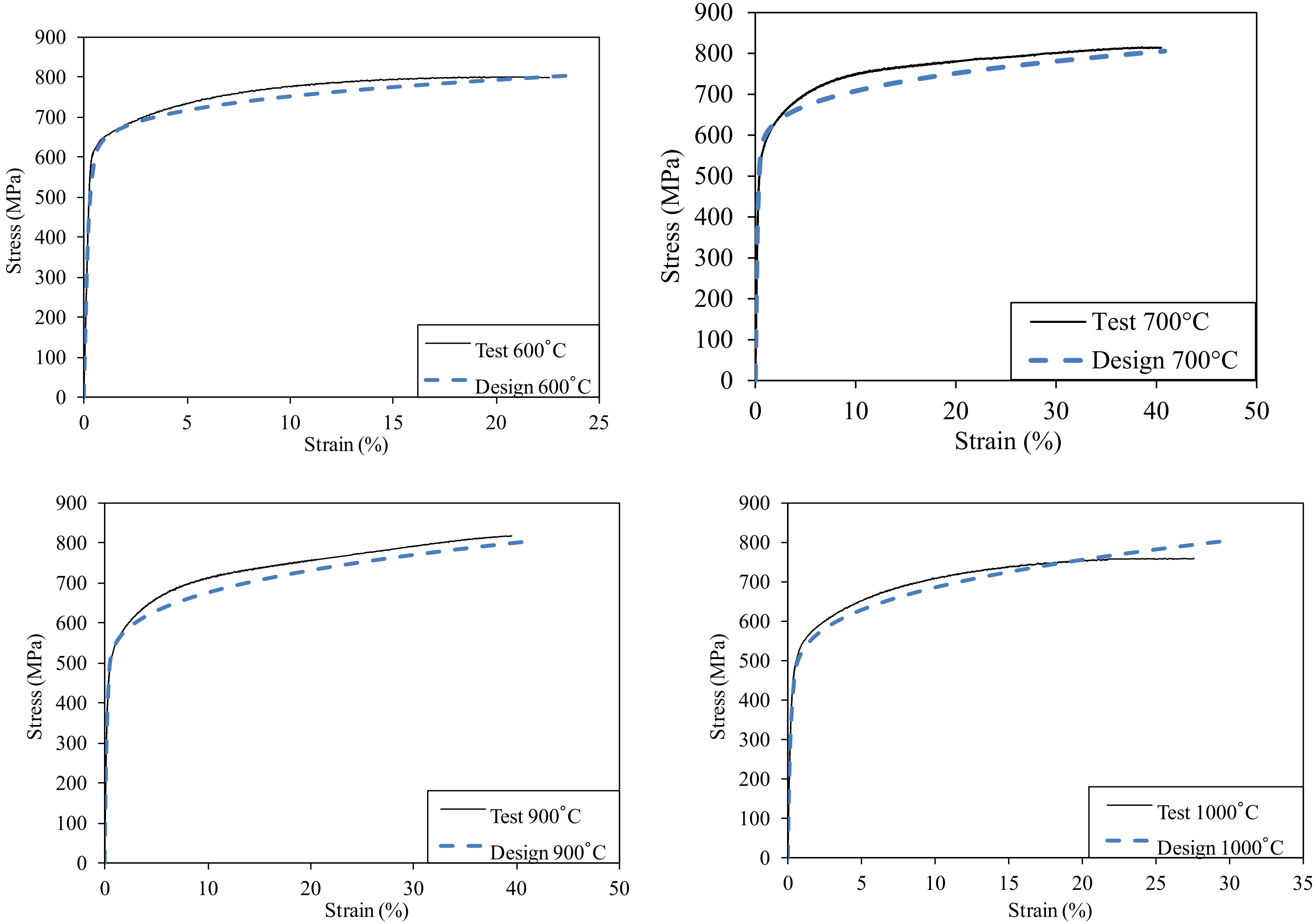


Fig 17: Stress-strain curve of lean duplex stainless steel (t = 2.5 mm)

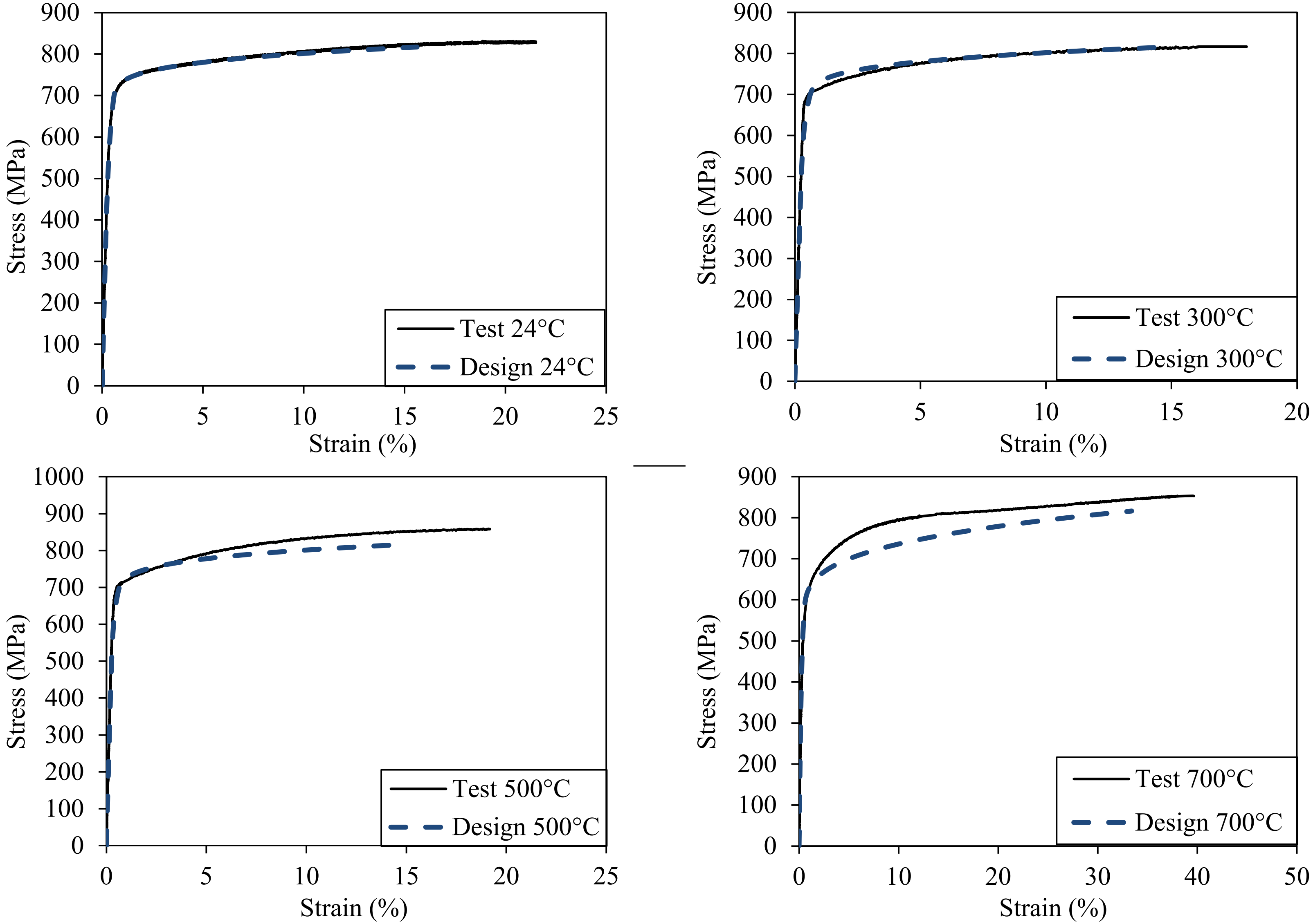


Fig 18: Stress-strain curve of lean duplex stainless steel (t = 1.5 mm)

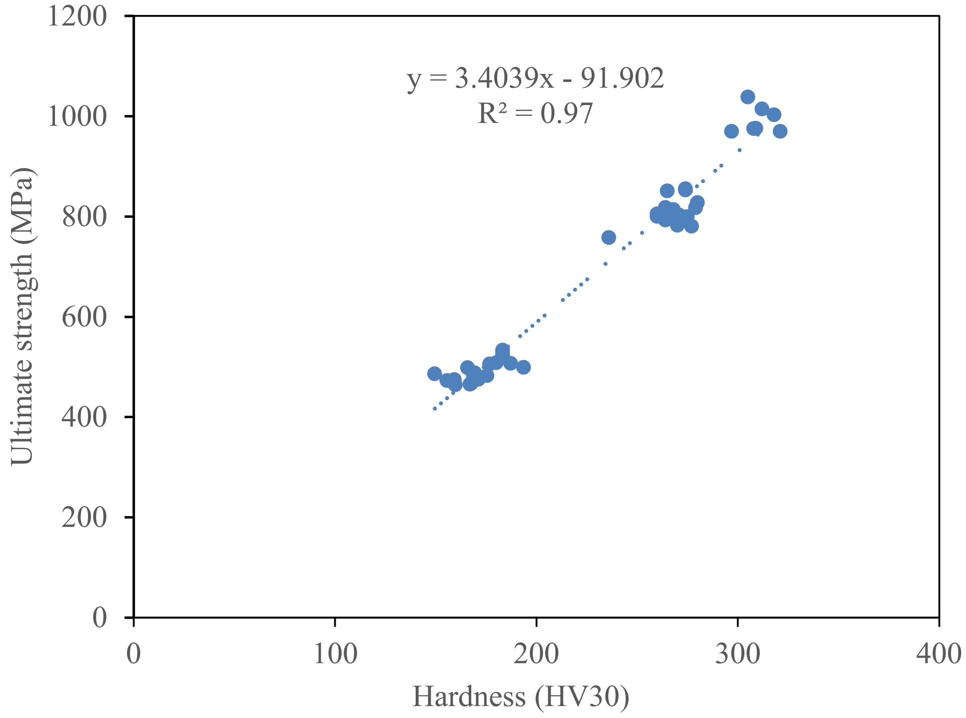


Fig 19: Relationship of the ultimate strength and Vickers hardness value

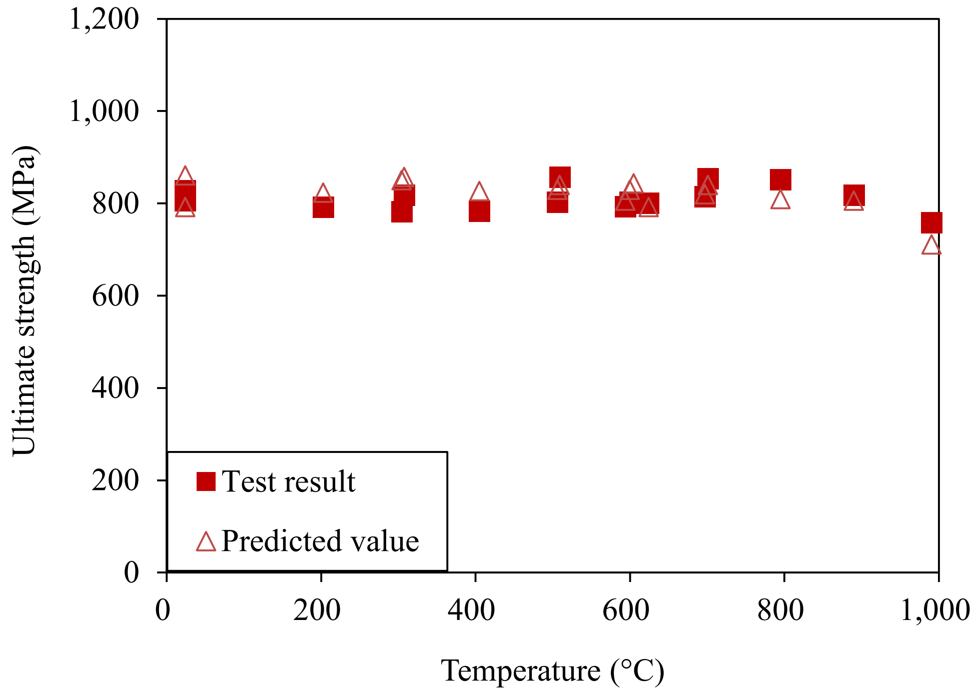


Fig 20: Comparison of the test results and predicted value of ultimate strength for lean duplex stainless steel

Highlights

- Investigation on lean duplex stainless steel post-fire properties was performed.
- Effects of exposed temperature and soak time are investigated.
- The exposed temperatures ranged from 24 to 1000 ºC.
- Existing design rules are assessed by comparing test results.
- Design rules to predict residual mechanical properties were proposed.
- Constitutive model to predict stress-strain curves after fire exposure was proposed.

Mechanical properties of lean duplex stainless steel at post-fire condition

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ABSTRACT

This paper reports an experimental investigation of the mechanical properties of cold-formed lean duplex stainless steel after exposure to high temperatures up to 1000°C. The test specimens were extracted from rectangular and square hollow sections that were cold-rolled from flat plates of lean duplex stainless steel. The mechanical properties, Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter and strain at ultimate strength of lean duplex stainless steel, are reported. The residual mechanical properties of steel materials are compared with the predicted values calculated by the existing equations. It is shown that the existing equations cannot provide accurate predictions for the post-fire mechanical properties of lean duplex stainless steel materials. Thus, a unified equation is proposed to predict residual mechanical properties for lean duplex stainless steel specimens in post-fire conditions. A constitutive model is also proposed to predict the stress-strain relationship of the test specimens after exposure to high temperatures up to 1000°C. A reliability analysis was conducted for the proposed equation. The proposed equation compared favourably with the experimental results, and was found to be reliable for predicting lean duplex stainless steel mechanical properties after exposure to high temperatures.

KEYWORDS: Lean duplex; stainless steel; mechanical properties; post-fire; stress-strain curve.

1. INTRODUCTION

Lean duplex stainless steel (EN 1.4162), which is a relatively new type of steel material, has been used increasingly in construction in recent years. It has a high strength-to-cost ratio compared with other types of stainless steel materials, due to a low nickel (Ni) content of 1.5%, compared with over 5% in other duplex and austenitic stainless steel materials. It has an excellent corrosion resistance, which leads to an aesthetic appearance, ease in future maintenance, and long life cycle. Fire hazards are normally destructive for steel structures, as both stiffness and strength of steel materials decrease dramatically at elevated temperatures. Generally, stainless steel materials have a better fire resistance than carbon steel materials. The investigation of their post-fire mechanical properties provides evidence about the repair and reinforcement of stainless steel structures after exposure to fire hazards, which can reduce economic loss due to fire and improve sustainability of the built environment. The post-fire mechanical properties of lean duplex stainless steel have not been reported in literature. Hence, there was an eminent need to investigate the deterioration and residual mechanical properties of lean duplex stainless steel after exposure to high temperatures.

Previous researchers have investigated residual mechanical property factors of steel materials after fire, including high strength structural steel of grade S460, S690 [1] and S960 [2], structural steel and reinforcing steel [3], cold-formed steel of grades G300, G500 and G550 [4], and austenitic stainless steel of grade EN 1.4301 [5]. However, there is no available research on post-fire mechanical properties of lean duplex stainless steel. Therefore, the effect of the high temperatures on the mechanical properties of lean duplex stainless steel materials remain unknown to engineers and researchers. On the other hand, numerous stress-strain models to predict the full stress-strain behavior for stainless steel material at room temperature have been proposed by previous researchers. The Ramberg-osgood equation [6] has been used widely for a rounded stress-strain curve, and several 2-stage models have been modified from the Ramberg-osgood equation [7 – 9] for a more accurate prediction for stainless steel materials. The two-stage model was modified further to three-stage models [10 – 11]. Stress-strain models for austenitic and duplex stainless steel materials at elevated temperatures have also been proposed by Chen and Young [12] and Huang and Young [13]. It should be noted that there is no equation to predict stress-strain relationship of lean duplex stainless steel in post-fire conditions.

An experimental investigation of the post-fire mechanical properties of lean duplex stainless steel was conducted and is presented in this paper. A total of 17 lean duplex stainless steel specimens was tested. The residual mechanical property factors of the Young's modulus, yield strength, ultimate strength, Ramberg-osgood parameter, strain at the ultimate strength, hardness, and energy absorption were obtained and are reported here. The lean duplex stainless steel specimens were cooled down in the furnace from the specified elevated temperature to room temperature. The microstructure of the lean duplex stainless steel specimens before and after exposed to fire was investigated using a scanning electron microscope (SEM). The residual mechanical properties of lean duplex stainless steel after exposure to high temperatures were compared with the predicted values calculated by the existing equations for other types of steel materials. It should be noted that lean duplex stainless steel was not covered in the existing equations. It was found that the existing equations generally are not capable of providing accurate predictions for lean duplex stainless steel. A set of new equations is proposed, therefore, to predict the post-fire mechanical properties. A reliability analysis was performed to assess the reliability of the proposed equations.

2. EXPERIMENTAL INVESTIGATION

2.1 Test Specimen

The test specimens were extracted from a cold-formed lean duplex stainless steel rectangular hollow section (RHS) and square hollow section (SHS) with nominal dimensions (D×B×t) of 150×50×2.5 and 50×50×1.5, where D, B, t are respectively the depth, width and thickness, in millimeters, of the cross-sections. The coupons were taken from the center of the face at a 90° angle from the weld for all specimens; this coupon dimension agrees with the Australian Standard (AS

1979) [14] and American Standard (ASTM 2002) [15] using a 6 mm wide coupon and a gauge length of 25 mm. The specimens were labeled such that the steel section, the temperatures to which the specimens were exposed, and the soak time could be identified, as shown in Table 1. The first letter and the number indicates the steel section, where “L1” and “L2” represent sections 150×50×2.5 and 50×50×1.5, respectively. The number after “T” is the temperature that the specimen was exposed to in degrees Celsius. The third letter “s” represents soak time. The number after “s” is the time for which the specimen was exposed to a specified temperature in minutes. For example, the label “L1T600s20” represents a lean duplex stainless steel coupon specimen extracted from section 150×50×2.5 being exposed to 600 °C for 20 minutes. Specimens L1T24 and L2T24 did not undergo the heating and cooling process, but were tested in tensile loading at ambient temperatures after being extracted from the sections.

2.2 Test Procedure

2.2.1 Heating and cooling

The specimens were first heated to specified elevated temperatures, and cooled down to room temperature. Tensile coupon tests are then conducted at room temperature, in order to obtain their post-fire mechanical properties. An MTS tensile testing machine equipped with an MTS high temperature furnace and Flex Test SE controller were used for the heating and cooling, as shown in Fig 1. The furnace was able to generate elevated temperatures up to 1400 °C with an accuracy of 1 °C. There were three heating elements located at the upper, middle and lower parts on each of the two sides of the furnace. Three internal thermal couples were installed to measure the air temperature, while an external thermal couple was attached at the mid-length of the coupon specimen to measure the specimen temperature, as shown in Fig 1(b). First, the upper end of the coupon specimens was gripped, and the lower end was free to expand during the “heating and cooling” stage. Second, a calibrated high temperature extensometer of 25 mm gauge length with the ranged limitation of ± 2.5 mm was mounted onto the specimens to measure their thermal expansion (longitudinal strain) in the furnace. Third, the air temperatures in the furnace increased at a constant rate of 20 °C/min, until the corresponding specimen temperature reached the target temperature. Fourth, the specimens were heated under the target temperatures for a period of time (soak time). The average specimen temperature during the soak time is summarized in Table 1 for each specimen. The soak time was generally 20 mins, except that specimens L1T600s0, L1T600s60 and L1T600s180 were heated for 0 min, 60 mins and 180 mins, respectively, to investigate the influence of soak time for post-fire mechanical properties. After the soak time, the heating elements stopped generating heat. The specimens were left inside the chamber for cooling down until the specimen temperature was below 150 °C, and then they were taken out from the chamber for further cooling down to a room temperature of around 24 °C.

2.2.2 Tensile coupon test

Tensile coupon tests for the specimens exposed to elevated temperature were conducted at ambient temperature (24°C). Strain gauges and an extensometer were used to measure the longitudinal tensile strain of the coupon specimens in the initial part and plastic range, respectively. Two linear strain gauges were attached at mid-length to the center of both faces of each coupon, while an extensometer of 25 mm gauge length was mounted onto the specimen with three-point contact knife edges, as shown in Fig 2. The loading machine was driven by displacement control of stroke during the tensile coupon tests. The loading process follows Huang and Young [16] for lean duplex stainless steel flat coupons. Tensile loading was applied to the specimens until fracture, so that the whole stress-strain curve could be obtained. Static stress strain curves were used to determine the post-fire mechanical properties.

2.2.3 Scanning electron microscope

The change of microstructure and grain evolution in the lean duplex stainless steel material at different temperatures lead to a change of residual mechanical properties. Therefore, it was necessary to evaluate the microstructures of the specimens after fire exposure, in order to understand the characteristics of the tested stainless steel specimens after exposed to elevated temperatures. The HITACHI S-3400N scanning electron microscope in the Electron Microscope Unit of The University of Hong Kong was used, as shown in Fig 3. A sample of 6 mm width and 10 mm length was taken from the gauge length of each coupon specimen after exposure to elevated temperatures. The samples were grounded with silicon carbide grinding papers from 240 to 1200 grit, and then polished with 1.0 μm and 0.5 μm diamond compounds. Then, the samples were electrolytically etched with a solution of perchloric acid (70%) and ethanol (100%) by 1:4. The samples were placed on the sample holders of the SEM for examination. The microstructure of lean duplex stainless steel of the scale of 20 μm are shown in Fig 4. The chemical compositions of several specimens after exposure to different elevated temperatures were obtained from the energy-dispersive X-ray (SEM EDX) spectrum, as shown in Table 2.

2.2.4 Hardness test

The hardness test was also conducted at the ambient temperature (24°C) after tensile testing for the test specimens that were cooled in the furnace, in order to investigate the hardness of lean duplex stainless steel after exposure to different temperatures. The test method and procedure conformed to BS EN ISO 6507-1 [17] and ASTM E384-11[18]. The ESE WAY Hardness Tester was used for the Vickers hardness test (Fig 5). A square-based diamond pyramid indenter, with the angle between the opposite faces at the vertex equal to 136°, was used to apply an impact loading in this study. The location of the hardness measurement was away from the necking region of each specimen, in order to avoid the influence of tensile stress in the plastic range. The loading-unloading procedure in the plastic range may have led to an increased hardness value. A force equal to 30 kgf (294.2 N) was applied to the specimens for 10 seconds. Then the lengths of the two diagonals were measured under a microscope. The arithmetical mean of the two lengths was taken to determine the Vickers hardness value for each specimen, according to BS EN ISO 6507-4 [19]. The hardness values of the test specimens are summarized in Table 1 and Fig 6 for lean duplex stainless steel.

2.3 Test Results

2.3.1 Effect of elevated temperatures

The post-fire static stress-strain relationships of the lean duplex stainless steel specimens are shown in Figs 7 – 9. The post-fire mechanical properties of specimens exposed to temperature T, including Young's modulus (E_T), 0.2% proof stress (yield strength) ($f_{0.2,T}$), 0.5% proof stress ($f_{0.5,T}$), 1.5% proof stress ($f_{1.5,T}$), 2.0% proof stress ($f_{2.0,T}$), ultimate strength ($f_{u,T}$), strain at ultimate strength ($\varepsilon_{u,T}$), strain at fracture ($\varepsilon_{f,T}$) and Ramberg-Osgood parameter (n_T), were obtained from the static stress-strain curves as summarized in Table 1. The post-fire Ramberg-Osgood parameter (n_T) was calculated using $n_T = ln\ (0.01/0.2)\ /\ ln\ (f_{0.01,T}/f_{0.2,T})$, where $f_{0.01,T}$ is the 0.01% proof stress obtained from post-fire static stress-strain curve. The 0.2% proof stress ($f_{0.2,T}$) and 0.01% proof stress ($f_{0.01,T}$) are intersect points of the stress-strain curve and the proportional lines off-set by 0.2% and 0.01% strains, respectively. The 0.5% ($f_{0.5,T}$), 1.5% ($f_{1.5,T}$), and 2.0% ($f_{2.0,T}$) proof stresses are defined as 0.5%, 1.5% and 2.0% strains with non-proportional vertical lines intersected with the stress-strain curves. The energy absorptions for post-fire specimens were calculated by Eq. (1):

$$U_T = \int_0^{\varepsilon} f\,d\varepsilon \qquad (1)$$

where U_T is the total mechanical energy per unit volume absorbed by the material during the tensile testing after exposed to temperature T, f is stress and ε is strain. The energy absorption for each specimen is summarized in Table 1, and the relationship between energy absorption and specimen temperature is shown in Fig 10 for lean duplex stainless steel. The energy absorption of the tested specimens was subjected to a sudden increase by 33.5% from 600 °C to 700 °C. This may have been due to the change of microstructure, where ferrite started to transfer to austenite, as detailed in Section 2.3.3. The total thermal expansion during the heating process for the test specimens is summarized in Table 1. The relationship between thermal expansion and specimen temperature of the specimens with thickness = 2.5 mm are plotted in Fig 11.

The residual mechanical property factors of the test specimens, which are ratios of post-fire mechanical properties after exposure to elevated temperature T over the mechanical properties at ambient temperature (E_T/E_o, $f_{0.2,T}/f_{0.2,o}$, $f_{u,T}/f_{u,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o), were plotted against the specimen temperatures, as shown in Figs 12 – 16. It can be seen that the Young's modulus (E_T) and ultimate strength ($f_{u,T}$) generally remained the same with different temperatures, while the other mechanical properties varied. The 0.2% proof stress ($f_{0.2,T}$), 0.5% proof stress ($f_{0.5,T}$), 1.5% proof stress ($f_{1.5,T}$), 2.0% proof stress ($f_{2.0,T}$) generally decreased beyond 600°C with increasing specimen temperatures. The strain at ultimate strength ($\varepsilon_{u,T}$) increased with temperature when the specimen temperature was higher than 600°C, but a sudden drop was observed at 1000 °C. The hardness (HV30) of the specimens generally remained the same, ranging from 235.5 to 280.0 kgf/mm^2, after exposure to elevated temperatures up to 1000°C. Martensite is a hard material that generally leads to the change of hardness of steel materials. Martensite was not observed in the microstructure of the test specimens, as detailed in Section 2.3.3, thus the hardness of the test specimens after exposure to different temperatures generally remained the same.

2.3.2 Effect of soak time

The research project also investigated the influence of soak time (heating time) on the post-fire mechanical properties. The stress-strain curves for lean duplex stainless steel coupon specimens with thickness of 2.5 mm exposed to 600°C for 0, 20, 60 and 180 mins are shown in Fig 9, and the mechanical properties are summarized in Table 1. Previous research [5, 20] has shown that the soak time has negligible effect on post-fire mechanical properties for carbon steel and austenitic stainless steel. However, in this study it was found that the stress-strain curves for soak time of 0, 20, 60 mins generally coincided with each other, while the ductility of specimens for soak times of 180 minutes were larger than for the other three specimens. The strain at ultimate strength ($\varepsilon_{u,T}$) and strain at fracture ($\varepsilon_{f,T}$) increased by 28% and 15% respectively for a soak time of 180 mins, as shown in Table

1. The effect of soak time is similar to the annealing procedure, which is normally carried out to relieve stresses and improve ductility in steel manufacturing.

2.3.3 Microstructure and chemical composition

The microstructure and chemical composition of lean duplex stainless steel specimens after exposure to high temperatures were examined using scanning electron microscopy analysis. The microstructure and chemical composition generally remained the same for specimens after exposure to elevated temperatures up to 800°C, as shown in Fig 4 and Table 2. The specimens exhibited similar grain sizes and generally rounded grain shapes for various temperatures. The grains of darker colour are ferrite, and the grains of lighter colour are austenite. The content of ferrite (alpha-phase iron) and austenite (gamma-phase iron) were roughly the same in the lean duplex stainless steel specimens after exposure to high temperatures up to 800°C. The ferrite transited to austenite at high temperatures of around 900°C, and it underwent a phase transition from body-centred cubic (BCC) to face-centred cubic (FCC) [21]. The content of austenite increased beyond 800°C, as shown in Fig. 4.

3. EVALUATION OF EXISTING EQUATIONS

The values predicted by design rules in the EC3 Part 1.2 [22] and previous research on post-fire mechanical properties were compared with the test results. The thermal expansion predicted by the EC3 Part 1.2 [22] for austenitic stainless steel was compared with the lean duplex stainless steel specimens in Fig 11. It should be noted that the design rule for the lean duplex stainless steel was not available in EC3 Part 1.2 [22]. It was shown that the equation is not suitable to be used for lean duplex stainless steel. The design rule generally provides a lower value of thermal expansion than the experimental results for lean duplex stainless steel.

The test results of residual mechanical property factors (E_T/E_o, $f_{0.2,T}/f_{0.2,o}$, $f_{u,T}/f_{u,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o) for lean duplex stainless steel were compared with the values calculated by the existing equations [1-5], as shown in Figs 12 – 16. For lean duplex stainless steel, it was found that the equations proposed by Wang et al. [5] are generally capable of predicting residual mechanical property factors of Young's modulus (E_T/E_o) and ultimate strength ($f_{u,T}/f_{u,o}$) by taking residual mechanical property factor equals to 1. However, the other existing equations are not applicable for lean duplex stainless steel post-fire mechanical properties. Therefore, it is necessary to propose new equations for lean duplex stainless steel residual mechanical property factors of $f_{0.2,T}/f_{0.2,o}$, $\varepsilon_{u,T}/\varepsilon_{u,o}$ and n_T/n_o.

4. PROPOSED DESIGN RULES

4.1 Residual Mechanical Property Factors

The design proposal consists of two parts, residual mechanical property factor (χ) and stress-strain model. It can be observed from Fig 12 and Fig 14 that the residual mechanical property factors of Young's modulus (E_T/E_o) and ultimate strength ($f_{u,T}/f_{u,o}$) for lean duplex stainless steel can be taken as unity ($\chi = 1$). Existing equations have been reviewed to propose a suitable design rule for residual mechanical property factors in this study. Chen and Young [12] proposed a unifying equation as showed in Eq. (2) to predict the residual mechanical property factors at elevated temperatures. An equation, as shown in Eq. (3), that modified from Eq. (2) [12], is proposed to predict residual factors of different post-fire mechanical properties for both lean duplex stainless steel materials by changing the parameters of a, b, c and d. Compared with Eq. (2), the Eq. (3) used in this study is more flexible in predicting the value of residual mechanical property factors with temperature.

The proposed parameters for Eq. (3) to calculate residual mechanical property factors of lean duplex stainless steel are summarized in Table 3. The comparison of residual mechanical property factors obtained from the tests and those calculated from the proposed design rule are shown in Figs 12 – 16. It is shown that the proposed design rules are generally capable of providing accurate predictions for residual mechanical property factors of lean duplex stainless steel after exposure to fire. Therefore, the post fire mechanical properties can be obtained by multiplying the residual factor (χ) with the mechanical properties obtained at room temperature.

$$\chi = a - \frac{(T-b)^n}{c} \tag{2}$$

$$\chi = a + \frac{c}{T}(T-d)^b \tag{3}$$

4.2 Reliability Analysis

The reliability of the proposed design rules to predict the residual mechanical property factors of lean duplex stainless steel after exposure to fire was evaluated using reliability analysis, which is detailed in the Commentary of the ASCE [23]. However, the target reliability index (β) and the resistance factor (ϕ) for stainless steel material properties under post-fire conditions are not specified by the design specifications. Therefore, the target reliability index of 2.50 for stainless steel members was adopted in this study. If the reliability index is greater than or equal to 2.50, then the design rules are considered to be reliable. The resistance factors of the design rules were determined using Eq. 6.2-2 of the ASCE Specification [23]. The load combination of 1.2DL+1.6LL was used in calculating the resistance factors (ϕ) for the proposed equation for the residual mechanical property factor (χ), where DL is the dead load and LL is the live load. The statistical parameters $M_m = 1.10$, $F_{ym} = 1.00$, $V_{ym} = 0.10$ and $V_F = 0.05$, which are the mean values and coefficients of variation for material properties and fabrication factors for yield strength and Young's modulus in the Commentary of the ASCE Specification [23] were adopted for post-fire Young's modulus (E_T) and 0.2% proof stress ($f_{0.2,T}$). The statistical parameters $M_m = 1.10$, $F_{um} = 1.00$, $V_{um} = 0.05$ and $V_F = 0.05$ for ultimate strength in the commentary were adopted for post-fire ultimate strength, strain at ultimate strength ($\varepsilon_{u,T}$) and Ramberg-osgood parameter (n_T). The mean value (P_m) and coefficient of variation of tested-to-predicted load ratio (V_p) are shown in Table 4 for lean duplex stainless steel.

The correction factor Eq. F1.1-3 in the North American Cold-formed Steel Specification AISI S100 [24] was used to account for the influence of the amount of data.

In this study, two sets of resistance factor (ϕ_0 and ϕ_1) and reliability index (β_0 and β_1) were determined, as shown in Table 4. The resistance factor (ϕ_0) is calculated based on the reliability index (β_0) of 2.50. In other words, the value of ϕ_0 is the maximum resistance factor required to achieve the target reliability index (β_0). However, a slightly smaller resistance factor (ϕ_1) that rounded to integer or a decimal of 0.5 is recommended for practical use by engineers, as reported in Table 4. It is shown that the proposed design rules provide accurate predictions for post-fire mechanical properties of lean duplex stainless steel. The mean values of χ_t / χ_d range from 0.99 to 1.03 for various post-fire mechanical properties with the coefficient of variation (COV) of 0.026 to 0.179 for lean duplex stainless steel. The χ_t and χ_d are residual mechanical property factors obtained from the test results and those calculated from the proposed design rule, respectively. The resistance factors (ϕ_1) are recommended for lean duplex stainless steel Young's modulus, 0.2% proof stress, ultimate strength, strain at ultimate strength and Ramberg-osgood parameter, as shown in Table 4. The reliability indexes (β_1) corresponding to the recommended resistance factors (ϕ_1) are all larger than or equal to the target reliability of 2.50. Therefore, the proposed design rules are considered to be reliable with the recommended resistance factors. It is recommended that the resistance factor of Young's modulus, yield strength, ultimate strength, strain at ultimate strength and Ramberg-osgood parameter equal to 0.95, 0.90, 0.95, 0.90 and 0.80 for lean duplex stainless steel, respectively, in order to achieve the reliability index higher than the target value of 2.5.

4.3 Stress-strain Model

The post-fire mechanical properties, including Young's modulus (E_T), 0.2% proof stress ($f_{0.2,T}$), ultimate strength ($f_{u,T}$), Ramberg-Osgood parameter (n_T) and strain at ultimate strength ($\varepsilon_{u,T}$), are used to obtain the stress-strain relationship. The stress-strain curves of lean duplex stainless steel after exposed to fire have a round-house type non-linear behaviour without a plateau. Various existing stress-strain models for rounded stress-strain curves are reviewed and compared with the test results. Considering the accuracy and convenience in calculation procedure, the two-stage model [8] is adopted, except that the post fire mechanical properties (E_T, $f_{0.2,T}$, $f_{u,T}$, n_T, $\varepsilon_{u,T}$) calculated from the proposed design rule are used, as expressed by the stress-strain relationship in Table 3. Generally, the Rasmussen's model that used for post-fire mechanical properties are capable of providing accurate prediction for the full stress-strain curve. The comparison of stress-strain curves obtained from tests and calculated from equations for the test specimens are shown in Figs 17 - 18. Therefore, it is recommended that the 2-stage stress-strain curve model [8] together with the proposed equations for post-fire mechanical properties can be used for lean duplex stainless steel.

4.4 Relationship of Hardness Value and Ultimate Strength

Compared with the tensile coupon tests, the hardness test is much cheaper and easier to conduct. It is a non-destructive testing technique, thus the structure does not need to be damaged to obtain the mechanical properties. The hardness value can be obtained quickly on-site after a structure is exposed to a fire hazard. The previous investigations [25, 26] have shown that the ultimate strength of a steel material is generally equal to three times its Vickers hardness value (f_u = 3×HV). However, the previous research has been based on carbon steel specimens, and the relationship between hardness value and ultimate strength for stainless steel after exposure to elevated temperatures is not available. Therefore, the relationship between ultimate strength and hardness values of the lean duplex and ferritic stainless steel specimens after exposure to 24 – 1000 °C is plotted in Fig 19. The test data of ferritic stainless steel material were obtained by Huang and Young [27]. It can be seen that the ultimate strength and hardness values exhibits a linear relationship, which can be expressed as Eq. (4) with the least square root value equal to 0.97, where $f_{u,d}$ is the predicted value of ultimate strength, and HV is the Vickers hardness value. The mean values of the test-to-design ratio ($f_{u,d}/f_{u,T}$) for lean duplex stainless steel are equal to 0.99 with a coefficient of variation (COV) of 0.040.

Therefore, the equation is accurate and convergent for lean duplex stainless steel specimens after exposure to 24 – 1000 °C. The test results and predicted values of ultimate strengths of lean duplex stainless steel materials are plotted in Fig 20. The Eq. (4) can be used to predict the ultimate strength of lean duplex and ferritic stainless steel structures after exposure to elevated temperatures using the non-destructive hardness tests.

$$f_{u,d} = 3.4\times\text{HV} - 91.9 \tag{4}$$

5. CONCLUSIONS

An experimental investigation of post-fire mechanical properties of lean duplex stainless steel has been presented in this paper. The test specimens were extracted from square and rectangular hollow sections of lean duplex stainless steel. The coupon specimens were heated and maintained at specified elevated temperatures up to 1000 °C for a certain soak time, and then cooled down to room temperature. Tensile coupon tests were conducted on the specimens after exposure to high temperatures. Various post-fire mechanical properties, including the thermal expansion, Young's modulus, 0.2% proof stress (yield strength), ultimate strength, strain at ultimate strength, strain at fracture, Ramberg-osgood parameter, and energy absorption were obtained. Vickers hardness tests were conducted for post-fire specimens, and the linear relationship between Vickers hardness value and ultimate strength was obtained and reported. The Young's modulus, ultimate strength and hardness of lean duplex stainless steel specimens generally remained the same after exposure to elevated temperatures. It was shown that the soak time had negligible effect on the material strength of the stainless steel specimens in this study. The test results were compared with the predictions obtained from previous investigations. It is found that the existing design rules are generally not applicable for lean duplex stainless steel post-fire mechanical properties, as the existing design rules were developed mainly base on carbon steel. New equations are proposed for residual mechanical property factors and stress-strain relationships in post-fire conditions. The values predicted from the new equations were compared with the test results. It is found that the proposed design rules are capable of providing accurate predictions for the test specimens. Therefore, it is recommended that the proposed equations for residual mechanical property factors and post-fire stress-strain relationship can be used for cold-formed lean duplex stainless steel after exposure to high temperatures.

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NOTATION

The following symbols are used in this paper:

B = width of cross-section;

D = depth of cross-section;

E_o = initial Young's modulus at room temperature;

E_T = initial Young's modulus at temperature T ºC;

f = stress

$f_{0.2,o}$ = yield strength at room temperature;

$f_{0.2,T}$ = yield strength at temperature T ºC;

$f_{u,o}$ = ultimate strength at room temperature;

$f_{u,T}$ = ultimate strength at temperature T ºC;

$f_{0.01,T}$ = strength at 0.01% strain at temperature T ºC;

$f_{0.5,T}$ = strength at 0.5% strain at temperature T ºC;

$f_{1.5,T}$ = strength at 1.5% strain at temperature T ºC;

$f_{2.0,T}$ = strength at 2.0% strain at temperature T ºC;

n_o = Ramberg-Osgood parameter at room temperature;

n_T = Ramberg-Osgood parameter at elevated temperature T ºC;

T = temperature in ºC;

t = thickness;

U_T = total mechanical energy per unit volume absorbed by the material during tensile testing;

ε = strain;

$\varepsilon_{f,T}$ = tensile strain at fracture at temperature T ºC;

$\varepsilon_{u,o}$ = tensile strain at ultimate strength at room temperature; and

$\varepsilon_{u,T}$ = tensile strain at ultimate strength at temperature T ºC.

a = coefficient used in modified equations;

b = coefficient used in modified equations;

COV = coefficient of variation;

c = coefficient used in modified equations;

d = coefficient used in modified equations;

$E_{p,T}$ = initial modulus of elasticity at the onset of strain hardening

F_{um} = mean value of fabrication factor for ultimate strength;

F_{ym} = mean value of fabrication factor for yield strength and Young's modulus;

f_u = ultimate strength;

$f_{u,d}$ = ultimate strength predicted by Vickers hardness value;

HV = Vickers hardness value;

M_m = mean value of material factor;

m_T = parameter in stress-strain model;

N = coefficient used in Chen and Young (2006) equations;

P = parameter in the proposed stress-strain model;

P_m = mean value of tested-to-predicted load ratio;

V_F = coefficient of variation of fabrication factor;

V_p = coefficient of variation of tested-to-predicted load ratio;

V_{um} = coefficient of variation of material factor for ultimate strength;

V_{ym} = coefficient of variation of material factor for yield strength and Young's modulus;

β = reliability index;

β_0 = reliability index;

β_1 = reliability index;

χ = residual mechanical property factor;

χ_d = residual mechanical property factor calculated from proposed design rule;

χ_t = residual mechanical property factor obtained from test results;

$\varepsilon_{p,T}$ =strain at the onset of strain hardening;

ϕ = resistance factor;

ϕ_0 = resistance factor; and

ϕ_1 = resistance factor.

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TABLE 1. Post-fire mechanical properties of lean duplex stainless steel

Specimen	T (°C)	Thermal expansion (%)	E_T (GPa)	$f_{0.2,T}$ (MPa)	$f_{0.5,T}$ (MPa)	$f_{1.5,T}$ (MPa)	$f_{2.0,T}$ (MPa)	$f_{u,T}$ (MPa)	$\varepsilon_{u,T}$ (%)	$\varepsilon_{f,T}$ (%)	n_T	U_T (MPa)	HV30 (kgf/mm^2)
L1T24	24.0	---	208.8	648.1	676.2	748.1	753.0	805.4	21.7	33.4	7.1	251.3	260.0
L1T200s20	202.5	0.71	212.3	634.5	634.4	673.8	683.6	791.9	23.8	34.7	10.9	260.2	269.0
L1T300s20	304.1	0.29	216.3	632.4	632.2	668.7	679.1	781.1	20.5	34.1	11.8	252.8	277.0
L1T400s20	404.8	1.89	212.7	629.7	630.0	666.9	676.6	782.8	19.4	29.3	15.7	217.2	270.0
L1T500s20	505.9	2.50	214.5	638.2	637.4	659.9	673.3	802.3	18.7	33.5	11.5	253.1	271.0
L1T600s0	624.1	1.66	215.1	607.4	608.6	652.7	667.9	800.6	19.6	33.0	13.9	249.0	260.0
L1T600s20	604.6	5.3	209.8	616.2	616.8	668.3	681.3	800.2	19.9	33.2	12.7	251.7	275.0
L1T600s60	599.7	1.73	214.8	561.2	560.9	635.6	655.2	803.0	19.7	32.0	6.4	244.2	271.0
L1T600s180	594.1	0.90	215.2	538.9	549.5	640.8	658.2	793.3	28.4	39.1	4.7	299.4	264.0
L1T700s20	697.0	3.93	209.5	517.0	531.2	610.4	630.5	814.2	39.5	43.9	4.5	335.0	268.0
L1T800s20	795.0	4.06	217.3	509.6	526.1	613.9	633.7	851.2	39.5	44.6	3.7	346.4	265.0
L1T900s20	889.8	8.76	218.2	462.8	486.2	567.0	586.5	818.1	41.7	49.1	3.7	366.6	264.0
L1T1000s20	990.7	8.45	211.8	467.9	488.3	568.5	586.5	758.1	27.9	43.6	4.3	310.9	235.5
L2T24	24.0	---	198.7	682.4	666.5	748.8	753.7	828.1	20.2	30.6	6.4	243.2	280.0
L2T300s20	307.4	0.35	209.2	697.62	693.4	726.9	738.1	817.6	18.8	30.4	12.6	238.3	279.0
L2T500s20	509.1	0.70	212.8	703.84	694.5	731.7	742.7	855.9	19.0	30.9	9.4	251.6	274.0
L2T700s20	701.0	1.12	215.8	524.3	542.8	659.9	679.6	853.5	39.5	47.1	3.8	378.8	274.0

Note: L1 and L2 are extracted from sections 150×50×2.5 and 50×50×1.5, respectively.

TABLE 2. Chemical composition of lean duplex stainless steel specimens

Element	L200	L500	L900
C	1.89	2.30	4.57
Si	0.65	0.53	0.64
Cr	21.13	20.20	21.79
Mn	5.90	5.89	5.21
Fe	69.16	69.41	66.17
Ni	1.27	1.66	1.62

TABLE 3. Proposed post-fire mechanical properties for lean duplex stainless steel

Residual mechanical property factor $\chi = a + \frac{c}{T}(T-d)^b$	a	b	c	d	Temperature, T (°C)
$\frac{E_T}{E_o}$	1	0	0	0	24 ≤ T ≤ 1000
$\frac{f_{0.2,T}}{f_{0.2,o}}$	1	0	0	0	24 ≤ T ≤ 500
	1	1	-0.63	500	500 < T ≤ 1000
$\frac{f_{u,T}}{f_{u,o}}$	1	0	0	0	24 ≤ T ≤ 1000
$\frac{\varepsilon_{u,T}}{\varepsilon_{u,o}}$	1	2.5	-7.54E-06	24	24 ≤ T ≤ 600
	-4.1	2	8.50E-03	0	600 < T ≤ 700
	1.85	0	0	0	700 < T ≤ 900
	6.98	2	-5.70E-03	0	900 < T ≤ 1000
$\frac{n_T}{n_o}$	1	2.5	1.75E-04	24	24 ≤ T ≤ 400
	2.2	1.2	-1.03	400	400 < T ≤ 800
	0.5	2	2.86E-03	800	800 < T ≤ 1000

Stress-strain relationship: (24 ≤ T ≤ 1000)

$$\varepsilon = \frac{f}{E_T} + 0.002\left(\frac{f}{f_{0.2,T}}\right)^{n_T} \quad \text{for} \quad f \le f_{0.2,T}$$

$$= \frac{f - f_{0.2,T}}{E_{0.2,T}} + \varepsilon_{u,T}\left(\frac{f - f_{0.2,T}}{f_{u,T} - f_{0.2,T}}\right)^{m_T} + 0.002 + \frac{f_{0.2,T}}{E_T} \quad \text{for} \quad f_{0.2,T} < f \le f_{u,T}$$

where $E_{0.2,T} = \frac{E_T}{1 + 0.002 n_T E_T / f_{0.2,T}}$, $m_T = 1+3.5 f_{0.2,T}/f_{u,T}$

TABLE 4. Comparison of residual factors obtained from test results with design values for lean duplex stainless steel

Specimen	T (°C)	χ_t					χ_d					$\frac{\chi_t}{\chi_d}$				
		E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T	E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T	E_T	$f_{0.2,T}$	$f_{u,T}$	$\varepsilon_{u,T}$	n_T
L1T24	23.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
L1T200s20	202.5	1.02	0.98	0.98	1.09	1.54	1.00	1.00	1.00	0.98	1.37	1.02	0.98	0.98	1.11	1.13
L1T300s20	304.1	1.04	0.98	0.97	0.94	1.68	1.00	1.00	1.00	0.97	1.76	1.04	0.98	0.97	0.98	0.95
L1T400s20	404.8	1.02	0.97	0.97	0.89	2.22	1.00	1.00	1.00	0.95	2.18	1.02	0.97	0.97	0.94	1.02
L1T500s20	505.9	1.03	0.98	1.00	0.86	1.63	1.00	0.99	1.00	0.92	1.65	1.03	0.99	1.00	0.93	0.98
L1T600s0	624.1	1.03	0.94	0.99	---	---	1.00	0.88	1.00	---	---	1.03	1.07	0.99	---	---
L1T600s20	604.6	1.00	0.95	0.99	0.92	1.80	1.00	0.89	1.00	1.04	1.19	1.00	1.07	0.99	0.88	1.51
L1T600s60	599.7	1.03	0.87	1.00	---	---	1.00	0.90	1.00	---	---	1.03	0.97	1.00	---	---
L1T600s180	594.1	1.03	0.83	0.98	---	---	1.00	0.90	1.00	---	---	1.03	0.92	0.98	---	---
L1T700s20	697.0	1.00	0.80	1.01	1.82	0.64	1.00	0.82	1.00	1.82	0.83	1.00	0.97	1.01	1.00	0.77
L1T800s20	795.0	1.04	0.79	1.06	1.82	0.53	1.00	0.77	1.00	1.85	0.51	1.04	1.02	1.06	0.98	1.02
L1T900s20	889.8	1.04	0.71	1.02	1.92	0.52	1.00	0.73	1.00	1.85	0.53	1.04	0.98	1.02	1.04	0.99
L1T1000s20	990.7	1.01	0.72	0.94	1.28	0.61	1.00	0.69	1.00	1.33	0.60	1.01	1.05	0.94	0.96	1.00
L2T24	23.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
L2T300s20	307.4	1.05	1.02	0.99	0.93	1.98	1.00	1.00	1.00	0.97	1.77	1.05	1.02	0.99	0.96	1.12
L2T500s20	509.1	1.07	1.03	1.03	0.94	1.48	1.00	0.99	1.00	0.92	1.64	1.07	1.04	1.03	1.02	0.90
L2T700s20	701.0	1.09	0.77	1.03	1.96	0.60	1.00	0.82	1.00	1.85	0.82	1.09	0.94	1.03	1.06	0.74
											# of data	17	17	17	14	14
											Mean	1.03	1.00	1.00	0.99	1.01
											COV	0.024	0.042	0.027	0.058	0.179
											Resistance factor (ϕ_0)	0.95	0.91	0.96	0.93	0.81
											Reliability index (β_0)	2.50	2.50	2.50	2.50	2.50
											Resistance factor (ϕ_1)	0.95	0.90	0.95	0.90	0.80
											Reliability index (β_1)	2.50	2.56	2.51	2.63	2.52

Note: L1 and L2 are extracted from sections 150×50×2.5 and 50×50×1.5, respectively.

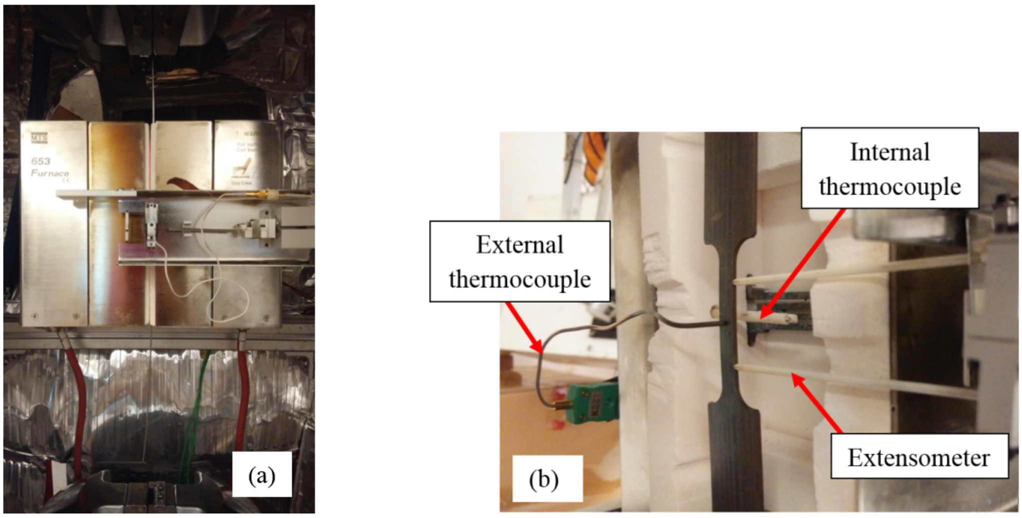


Fig. 1. (a) MTS high temperature furnace. (b) Test specimen in furnace.

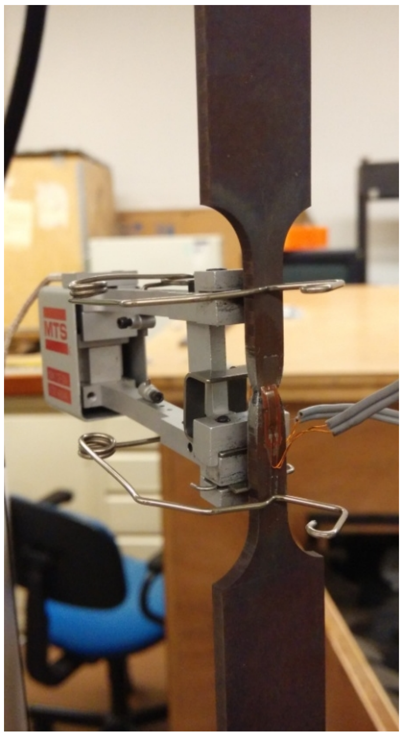


Fig. 2. Tensile coupon test

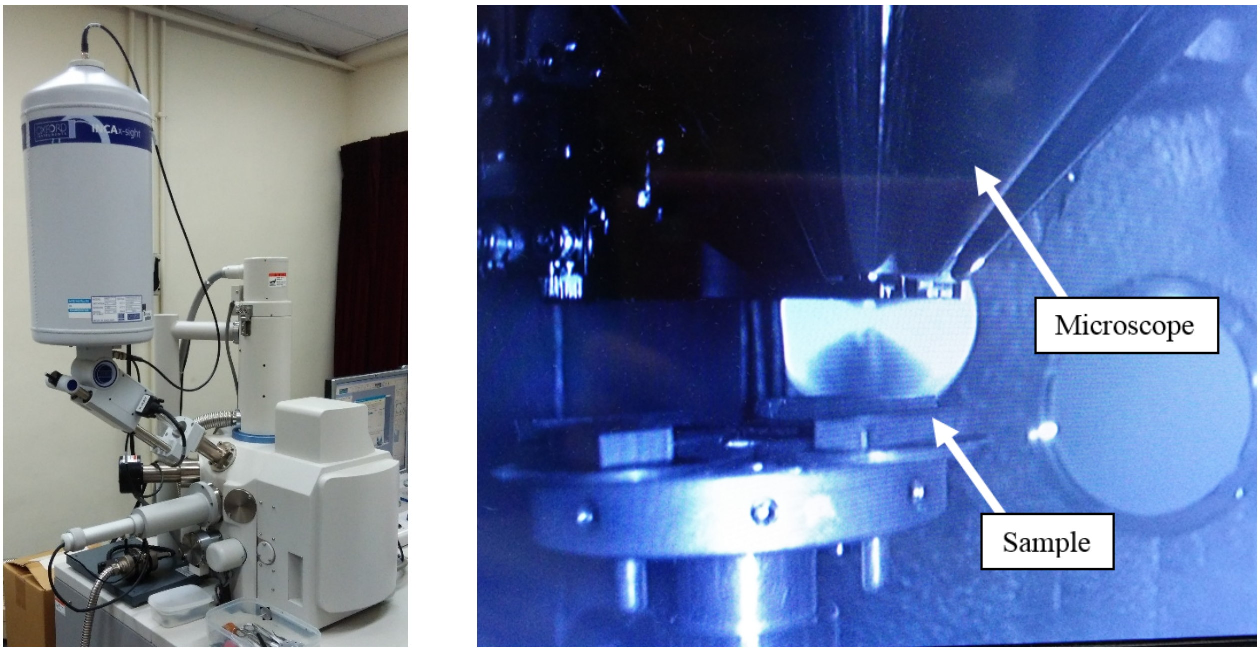


Fig. 3. Test setup for scanning electron microscopy analysis.

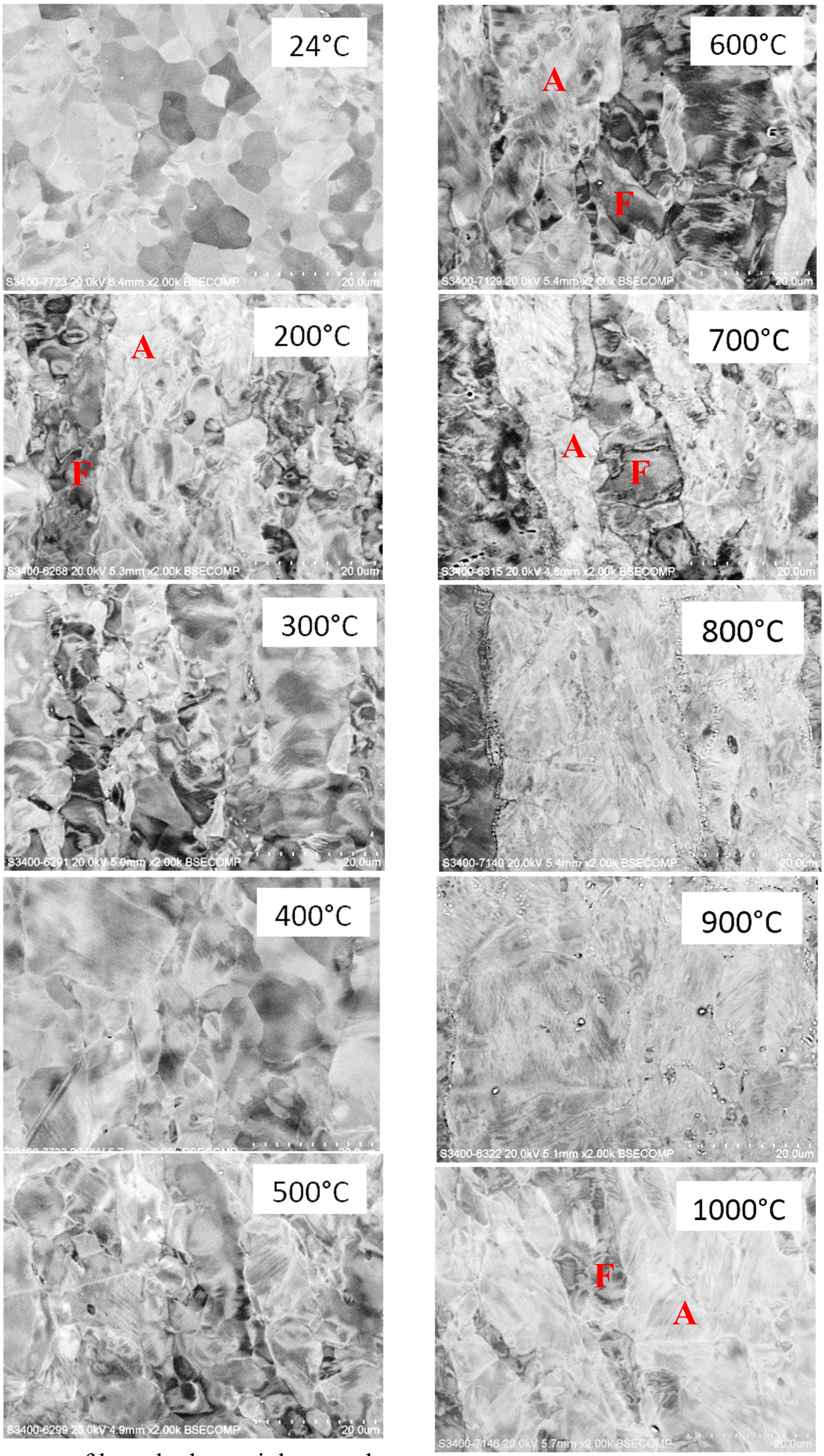
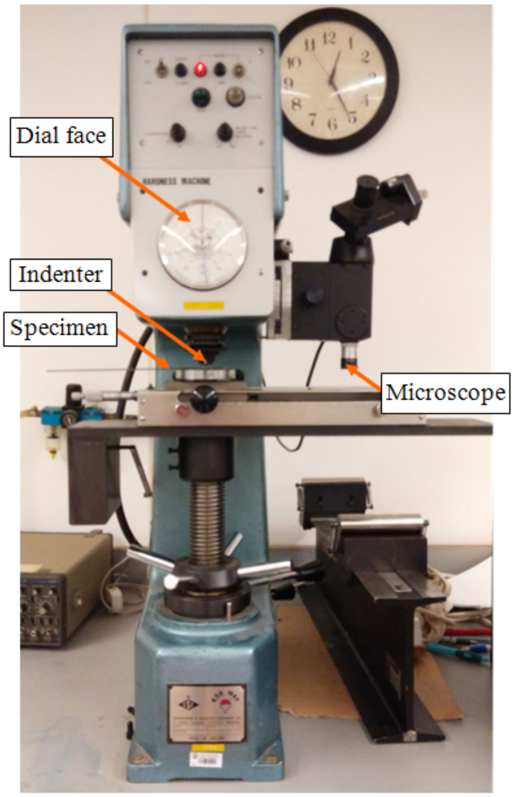
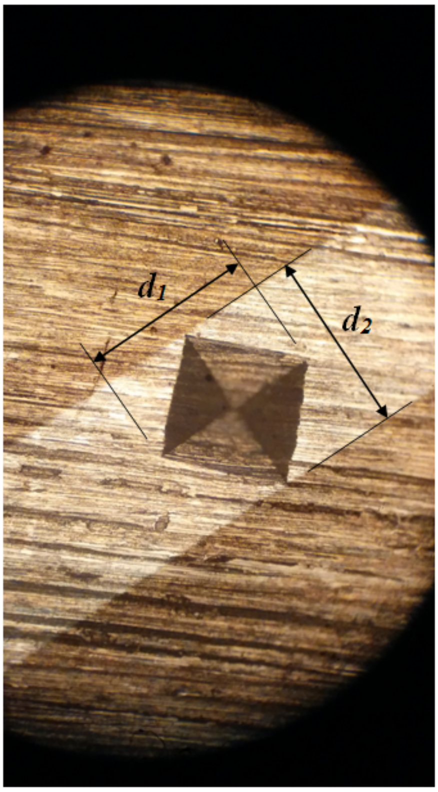


Fig. 4.
Microstructure of lean duplex stainless steel specimens after exposed to elevated temperature (A = Austenite, F = Ferrite).



(a)



(b)

Fig. 5. (a) Test setup of hardness test. (b) Indentation of test specimen in microscope.

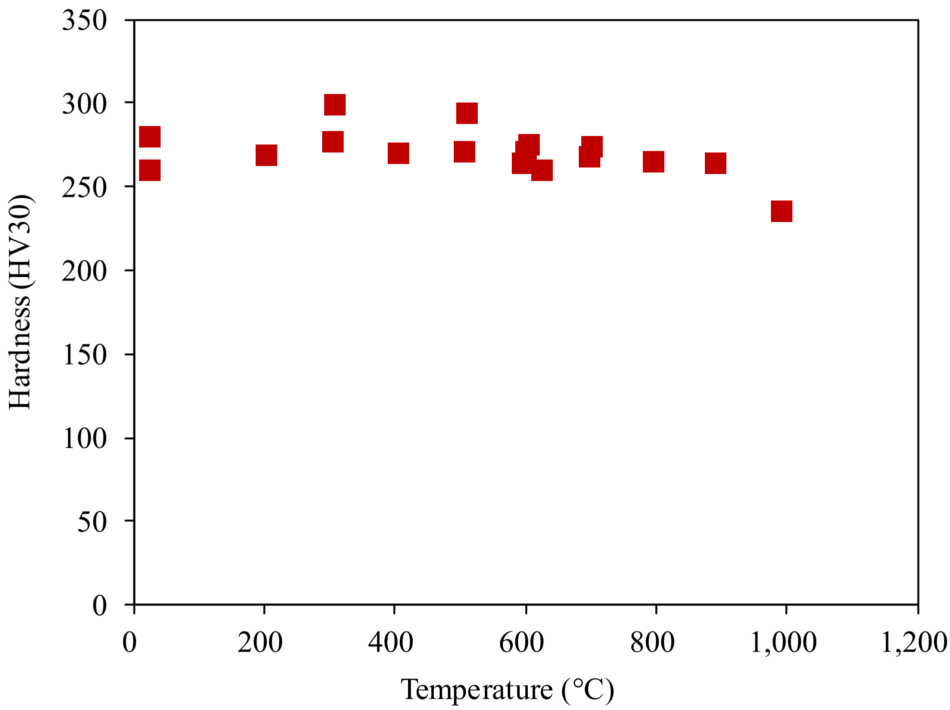


Fig. 6. Hardness of lean duplex stainless steel at different temperatures.

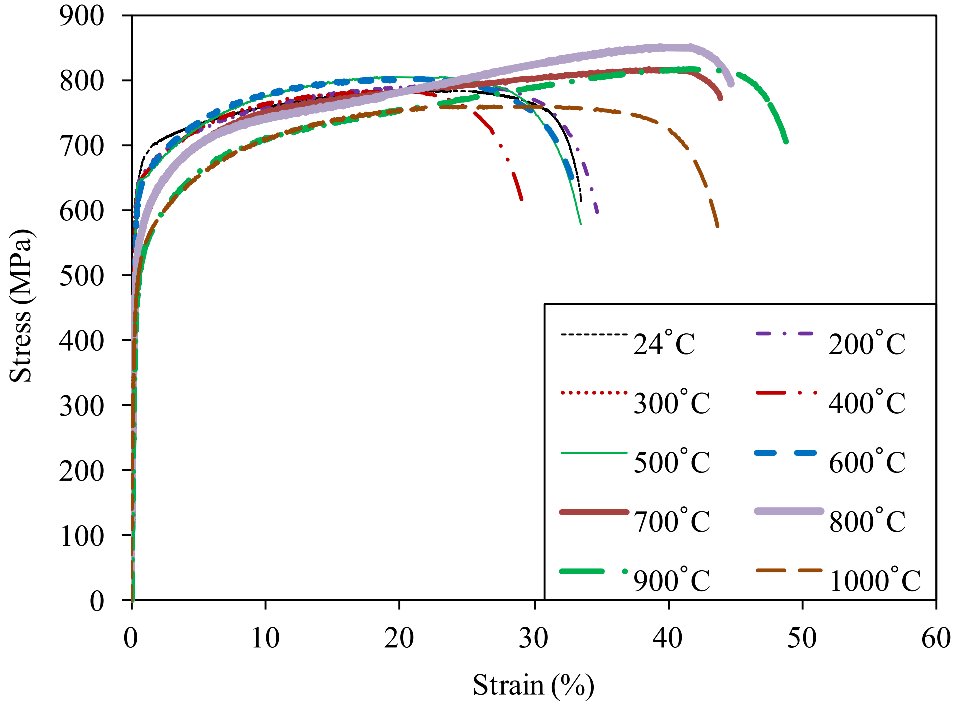


Fig. 7. Stress-strain curves of lean duplex stainless steel type "L1" at different temperatures.

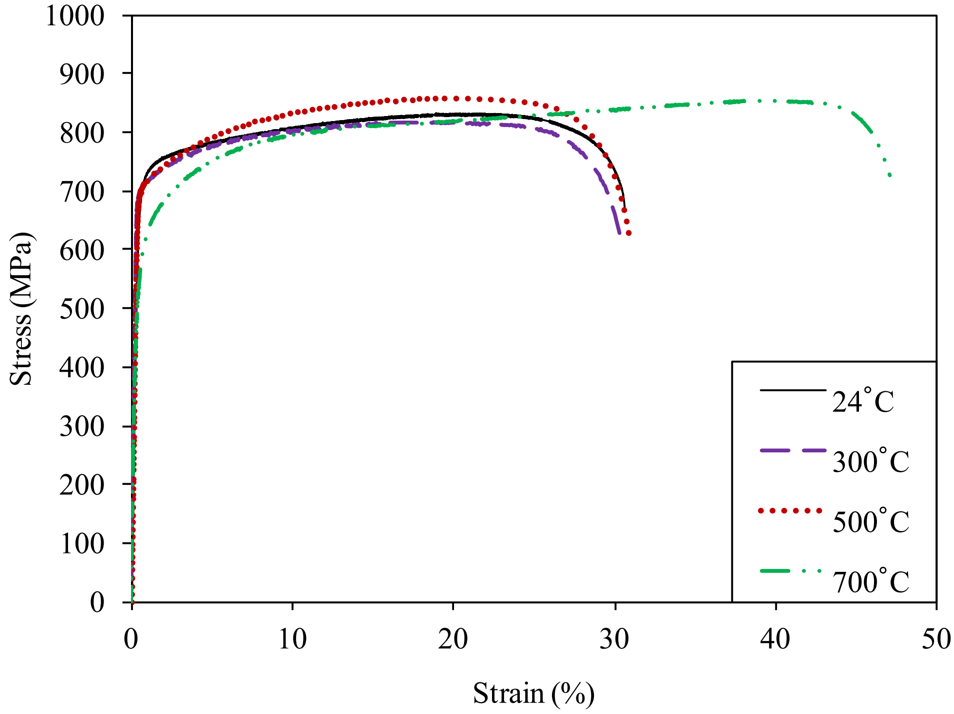


Fig. 8. Stress-strain curve of lean duplex stainless steel type "L2" at different temperatures.

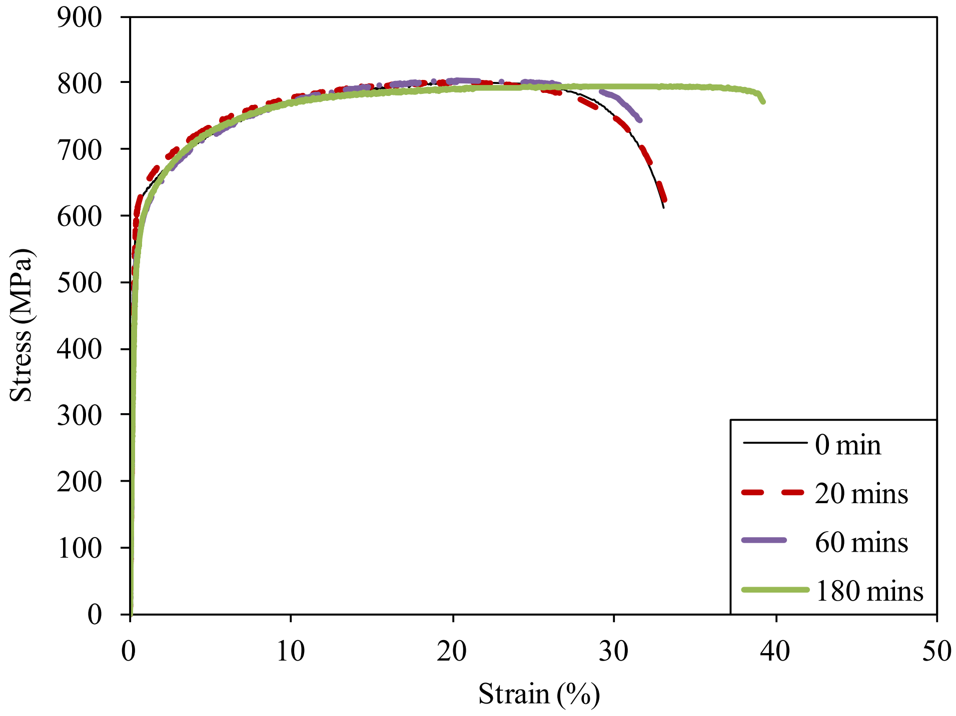


Fig. 9. Stress-strain curves of lean duplex stainless steel at 600 °C with different soak time.

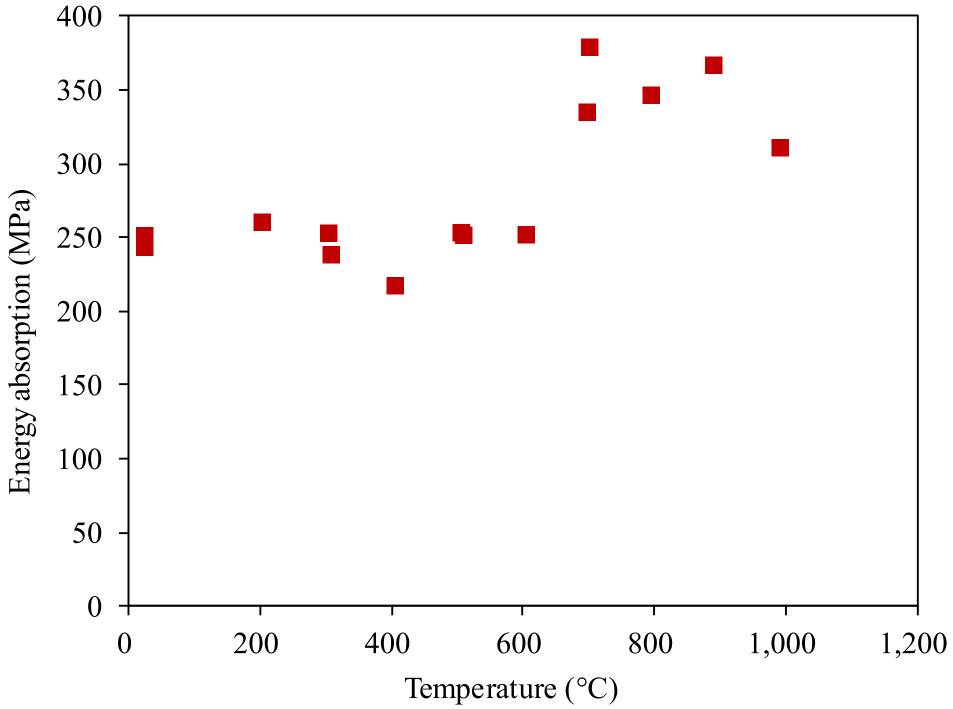


Fig. 10. Energy absorption of lean duplex stainless steel at different temperatures.

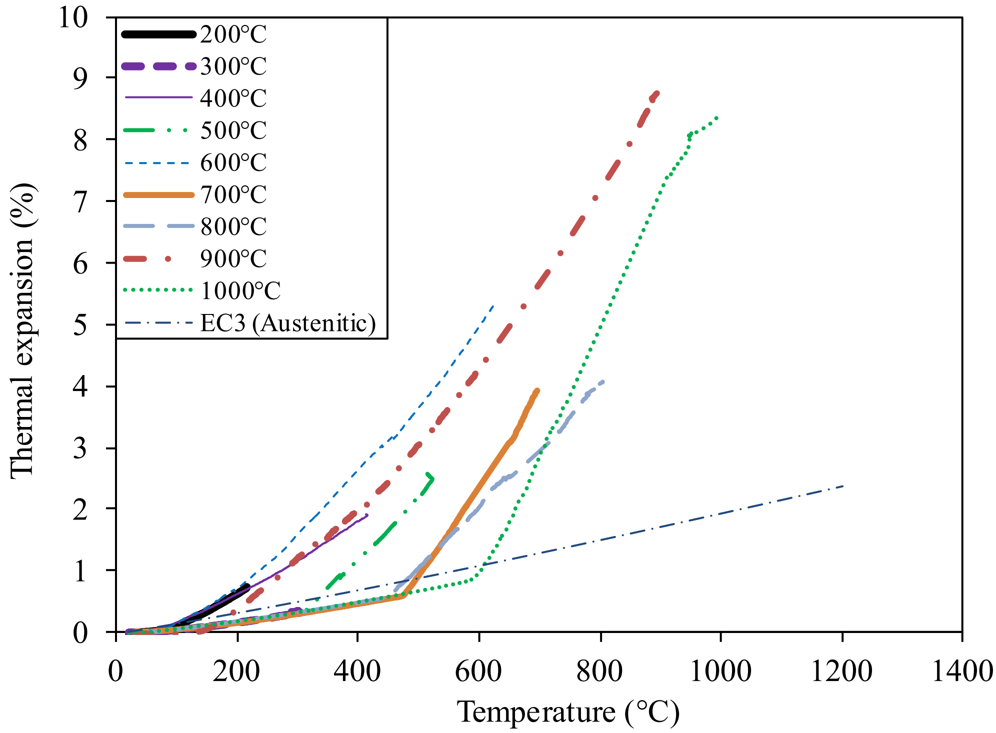


Fig. 11. Thermal elongation predicted by EC3 with lean duplex stainless steel test results.

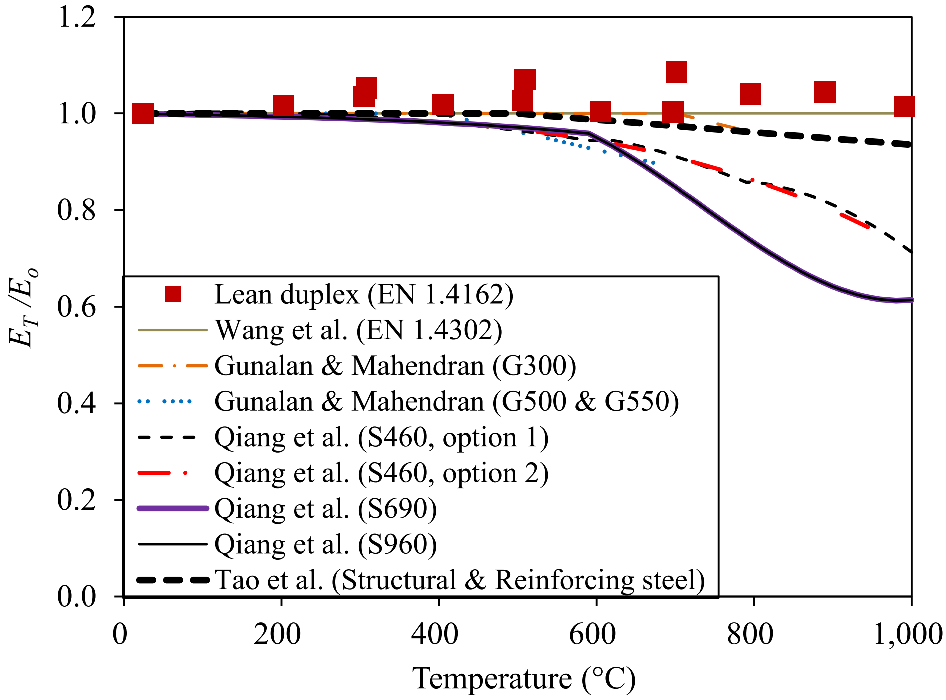


Fig. 12. Residual factor of Young's modulus

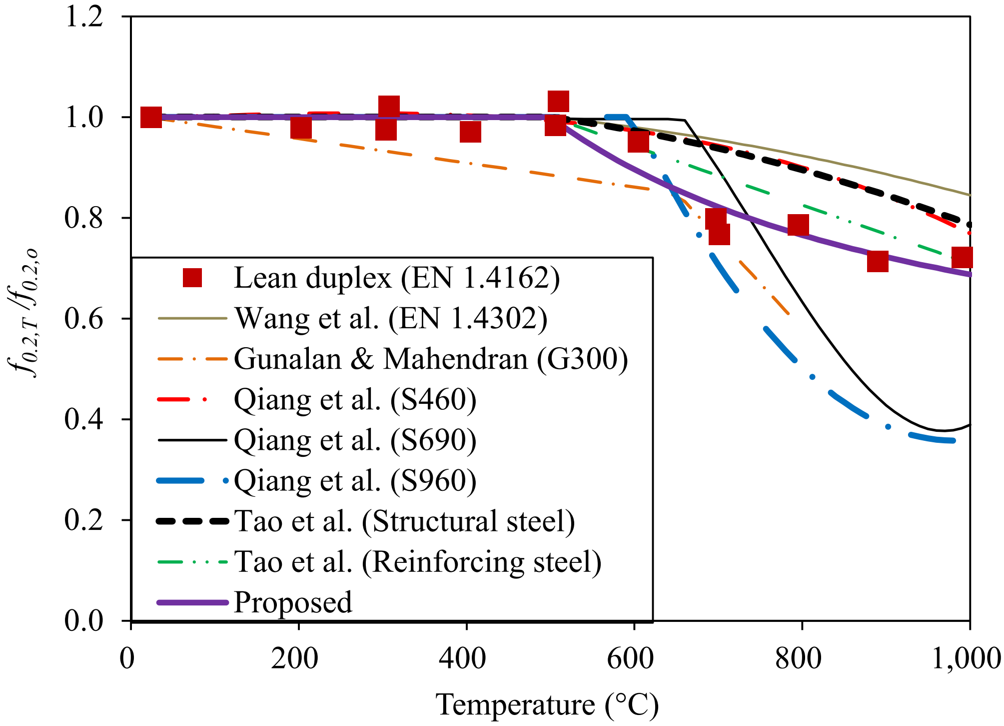


Fig. 13. Residual factor of yield strength

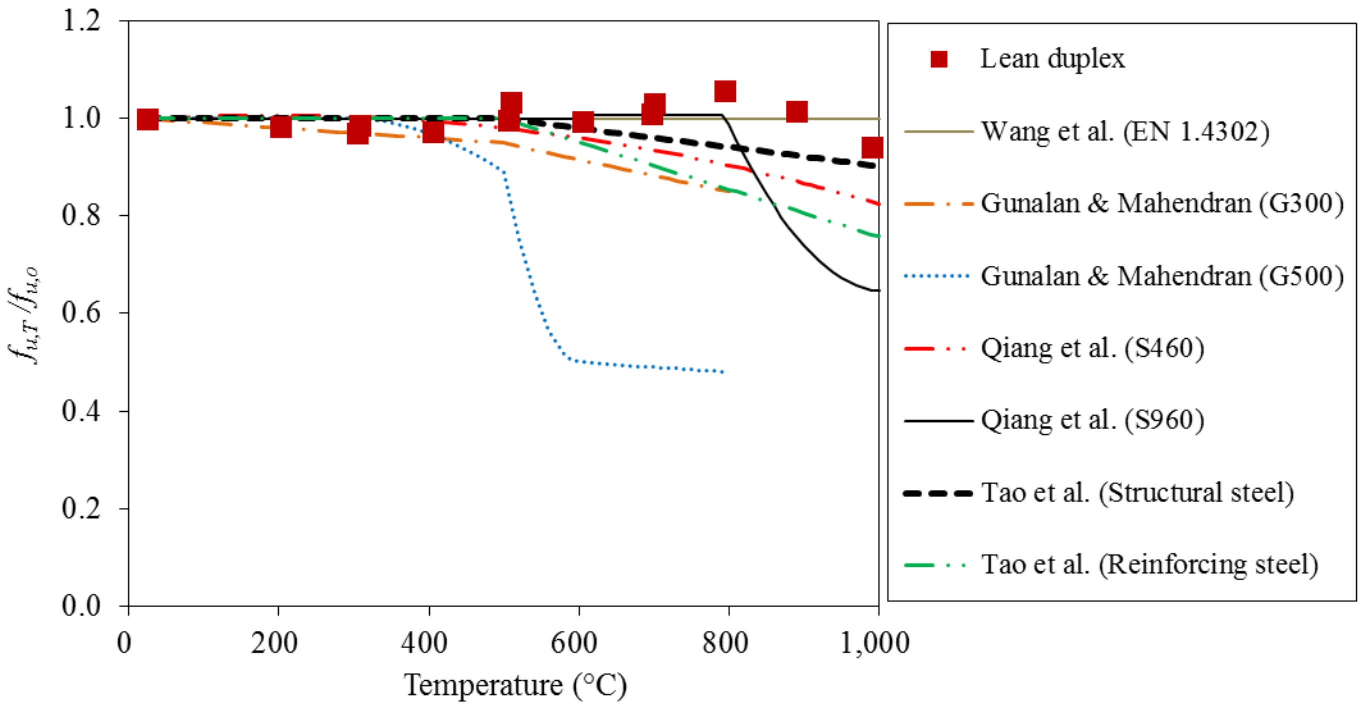


Fig. 14. Residual factor of ultimate strength

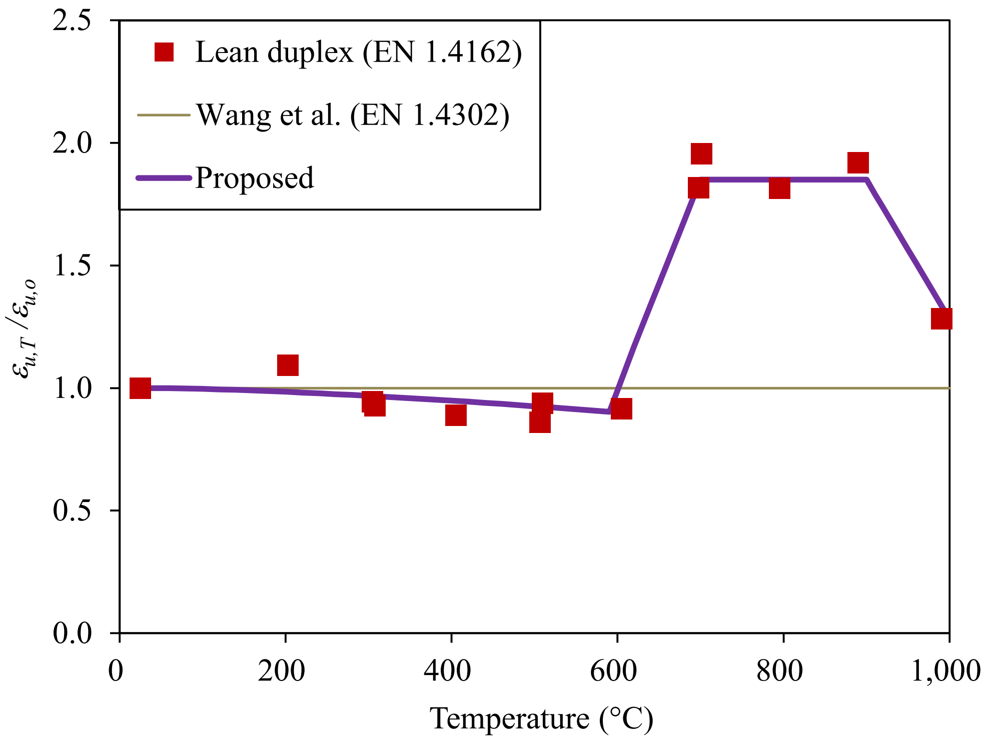


Fig. 15. Residual factor of ultimate strain

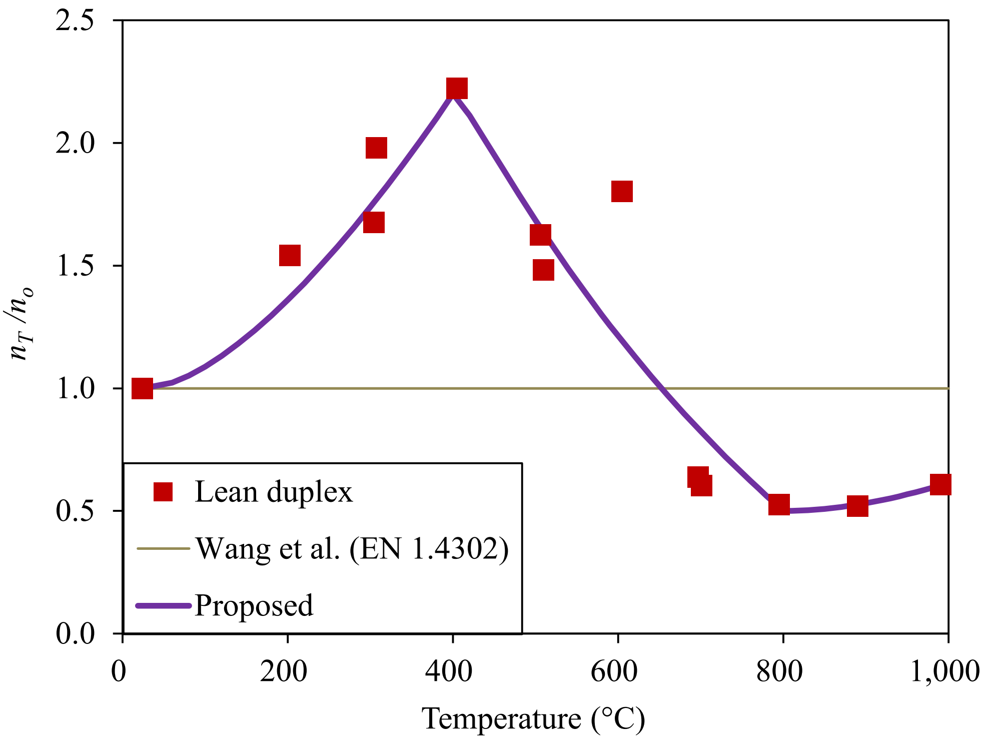
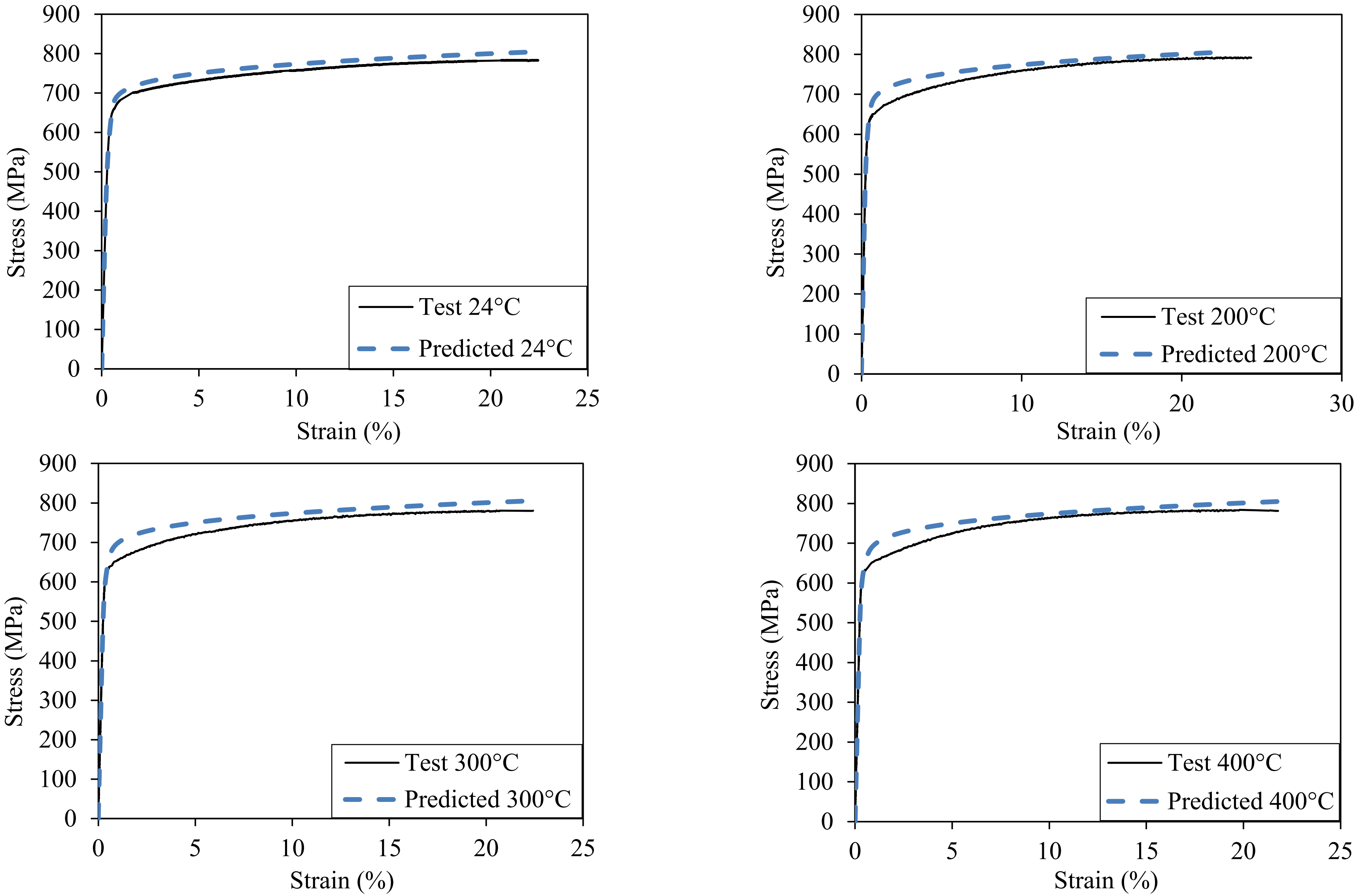


Fig. 16. Residual factor of Ramberg-Osgood parameter


Stress (MPa)
Strain (%)
Test 24°C
Predicted 24°C
Test 200°C
Predicted 200°C
Test 300°C
Predicted 300°C
Test 400°C
Predicted 400°C

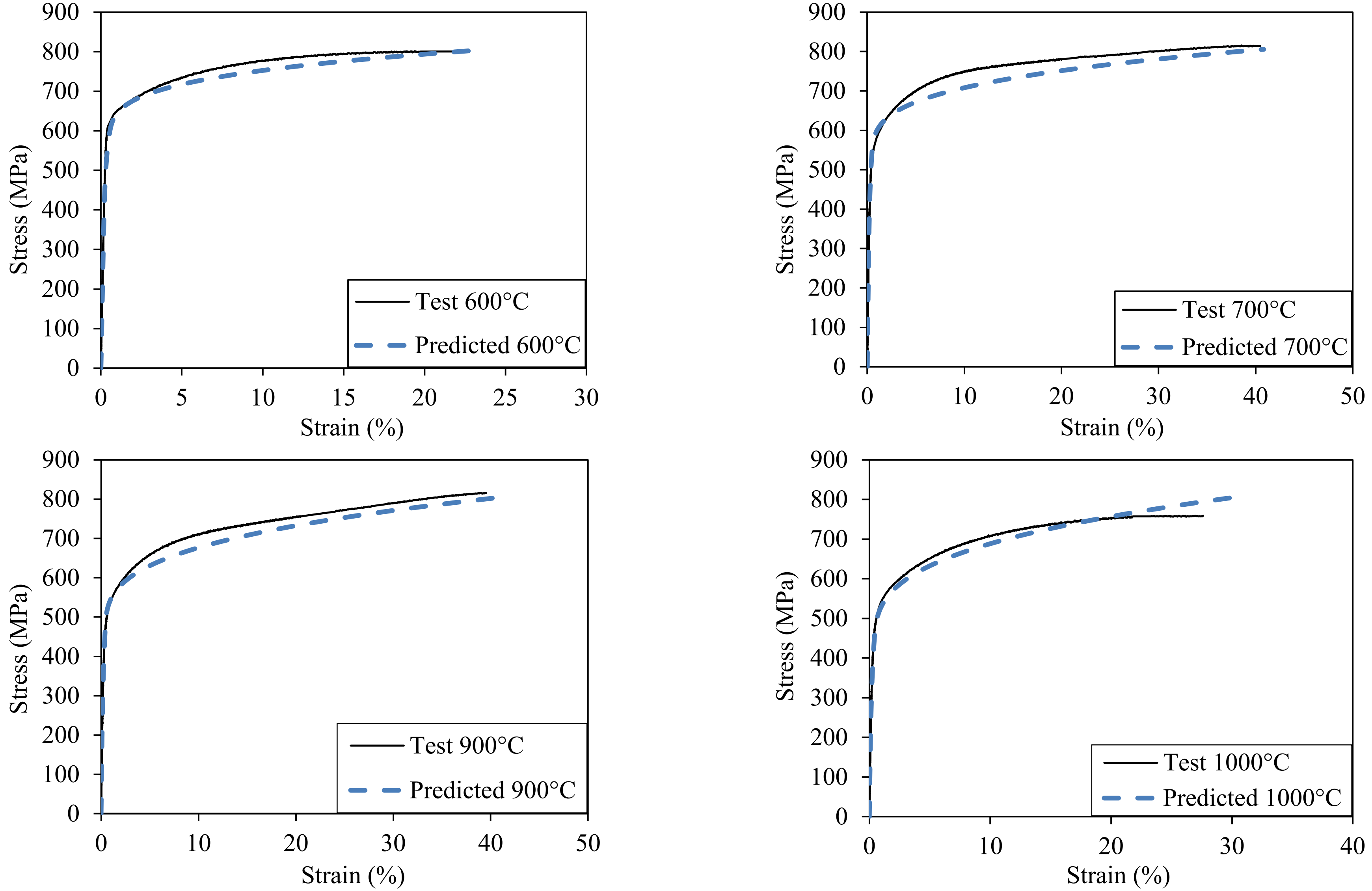


Fig. 17. Stress-strain curve of lean duplex stainless steel (t = 2.5 mm)

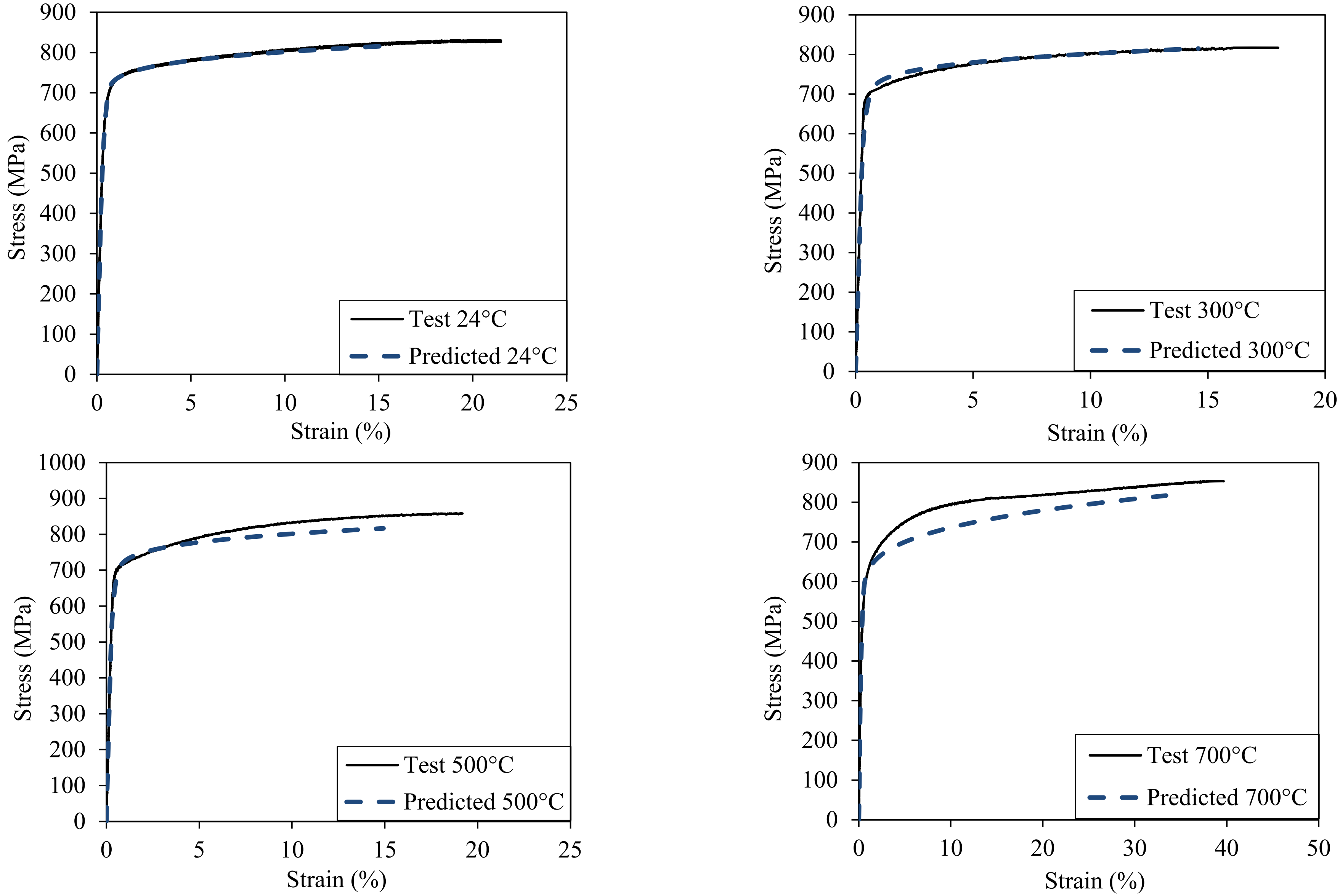


Fig. 18. Stress-strain curve of lean duplex stainless steel (t = 1.5 mm)

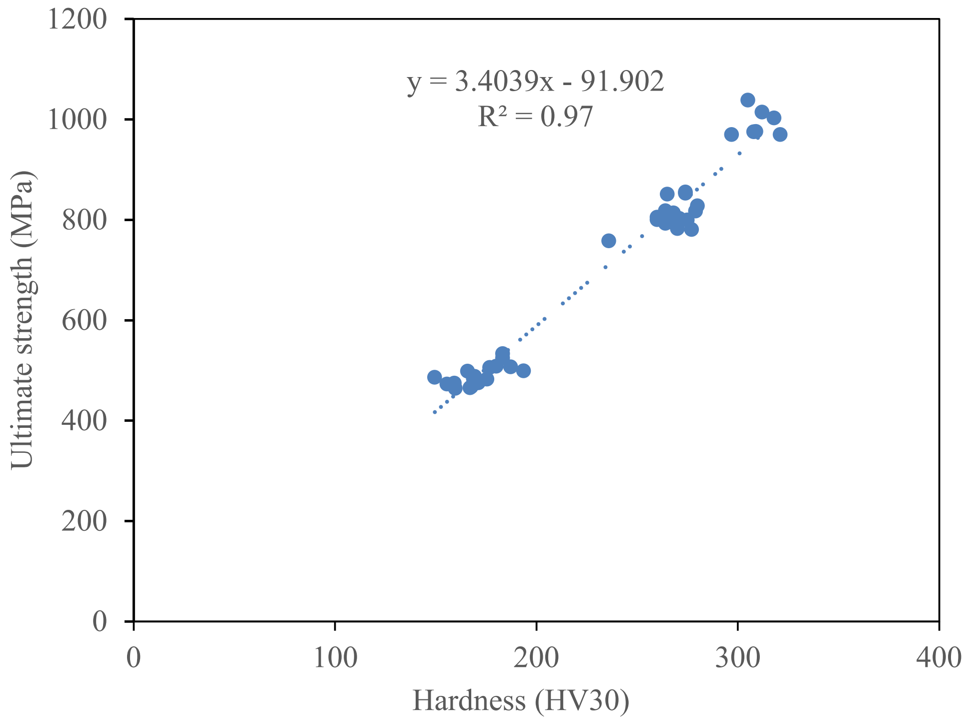


Fig. 19. Relationship of the ultimate strength and Vickers hardness value

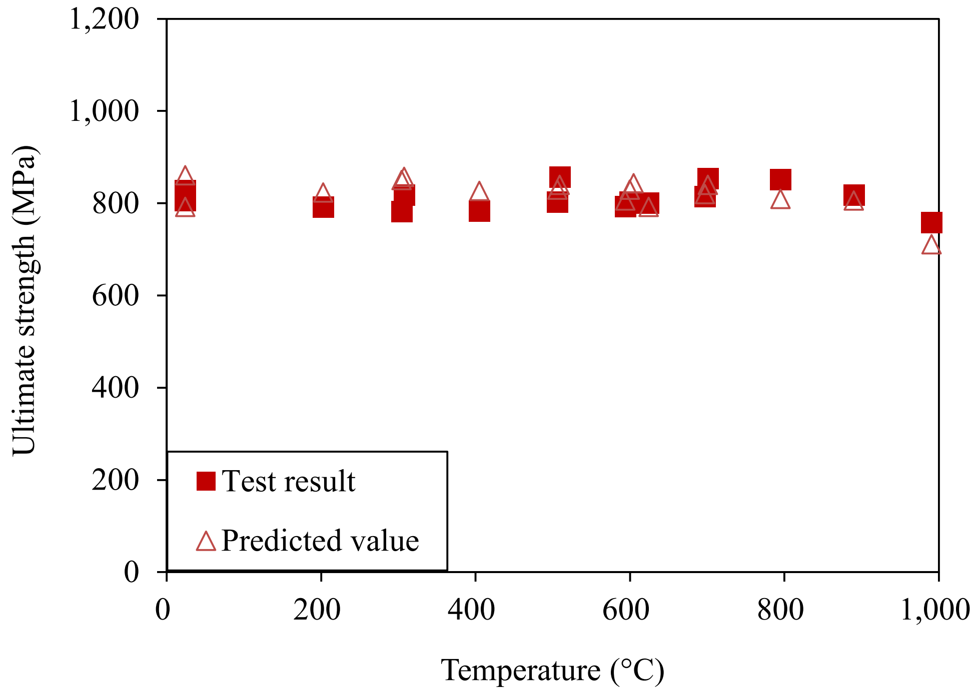


Fig. 20. Comparison of the test results and predicted value of ultimate strength for lean duplex stainless steel