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Mechanical Properties of Austenitic Stainless Steel After Exposure to Elevated Temperature

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ABSTRACT

Stainless steel has been widely used in the building industry as load-bearing elements such as beams and columns. Many fire accidents in stainless steel buildings were recorded, but only a few have collapsed entirely. These buildings can be rehabilitated and the undamaged parts can be reused, which reduces the economic losses in buildings exposed to fire. The residual mechanical properties of stainless steel after the fire, are the primary determinant of the validity of the stainless-steel structure. In this paper, the effect of high temperatures and the time of exposure and cooling method on the mechanical properties of S304 stainless steel was studied. The specimens were heated to 800°C and 1000°C for different heating times (30, 60,90 and 120 minutes) and cooling methods (air-cooled and water-cooled). Results showed that the post-fire yield stress was reduced by 24% and 18% after heating to 800°C for 120minutes and cooled in water and air respectively. However, heating to 1000°C showed a marginal effect on the yield stress of air-cooled specimens and a clear reduction (29%) in the water-cooled specimens. Elongation capacity increased with heating time for 1000ºC specimens but decreased for 800ºC specimens in both cooling methods.

1. Introduction

Stainless steel has been used in buildings since the beginning of the twentieth century. It was used in decorations and cladding the buildings. Then, the use of stainless steel became very popular as a structural element. It was also used in historical buildings for its excellent structural performance, aesthetics, corrosion resistance, and durability [1-2]. However, fire represents the most dangerous hazard for carbon and stainless-steel buildings. A number of studies in the literature aimed at evaluating the impact of high temperature on carbon steel structural elements during and after fire [3-11]. For stainless steel, several studies have been conducted on the structural behaviour and methods of designing stainless steel after being exposed to high temperatures, but few have reported the change in the mechanical properties of stainless steel after exposure to fire. Gardner [12] and Gardner and NG [13] studied the properties and composition of stainless steel and the change that occurs in its properties after exposure to fire. The strength and hardness of stainless steel are affected by the high temperatures, but the level of thermal expansion is also high. It was proposed to reduce the emissivity ratio from 0.4 to 0.2 and to increase the heat transfer coefficient to (35W/m^{2}K) instead of the value used (25 W/m^{2}K). This achieves a better correlation between predicted and measured temperature development in structural stainless-steel sections.

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Gao et al. [14] compared two different types of stainless steel S304 and S316 during heating at different temperatures and heating times (30 minutes and 180 minutes) and cooling in air or water. It was found that the modulus of elasticity increases when heating to a temperature less than 1000°C and then decreases with increasing heating temperature. Yield strength decreases proportionally with increasing temperature. Heating time and cooling method have limited impact on the modulus of elasticity, nominal yield strength, final tensile strength, rupture stress, and post-fracture elongation of stainless steels. Nagie [15] presented that water-cooling can increase the hardness and tensile strength and air-cooling improve the ductility of carbon steel. Huang and Young [16] heated specimens of lean duplex stainless steel to a temperature of 1000°C. The residual mechanical properties of stainless steel were compared with the expected values calculated by current equations, and a standardized equation was proposed to predict the residual mechanical properties of lean duplex stainless steel specimens in post-fire conditions. Choi et al. [17] analysed the evolution of the microstructure of a group of stainless steel coupons and studied the changes in their chemical properties after exposure to high temperatures, a decrease in strength, hardness, and an increase in elongation, with the increase of heating time was recorded. Fan et al. [18] tested stainless steel coupons after being heated to temperatures from 100°C to 900°C and heating time (30 and 60) minutes, and it was found that the deformation of the coupons increased with increasing the temperature. Much research has been conducted on the behaviour of stainless steel after exposure to high temperatures. However, some aspects have not been addressed adequately to quantify the effect of fire on the post-fire properties of stainless steel in terms of combining the effect of temperature with a large range of variations in the time of exposure to fire and the method of cooling. Therefore, the purpose of this research is to study the post-fire physical, chemical and mechanical properties of stainless steel after exposure to high temperatures (800°C and 1000°C).

2. Experimental work

2.1 Specimen's geometry

The test programme includes tensile testing of stainless-steel coupons. The dimensions of the coupons are shown in Figure (1). They are according to EN 10002-1:2001[19]. The thickness of coupons is 4mm. The coupons are presented in Table (1). The coupon names reflect the investigated parameter. For example, CSt4 h800 t30 CA, (C) coupons, (St)stainless steel, (t4) the thickness of coupons is 4mm, (h800) 800ºC is the temperature at which the sample was heated, (t30) means the heating time is 30 minutes in the furnace, (CA) means cooled in air. Figure (2) presents specimen CSt4 h800 t30 CA.

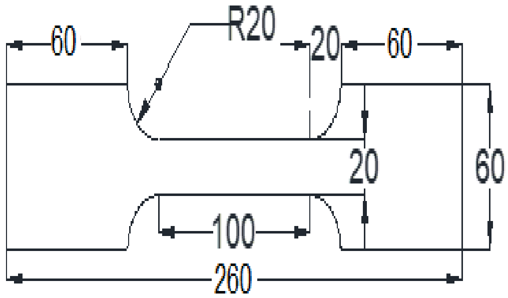


Figure 1. Coupon geometry (All dimensions in mm)

Figure 2. Specimen CSt4 h800 t30 CA

Table 1: Tested specimens

Coupons	Thickness after heating (mm)	Cooling method	Heating temperature	Time of heating (min)
Cst4 h20	---	---	20ºC	---
Cst4 h800t30 CW	3.87	CW	800 ºC	30
Cst4 h800 t30 CA	3.87	CA	800 ºC	30
Cst4 h800 t60 CW	3.87	CW	800 ºC	60
Cst4 h800 t60 CA	3.88	CA	800 ºC	60
Cst4 h800 t90 CW	3.87	CW	800 ºC	90
Cst4 h800 t90 CA	3.88	CA	800 ºC	90
Cst4 h800 t120 CW	3.86	CW	800 ºC	120
Cst4 h800 t120 CA	3.88	CA	800 ºC	120
Cst4 h1000 t30 CW	3.88	CW	1000 ºC	30
Cst4 h1000 t30 CA	3.88	CA	1000 ºC	30
Cst4 h1000 t60 CW	3.86	CW	1000 ºC	60
Cst4 h1000 t60 CA	3.85	CA	1000 ºC	60
Cst4 h1000 t90 CW	3.85	CW	1000 ºC	90
Cst4 h1000 t90 CA	3.83	CA	1000 ºC	90
Cst4 h1000 t120 CW	3.81	CW	1000 ºC	120
Cst4 h1000 t120 CA	3.80	CA	1000 ºC	120

2.2 Heating and cooling

The coupons are heated to a temperature of 800°C or 1000°C for heating times 30 minutes, 60 minutes, 90 minutes and 120 minutes inside the furnace. Then cooled to room temperature in two ways: the first method is CA air cooling and the second method is the water-cooled CW. Figure (3) shows the heating of the coupons in the furnace.

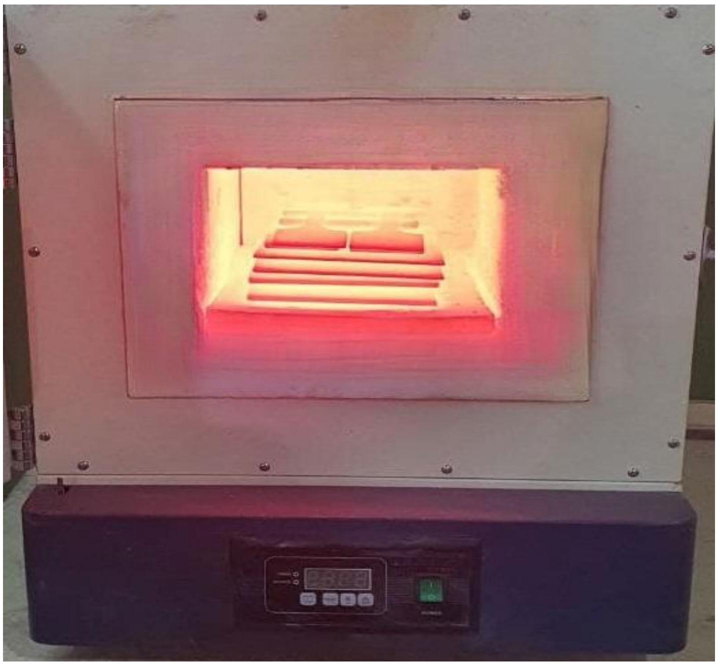
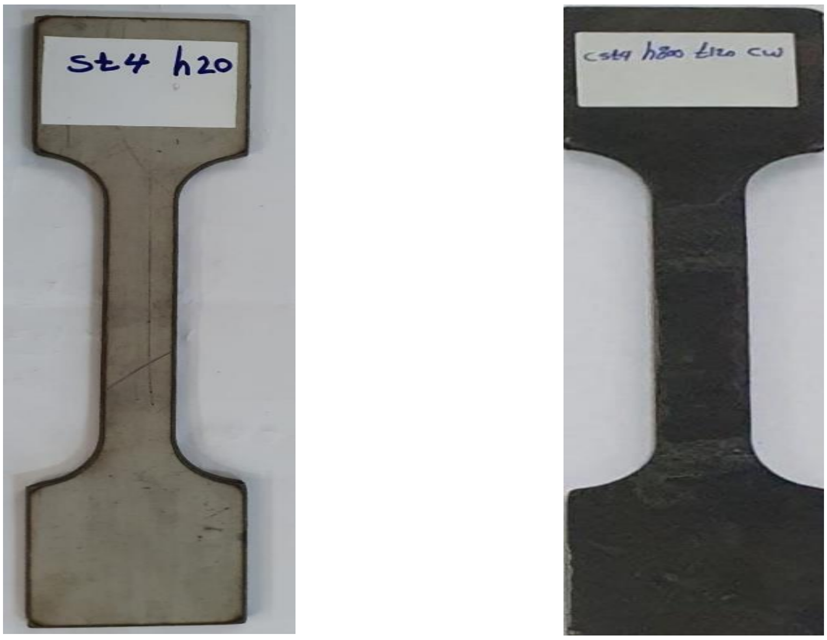


Figure 3. Coupons in the furnace



Silver Dark grey

Figure 4. Change in coupon colour

3. Results and discussions

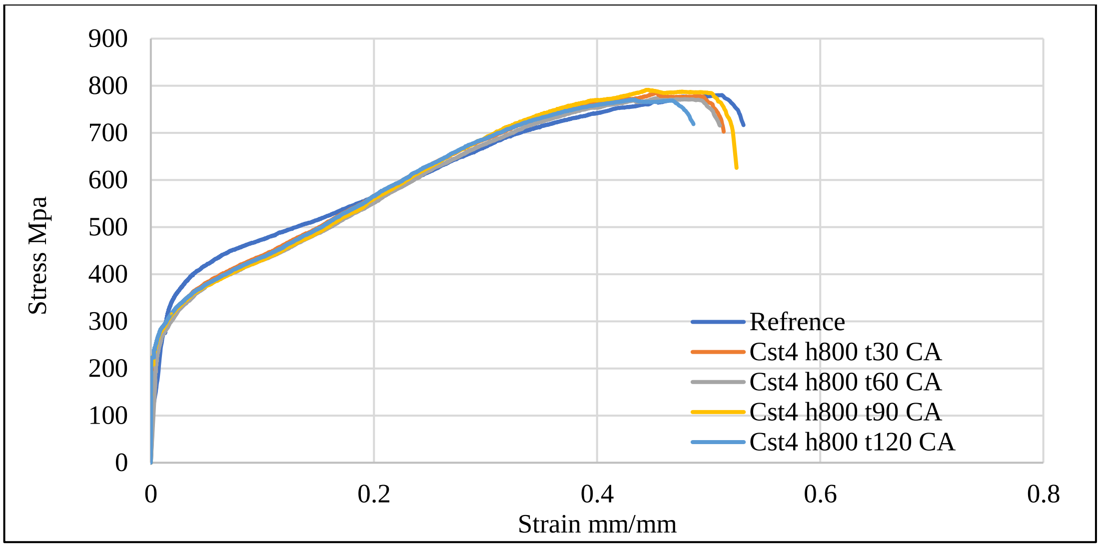
3.1 Physical changes

The dimensions of the coupons are measured by a digital calliper before placing them in the furnace. After that, the coupons are kept in the furnace according to the specified soaking time and are cooled according to the type of cooling. Then the dimensions of the coupons are measured to quantify the extent to which the coupons are affected by the high temperatures cooling method. There was some reduction in the thickness of the specimen due to the flacking of oxides at the surface (Figure 5). The maximum reduction was about 5% for coupons heated to 1000 ° C for120 minutes and cooled in air. The colour of the coupon changed from silver to dark grey at a temperature of 800°C, as shown in Figure (4). This darkening increased at a temperature of 1000°C. Also, fine grains resembling sand appeared on the surface of the coupon after being cooled by air at a temperature of 1000 ° C, as presented in Figure (5). This change might affect the corrosion resistance of stainless steel.

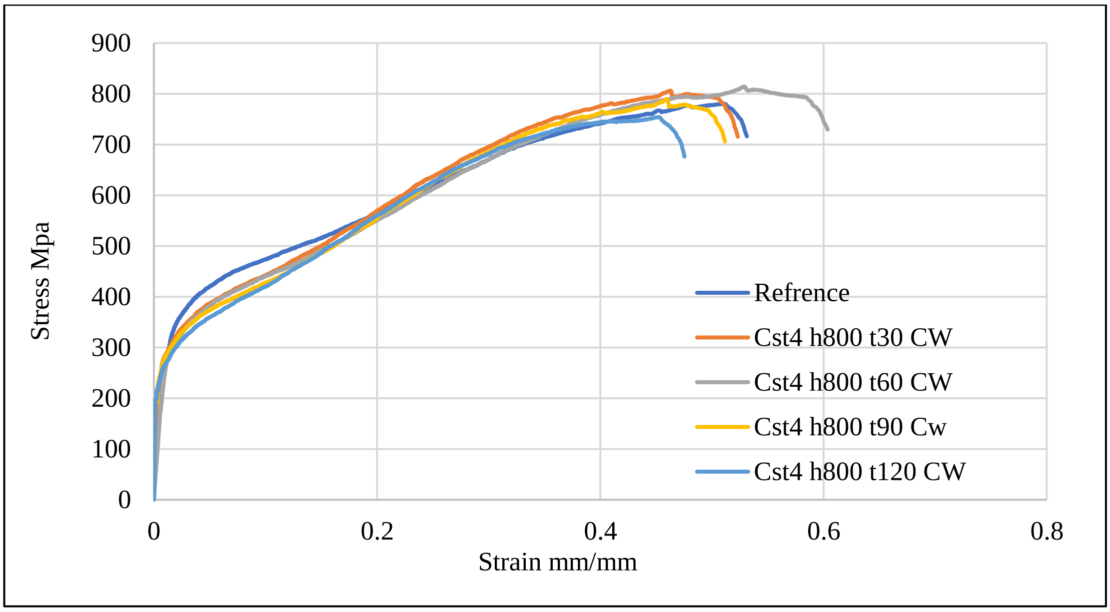
Figure 5. Surface flacking after heating to 1000°C

3.2 Failure mode

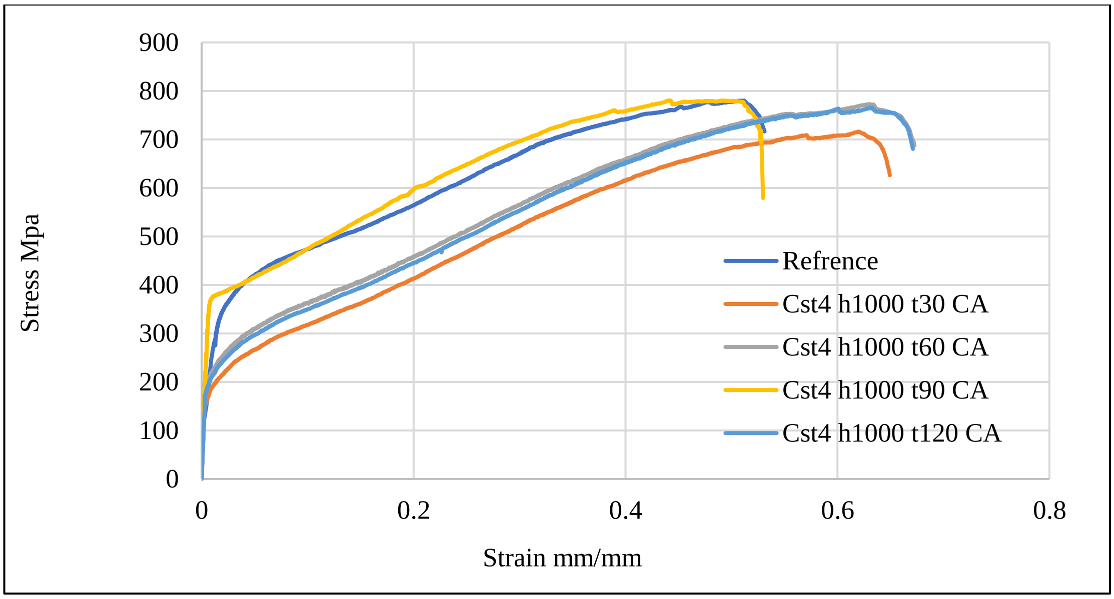
The tensile test is used to obtain the mechanical properties of the coupons, including yield stress, ultimate stress and elongation. The stress-strain curves for all specimens are shown in Figure (6). The high temperature and the cooling methods do not affect the shape of the stress-strain curve. The failure mode of the specimens is presented in Figure (7). All specimens failed in typical tensile fracture mode.


Stress Mpa
900
800
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
Strain mm/mm
Refrence
Cst4 h800 t30 CA
Cst4 h800 t60 CA
Cst4 h800 t90 CA
Cst4 h800 t120 CA

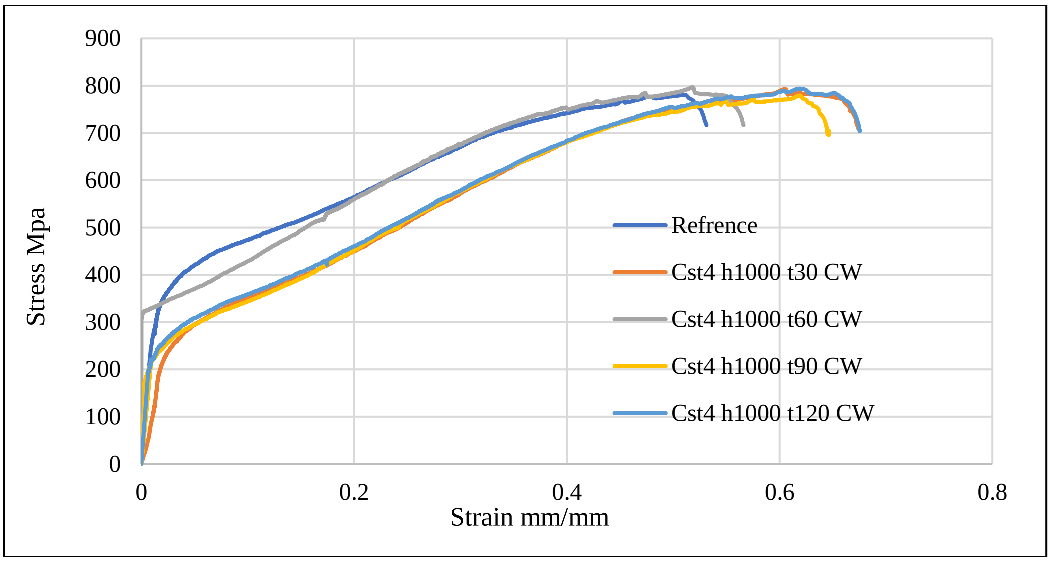
a)


Stress Mpa
900
800
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
Strain mm/mm
Refrence
Cst4 h800 t30 CW
Cst4 h800 t60 CW
Cst4 h800 t90 Cw
Cst4 h800 t120 CW

b)


Stress Mpa
900
800
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
Strain mm/mm
Refrence
Cst4 h1000 t30 CA
Cst4 h1000 t60 CA
Cst4 h1000 t90 CA
Cst4 h1000 t120 CA

c)



d)

Figure 6. Stress-strain curves for the tested specimens a) Specimens heated to 800ºC and cooled in air, b) Specimens heated to 800ºC and cooled in water, c) Specimens heated to 1000ºC and cooled in Air, d) Specimens heated to 1000ºC and cooled in water

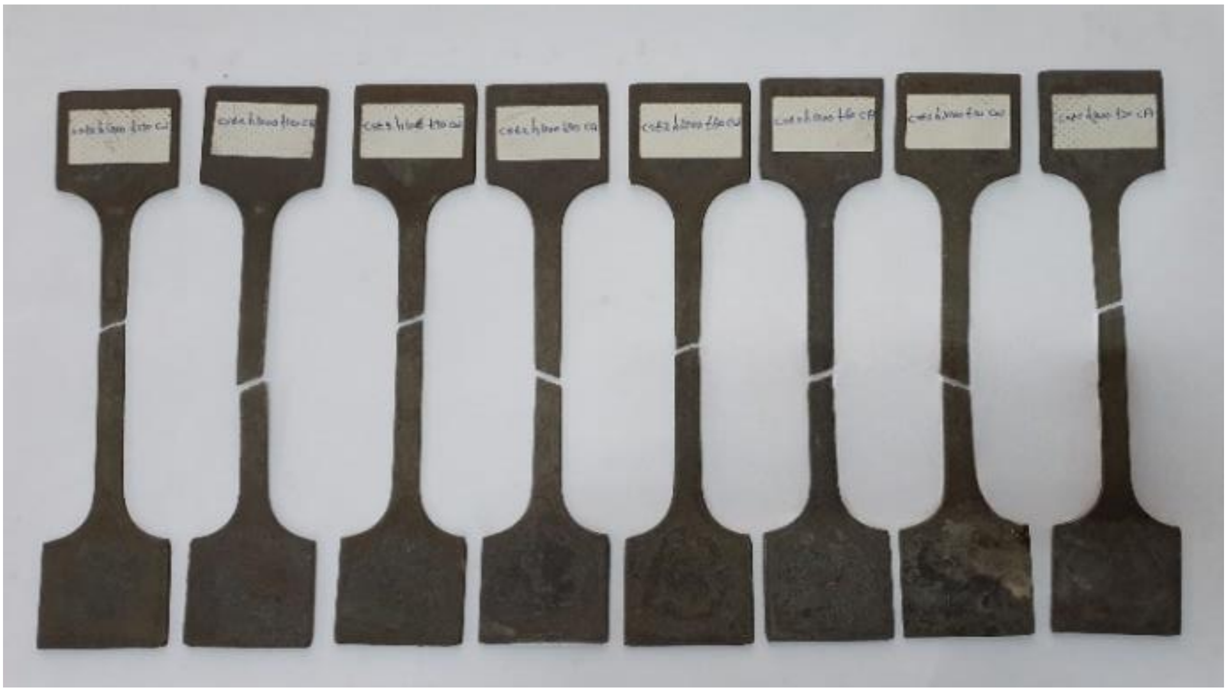


Figure 7. Coupon failure modes

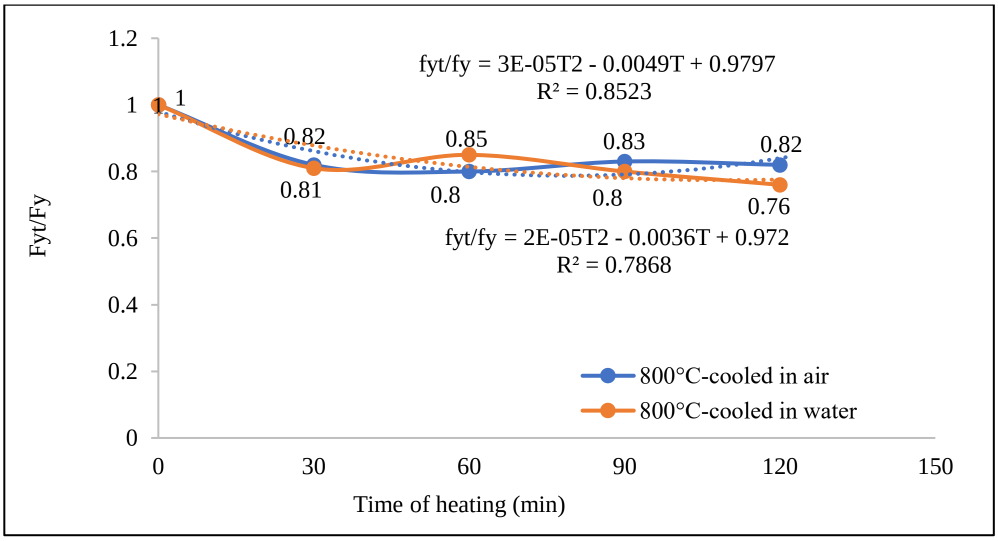
3.3. Effect of heating to 800°C

Table (2) shows the results of the specimens heated to 800°C and cooled in air or water. When specimens are cooled in air, the yield stress value decreases with heating. The reduction reaches 20% for Cst4 h800 t60 CA at a heating time of 60 minutes, then the yield stress showed scattering values in the reduction but it remains lower than the reference specimen. The ultimate stress value for the heated coupons was close to the reference coupon. The elongation for all heating times remains close to the elongation of the reference coupon. The elastic modulus values of the coupons subjected to heating are close to the value of the elastic modulus of the reference coupon. For water cooling, the yield stress decreases with increasing heating time it reaches 19% for coupon Cst4 h800 t30 CW and the reduction increases as the heating time increases. For coupon Cst4 h800 t120 CW it was 24%. The ultimate strength shows marginal variation. At a heating time of 30 min and 60 min, it was higher than the reference coupon by 3% and 4%, but it decreases at 120 min heating time by 3%. To understand the reason for this variation, further investigation is required by extending the heating time and analyzing the microstructure of the stainless steel after heating. The elongation ratio is close to that of the reference coupon, but a minor reduction in heating time of 120 minutes.

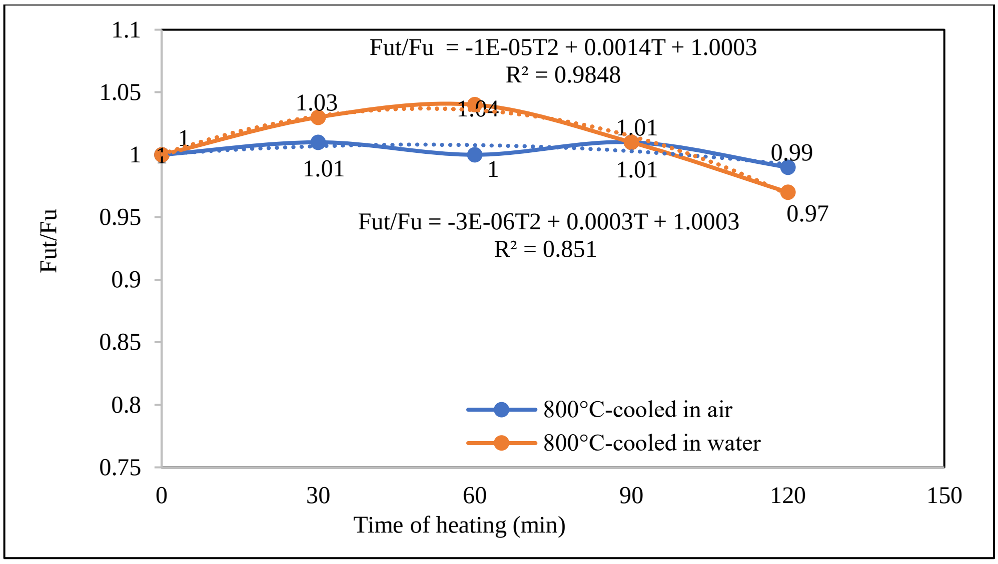
The value of the elasticity modulus is close to the value of the elasticity modulus of the reference coupon. The (F_u/F_y) ratio of water-cooled and air-cooled coupons improved with heating. The heating time and the cooling method seem to be not affecting F_u/F_y. Comparing the results of air cooling and water cooling, it is clear that there is no significant difference in the yield stress, the ultimate stress, elongation ratio and modulus of elasticity between them as the difference in cooling methods did not affect the results clearly (Figure 8).

Table 2: Results of specimens heated to 800°C and cooled by air and water

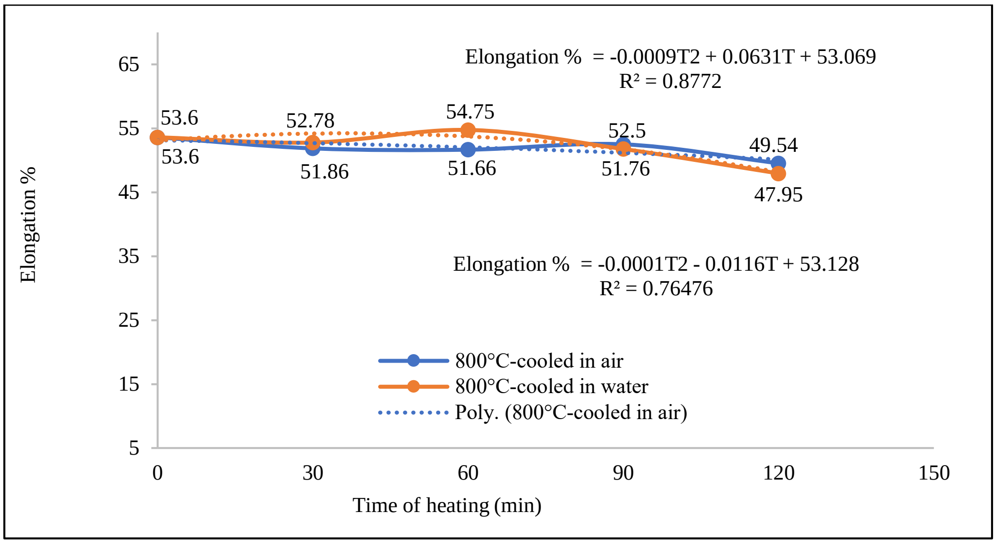
Coupons	**E, Modulus of elasticity (kN/mm^2)**	**F_y Yield stress (N/mm^2)**	**F_u Ultimate stress (N/mm^2)**	**F_u/F_y**
Cst4 h20	219,576	312	780	2.5
Cst4 h800 t30 CA	224,810	254	785	3.1
Cst4 h800t30 CW	224,083	253	806	3.2
Cst4 h800 t60 CA	223,075	248	773	3.1
Cst4 h800 t60 CW	226,817	264	814	3.1
Cst4 h800 t90 CA	221,296	258	791	3.06
Cst4 h800 t90 CW	225,976	248	790	3.2
Cst4 h800 t120 CA	220,665	255	771	3
Cst4 h800 t120 CW	222,114	235	754	3.2



a) Yield stress



b) Ultimate strength



c) Elongation

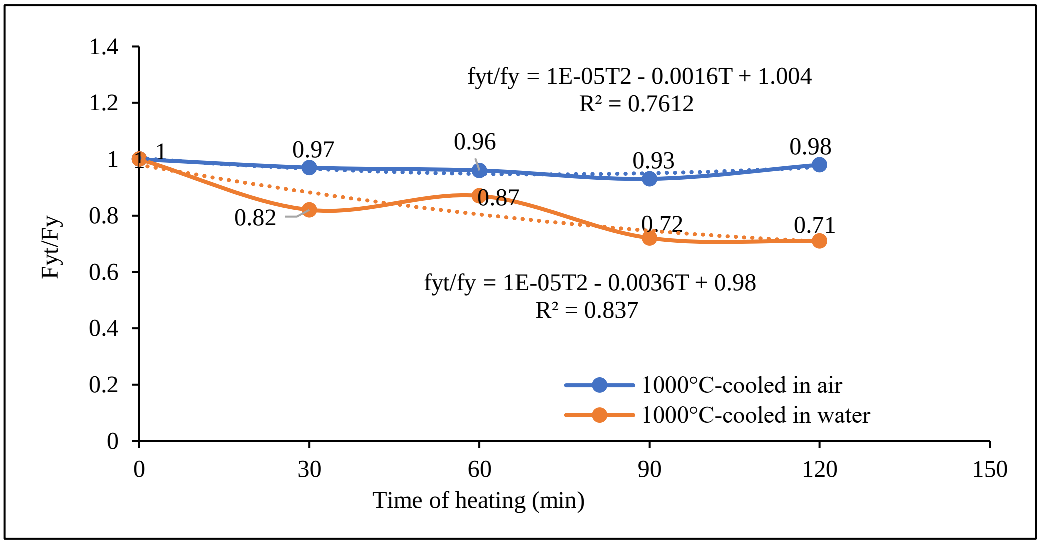
Figure 8. Effect of heating time and cooling method on yield and ultimate stress and elongation 4mm thickness 800°C

3.4. Effect of heating to 1000°C

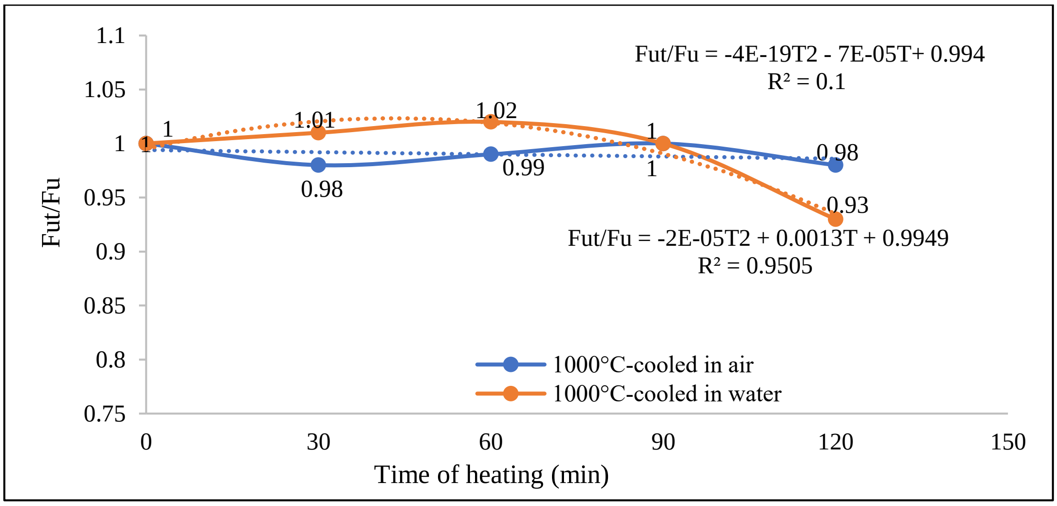
Table (3) shows the results of heating the coupons at a temperature of 1000°C and cooling them in air and water. The value of the yield stress decreases significantly as the heating time increases; the highest percentage of drop reaches 29% for Cst4 h1000 t120 CW. The yield stress remains close to the value of the reference coupon for all heating times, to understand the reason, further investigation is required by extending the heating time. The maximum reduction reaches 7% for specimen Cst4 h1000 t90 CA. The ultimate stress value of the water-cooled and air-cooled coupons showed a marginal difference from the ultimate strength value of the reference coupon. The highest percentage of reduction was 2% for the coupon Cst4 h1000 t120 CA and 7% for the coupon Cst4 h1000 t120 CW. The elongation ratio increases with increasing the heating temperature for both cooling methods. The value of the modulus of elasticity for water-cooled coupons and air-cooled coupons was close to the reference coupon, but the percentage of water-cooled coupons is lower than that of air-cooled coupons. F_u/F_y ratio for water-cooled coupons is higher than that of the reference coupon, but the ratio for air-cooled coupons is very close or equal to the reference coupon.

Table 3: Results of specimens heated to 1000°C and cooled by air and

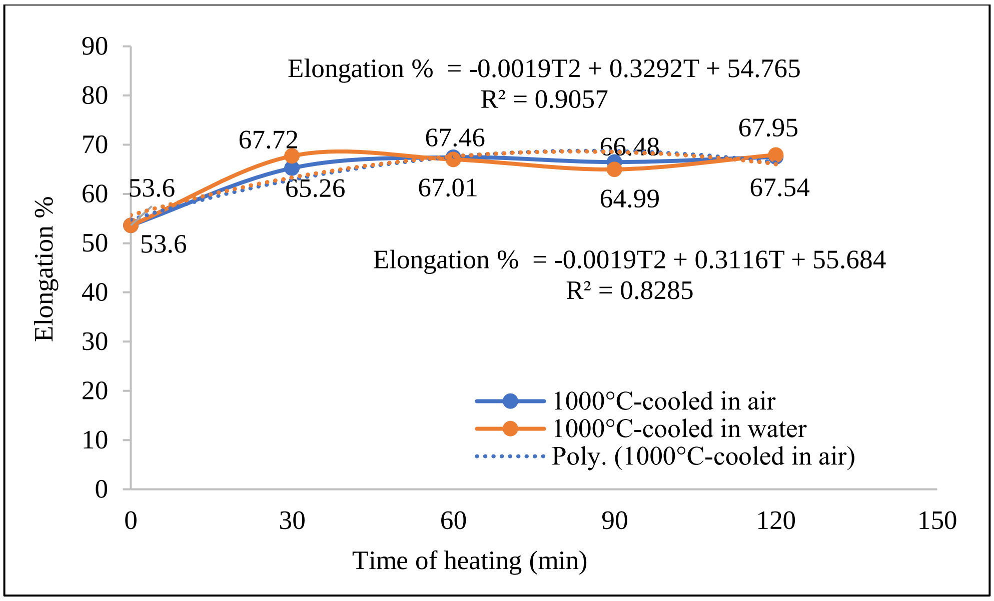
Coupons	**E, Modulus of elasticity (kN/mm^2)**	**F_y Yield stress (N/mm^2)**	**F_u Ultimate stress (N/mm^2)**	**F_u/F_y**
Cst4 h20	219,576	312	780	2.5
Cst4 h1000 t30 CA	206,125	304	761	2.5
Cst4 h1000 t30 CW	225,591	257	793	3.1
Cst4 h1000 t60 CA	212,039	298	773	2.6
Cst4 h1000 t60 CW	224,653	274	797	2.9
Cst4 h1000 t90 CA	214,771	289	780	2.7
Cst4 h1000 t90 CW	222,342	225	780	3.4
Cst4 h1000 t120 CA	218,337	307	766	2.5
Cst4 h1000 t120 CW	221,256	221	726	3



a) Yield stress



b) Ultimate stress



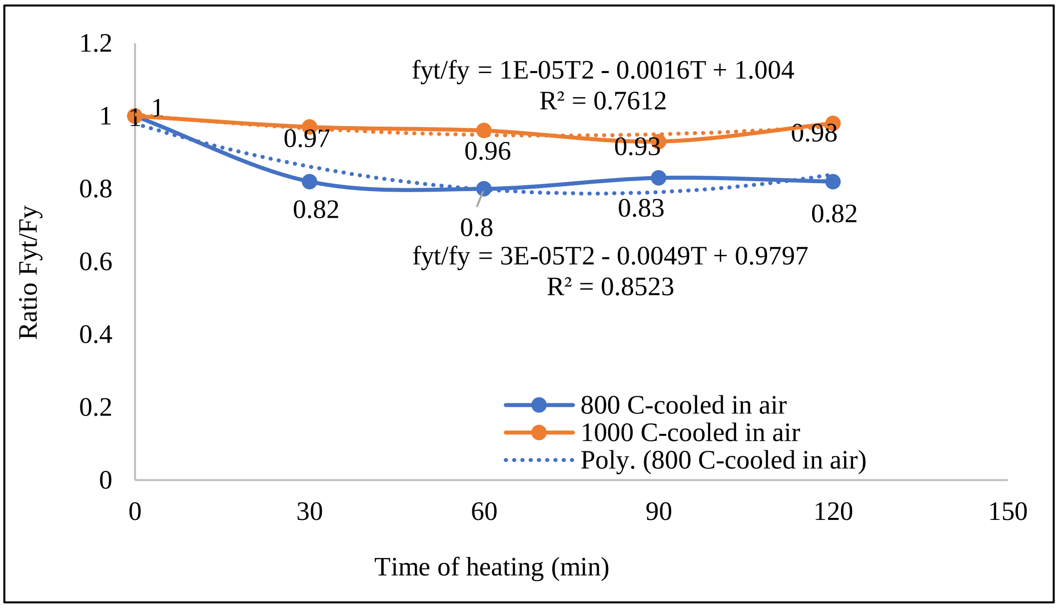
c) Elongation

Figure 9. Effect of heating time and cooling method on yield and ultimate stress and elongation 4mm thickness 1000°C

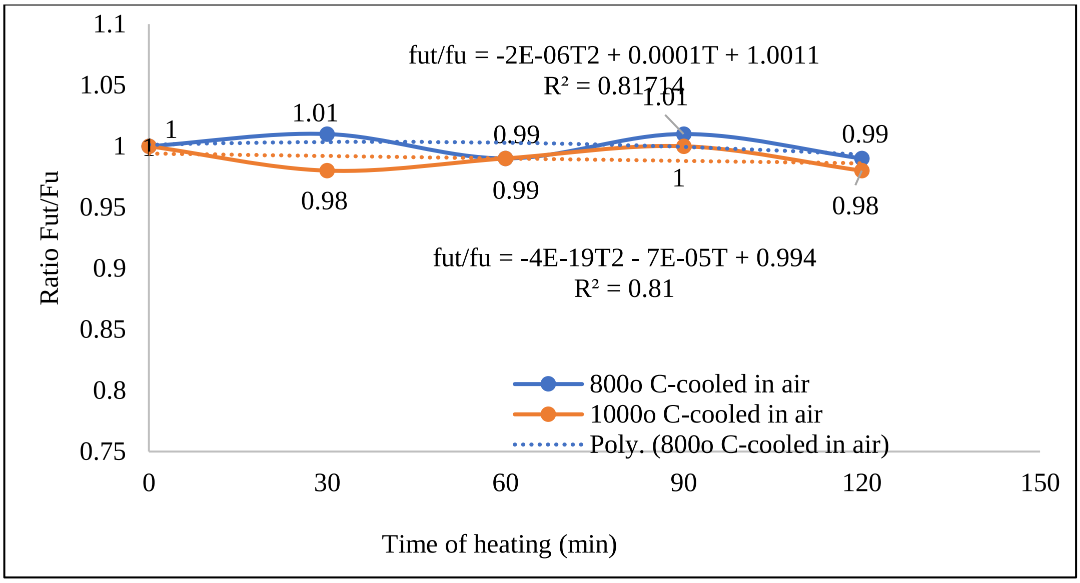
3.5 Effect of heating temperature

3.5.1 Air cooling

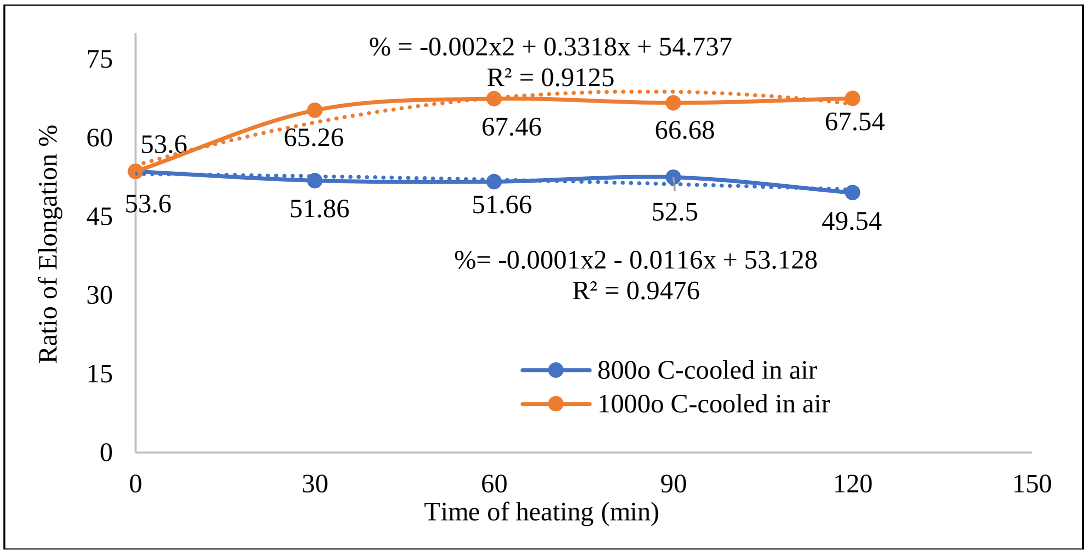
Figure (10-a) shows the difference in the yield stress for the coupons heated to a temperature of 800°C and 1000°C and cooled in air. The coupons heated to a temperature of 800°C show a clear decrease with the increase in the heating time, while the values of the coupons heated to a temperature of 1000°C remain close to the reference values. The value of the ultimate strength remains close to the coupons heated to a temperature of 800°C and 1000°C, and both of them are close to the values of the reference coupon (Figure 10-b). The elongation ratio of the coupons remains close to the reference coupon ratios for specimens heated to a temperature of 800°C, whereas the ratio increased for the specimens heated to 1000°C (Figure 10-C).



a) Yield stress



b) Ultimate stress

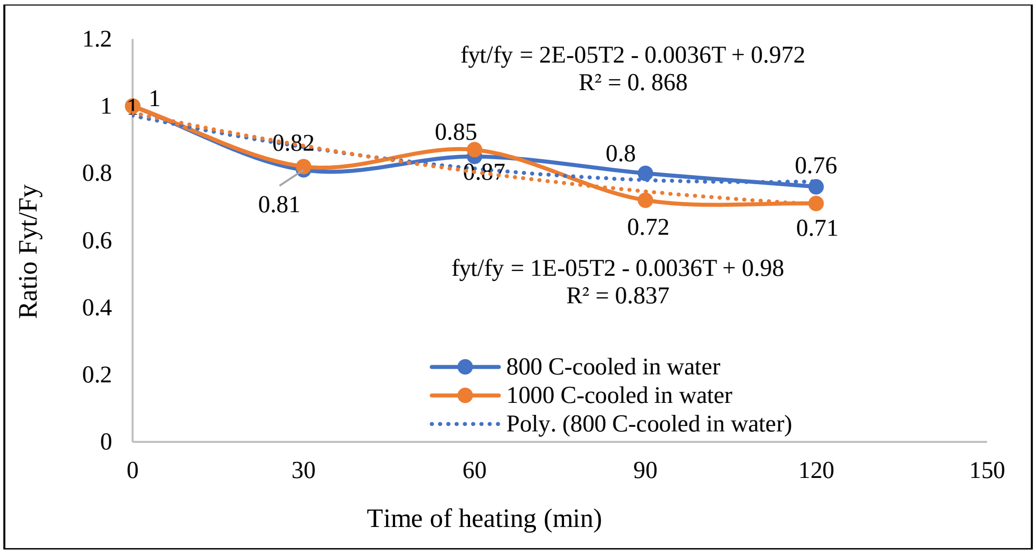


c) Elongation

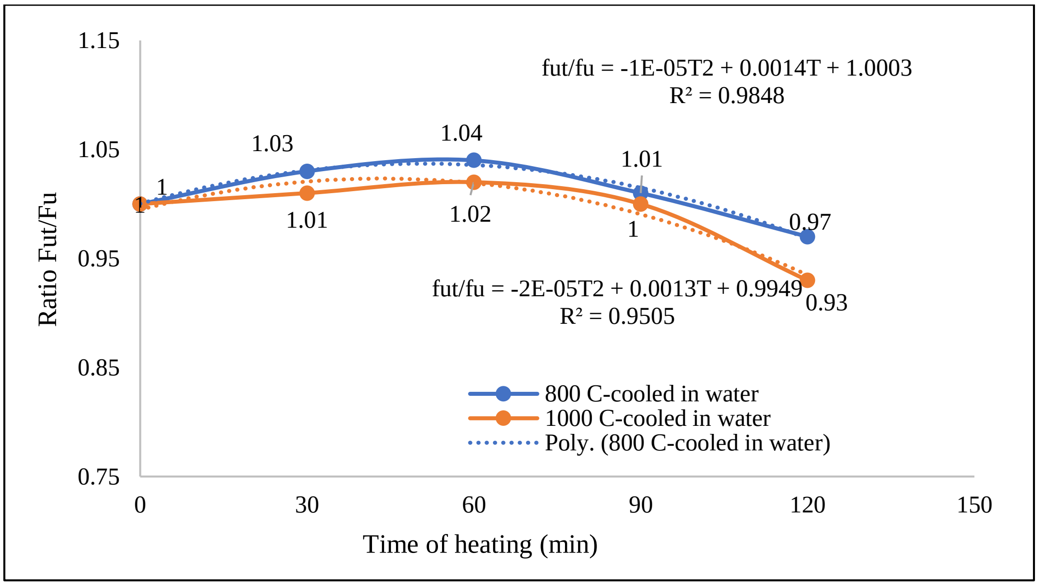
Figure 10. Effect of temperature and air-cooling on yield and ultimate stress and elongation

3.5.2 Water cooling

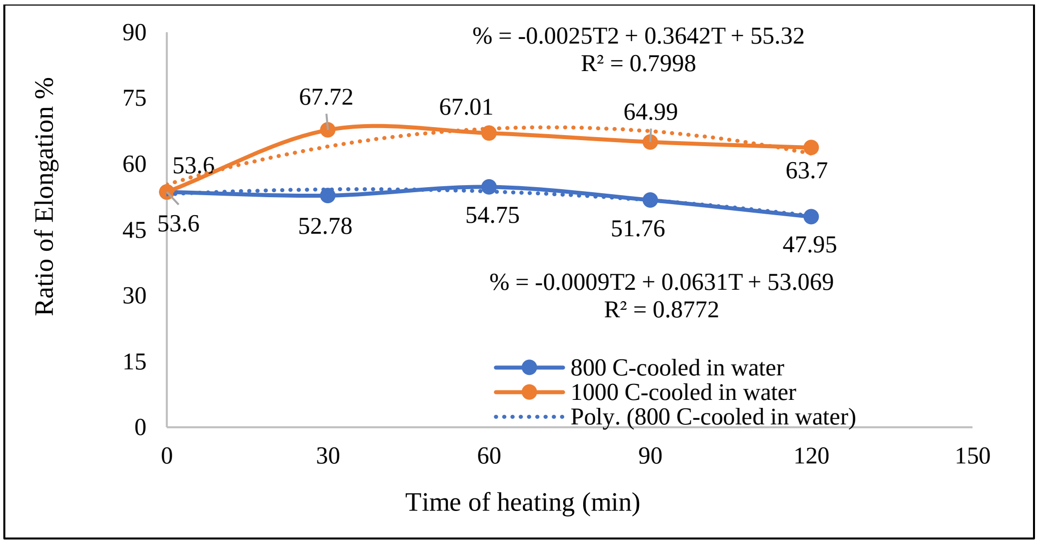
Figure (11-a) shows that there is a decrease in yield stress when heating the coupon to a temperature of 800°C and 1000°C compared to the reference coupon. The reduction increases with the increase of heating time at a temperature of 1000°C. The ultimate strength values for coupons heated to a temperature of 800°Cand 1000°C showed marginal improvement with the increase of heating time, but at a heating time of 120 minutes, a reduction in the ultimate strength was recorded, and the maximum was in the specimen heated to 1000°C and it was 7% (Figure 11-b) further investigation is required by extending the heating time. The elongation ratio of the coupons heated to a temperature of 800 °C limited reductions compared to the reference coupon, while the elongation percentage of coupons heated to a temperature of 1000 °C clear increases as the heating time increases (Figure 11-c). This is due to the increase in ductility with increasing heating temperature.



a) Yield stress

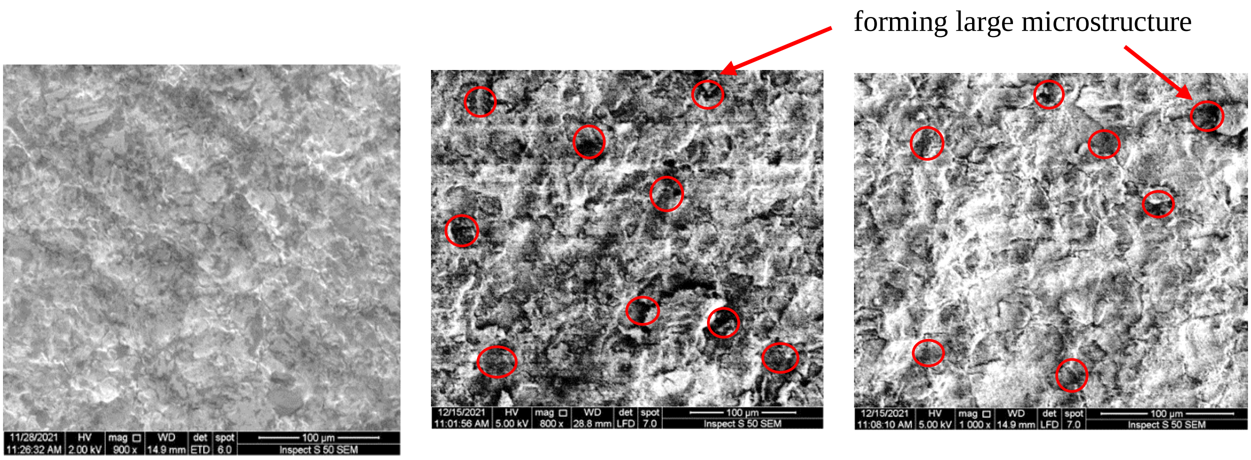


b) Ultimate stress



c) Elongation

Figure 11. Effect of temperature and water-cooling on yield and ultimate stress and elongation



Unheated | Heated to 1000°C and cooled in water | Heated to 1000oC and cooled in air

Figure 12. SEM for specimens before and after heating and air-cooled or air-cooled

Table 5: Chemical composition of the tested specimens

Chemical elements	Before heating	After heating		Limits for S304 stainless steel (%) [20]
	Cst4 h20 (%)	St4 h1000 t120 CA (%)	St4 h1000 t120 CW (%)	
Cr	19.311	21.92	22.57	17.5-19.5
Ni	7.15	2.76	1.45	8.0-10.5
C	0.08	0.02	0.03	≤ 0.08

4. Chemical test

Scanning Electron Microscopy (SEM) and Dispersive X-ray Spectroscopy (EDS) tests were performed to classify the used stainless-steel plate and analyse the effect of heating and the method of cooling on the chemical composition and the microstructure of the stainless steel. The test includes three samples from specimens Cst4 h20, St4 h1000 t120 CA and St4 h1000 t120 CW. Table (5) shows the results of the chemical analysis. The unheated specimen falls within the limits of ASTM A240 [20] for S304 stainless steel. A clear reduction in the Nickle was recorded in the heated specimens, and the maximum reduction was in the water-cooled specimens. This reduction is expected to reduce the corrosion resistance of the stainless steel. Figure (12) presents that the heating to 1000°C results in some changing in the microstructure of the stainless steel. Dark areas represent the formation of large microstructure [21] which causes a reduction in specimen strength as mentioned earlier in section 3.4.

5. Conclusions

An experimental study was carried out to evaluate the post-fire mechanical, physical and chemical properties of 304 stainless steel. The effect of heating time and the cooling method were also investigated. Within the range of the validity of the current study, the following conclusions were drawn:

1. The change in the physical properties was mainly a reduction in the thickness by about 5% and losing the shining state and the aesthetic appeal of the stainless steel.
2. The yield stress for the specimens heated to 800°C can drop significantly whether they were cooled in air or water, but the amount of reduction in water-cooled coupons was higher. In the specimens heated to 1000°C significant reduction was in the yield stress (about 29%) only in the water-cooled specimens.
3. The maximum stress was not

significantly affected by the heating temperature, cooling method and heating time. Where the value of the decrease was 3% for the temperature of 800 ° C at the plot Cst4 h800 t120 CW, and it was 7% for the temperature of 1000 ° C at the plot Cst4 h1000 t120 CW.

4. The elongation capacity of the stainless steel can decrease steadily with the increase of heating time for stainless steel heated to 800°C and cooled in air or water. On the other hand, the elongation capacity increased steadily with the increase of heating time for stainless steel heated to 1000°C.
5. The chemical analysis shows that the high temperature decreases the amount of Nickle in the alloy which is expected to reduce the corrosion resistance of the heated stainless steel. The microscopic examination presents a coarse microstructure in the heated specimens, especially in those cooled in water which reduces the strength of the heated elements.

References

[1] N.R. Baddoo, Stainless steel in construction: a review of research, applications, challenges and opportunities, J. Constr. Steel Res. 64 (11) (2008) 1199–1206.

[2] Barbara Rossi, Discussion on the use of stainless steel in constructions in view of sustainability, Thin-Walled Struct. 83 (October 2014) 182–189.

[3] Y. Cho, L. Teh, B. Young, A. Ahmed, Net section tension strength of bolted connections in ultra-high strength sheet steel during and after fire, Journal of Constructional Steel Research 172 (2020) 106237.

[4] Marwan Sarraj, The Behaviour of Bolted Connections in Fire, Department of Civil and Structural Engineering, The University of Sheffield (2007).

[5] A. Çalik, Effect of cooling rate on hardness and microstructure of AISI 1020, AISI 1040 and AISI 1060 Steels, International Journal of Physical Sciences Vol. 4 (9), pp. 514-518, September, 2009.

[6] Jinwoo Lee, Elevated-Temperature Properties of ASTM A992 Steel for Structural-Fire Engineering Analysis, Presented to the Faculty of the Graduate School of The University of Texas at Austin (2012).

[7] Jawad, F. A., Nimnim, S. T., & Attiya, M. A. J. K. J. o. E. (2017). EFFECT OF BOLT DIRECTION ON THE BEARING CAPACITY OF DOUBLE SHEAR CONNECTIONS. 8(2).

[8] Yang, K.-C., Hsu, R.-J., & Hsu, C.-F. (2013). Strength criteria for bolted connections at elevated temperature. Journal of Constructional Steel Research, 88, 43-52.

[9] Molkens, T., Cashell, K. A., Malaska, M., Alanen, M., & Rossi, B. (2021). Performance of structural stainless steel following a fire. Engineering Structures, 235, 112001.

[10] Cai, Y., & Young, B. (2020). Effects of end distance on thin sheet steel single shear bolted connections at elevated temperatures

[11] Qahtan A., Mohammed Mahmood (2020) Post-Fire Performance of Carbon Steel, Diyala Journal of Engineering Sciences, Vol (14) No 2, 2021: 28-41.

[12] L. Gardner, The use of stainless steel in structures, Prog. Struct. Eng. Mater. 7 (2005) 45–55

[13] L. Gardner, K.T. Ng, Temperature development in structural stainless-steel sections exposed to fire, Fire Safety. J. 41 (2006) 185–203.

[14] Xifeng Gao, Xupeng Zhang, Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure, Construction and Building Materials 165 (2018) 82–92.

[15] J. Nagie (2014) The effect of cooling rate on mechanical properties of carbon steel St 35, Diyala Journal of Engineering Sciences, Vol. 07, No. 01, pp. 109-118, March.

[16] Huang, Y. & Young, B. (2018). Mechanical properties of lean duplex stainless steel at post-fire condition. Thin-Walled Structures, 130, 564-576.

[17] Choi, J., Seok, C.-S., Park, S., & Kim, G. (2019). Effect of high-temperature degradation on microstructure evolution and mechanical properties of austenitic heat-resistant steel. Journal

of Materials Research and Technology, 8(2), 2011-2020.

[18] Fan, S., Ding, X., Sun, W., Zhang, L., & Liu, M. (2016). Experimental investigation on fire resistance of stainless-steel columns with square hollow section. Thin-Walled Structures, 98, 196-211.

[19] CEN (European Committee for Standardization, Method of test at Ambient Temperature, in Met al.lic materials -tensile testing, part1: E.N 10002:2001, CEN Brussels, Belgium.

[20] ASTM International, ASTM A240/A240M-18 Specification for Chromium and Chromium-Nickel Stainless Steel Plate, (2018).

[21] Blaoui, M.M., M. Zemri, and A. Brahami, Effect of Heat Treatment Parameters on Mechanical Properties of Medium Carbon Steel. Mechanics and Mechanical Engineering, 2018. 22(4): p. 909-918.