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Post-Fire Performance of Carbon Steel

Qahtan A. Sulayman *, Mohammed Mahmood

Department of Civil Engineering, College of Engineering, University of Diyala, 32001 Diyala, Iraq

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ABSTRACT

Carbon steel is widely used in building industry. The different structural element might be exposed to high temperature during fire. The structural safety of steel buildings must be evaluated after they have suffered a fire. The assessment requires understanding the behaviour of carbon steel after heating. Therefore, this paper is aimed at studying the post-fire behaviour of carbon steel. A total of seventeen coupon specimens were tested by uniaxial tensile test. One of them was tested without heating and considered as a reference. Sixteen specimens were heated at a temperature of either 400°C or 700°C for different durations. Eight specimens were cooled in air and the others cooled in water. Heating durations were 30 min, 60 min, 90 min and 120 min. Results showed that the high-temperature has a great influence on decreasing the ultimate and yield stress and elongation for specimens cooled in the air. For specimens cooled in water, the decreased in yield and ultimate stress was minor comparing to the reference specimen. The ductility of water-cooled specimens showed a noticeable reduction comparing to specimens cooled in air. Increasing the heating time results in higher elongation for specimens heated to 400oC and lower elongation for specimens heated to 700°C, but the specimen loses strength in both cases.

1. Introduction

In new construction, steel structures are used for many types of structures including heavy industrial buildings, high-rise buildings, bridges and towers. This is due to its high ability to withstand forces and high strength to weight ratio [1]. The structural safety of steel buildings must be maintained after the fire, to save lives and reduce property losses. The mechanical properties of steel are the main aspects required for the redesign of these structures. They described mainly through the strength-strain relationship [2]. During the fire, the steel experiences a gradual loss of strength and stiffness and after the fire recovered strength and stiffness can be different from the original. This phenomenon may cause excessive possible deformation, which leads to failure [3]. Many studies for different elements of the steel frame buildings at elevated temperature and after cooling are available in the literature [4-11].

Gewain et al. [12] stated that the high temperatures decreases the yield strength and tensile strength of carbon steel, as does the modulus of elasticity. Gebril et al. [13] showed that temperature of 950°C and higher is effective to increasing the hardness of cooled carbon steel specimens. Nagie [14] presented that heat treatment contributes to improve the mechanical properties of carbon steel such as hardness, ductility and toughness. Aziz et al. [15] stated that steel structural members possess low fire resistance due to its high thermal conductivity and low specific heat, which results in faster degradation in the strength with temperature . As a result, steel structural members can lose load carrying capacity at high temperature.

* Corresponding author.
E-mail address: eng_grad_civil023@uodiyala.edu.iq
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Fan et al [16] tested coupons to investigate the post-fire behaviour of stainless steel.The test controlling temperatures were ranged from 100° C to 900° C and specimens were subjected to heating time between thirty minutes to sixty minutes. It was reported that the distortion in the cooled coupon increases with increase of heating time.

Choi et al. [17] used a group of coupons from Austenian steel exposed to a high temperature. It was stated that after exposure to high temperatures and cooled a decrease in strength and stiffness is expected. Cai and Young [18] suggested a reduction factor to calculate the strength of steel structural elements exposed to high temperature.

It is clear that the post-fire behaviour of steel structures attracted many researchers and they have published test data for different aspects in terms of mechanical properties and behaviour. Nevertheless, acritical evaluation of the post-fire behaviour of carbon steel considering the effect of temperature level, fire exposing time and cooling method has not been conducted yet even if design codes approve reliability-based approach for the assessment of steel structure that exposed to fire. Therefore, this study is aimed at providing a fundamental understanding of the post-fire behaviour of carbon steel. Coupons were tested in uniaxial tension after they were exposed to different temperatures for different durations and cooled either by air and water.

2- Experimental work

2.1. Specimens

Coupons specimens were considered to evalute the mechanical properties of carbon steel used in different parts of steel structures. The dimensions of the specimen and the test method were according to the EN 1002-1[19]. The thickness was (2mm), and the other dimensions are explained in Figure 1.

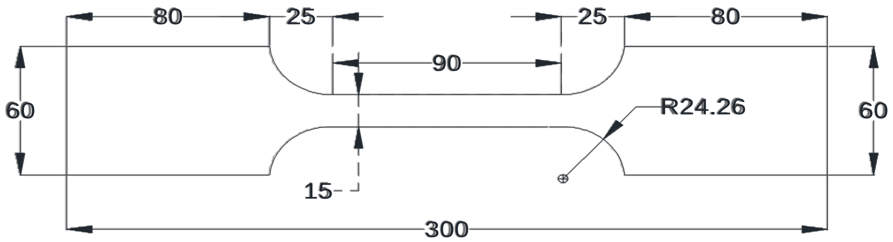


Figure 1. Specimen dimensions (All dimensions in millimeters)

The experimental programme includes testing of seventeen specimens (Figure 2). The labelling considered all the parameters: the thickness of the specimen (T), the temperature to which the specimen was exposed (Te), the time that the specimen remains in the furnace under a constant temperature (D) and the cooling method either (CA) for Air cooling or (CW) for water cooling. For example, T2Te400D30CW is the specimen of thickness 2mm, heated to 400^{o}C for 30 minutes and cooled in water. Table 1 presents the tested specimens.

Figure 2. The specimens after heating and cooling

2.2. Heating and cooling process

Sixteen specimens were exposed to elevated temperatures by placing them in the furnace (Figure 3). The specimen remains in the furnace at constant temperature (400°C or 700°C) for a specified period (30 minutes, 60 minutes, 90 minutes, and 120 minutes). Then the specimens were taken out of the furnace to be cooled either in air or in water.

Table 1: Test programme

NO	Specimen	Thickness (mm)	Temperature	Duration in furnace (min)	Cooling method
1	T2Te40 (Reference)	2	30ºC	---	---
2	T2 Te400 D30 CA	2	400°C	30	Air
3	T2 Te400 D30 CW	2	400°C	30	Water
4	T2 Te400 D60 CA	2	400°C	60	Air
5	T2 Te400 D60 CW	2	400°C	60	Water
6	T2 Te400 D90 CA	2	400°C	90	Air
7	T2 Te400 D90 CW	2	400°C	90	Water
8	T2 Te400 D120 CA	2	400°C	120	Air
9	T2 Te400 D120 CW	2	400°C	120	Water
10	T2 Te700 D30 CA	2	700°C	30	Air
11	T2 Te700 D30 CW	2	700°C	30	Water
12	T2 Te700 D60 CA	2	700°C	60	Air
13	T2 Te700 D60 CW	2	700°C	60	Water
14	T2 Te700 D90 CA	2	700°C	90	Air
15	T2 Te700 D90 CW	2	700°C	90	Water
16	T2 Te700 D120 CA	2	700°C	120	Air
17	T2 Te700 D120 CW	2	700°C	120	Water

Figure 3. Specimen in the furnace

2.3. Physical properties

The dimensions of the specimens measured before heating by a digital vernier calliper. Then the specimens placed in the furnace and heated to the pre-set temperature with the time required to heat the specimen. After heating and cooling, the dimensions of the specimens are measured to quantify the heating effect on dimensions. The surface of the specimens was crusting after heating and cooling in the air. This state occurred at a temperature of 700°C, (Figure 4). Specimen cooled in water showed corrosion of the metal surface as presented in Figure (5). The decrease in the cross-sectional area of the specimens after heating for 120 minutes in 700°C reached 9% of the cross-sectional area in the two cooling methods.

Figure 4. Crusting of surface layer

Figure 5. Corrosion on surface

2.4 Test arrangement

Coupons tests are essential to provide a database of mechanical properties including yield stress, ultimate stress and elongation. The device used to test the specimens was hydraulic universal testing machine. The tension load is applied to the specimen and it was fixed to (0.1 KN/sec). The test finishes after the fracture of the specimen as shown in Figure (6).

Figure 6. Failed specimens

3- Results and discussions

Through the data that was obtained after the end of each test, the relationship of stress - strain as presented in Figure (7). This relation was used to find the values of the yield stress, ultimate stress, modulus of elasticity and the percentage of elongation of the specimens. The results for all specimens are organized in Tables 2, 3, 4, and 5.

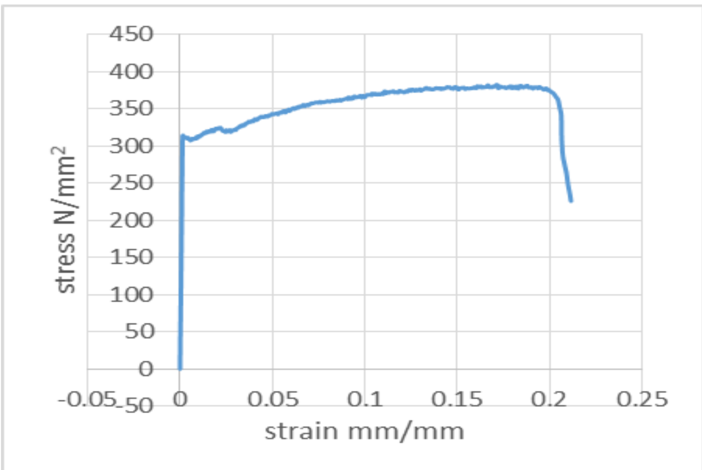
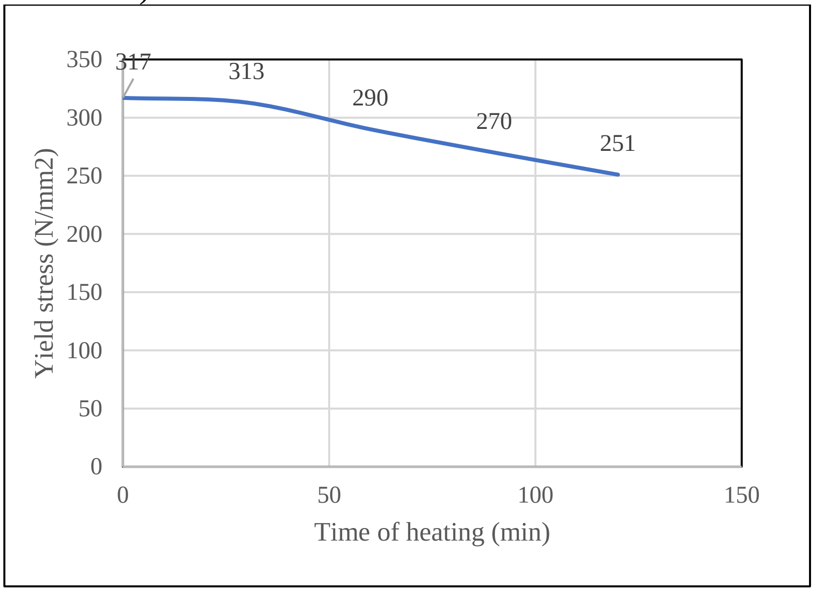


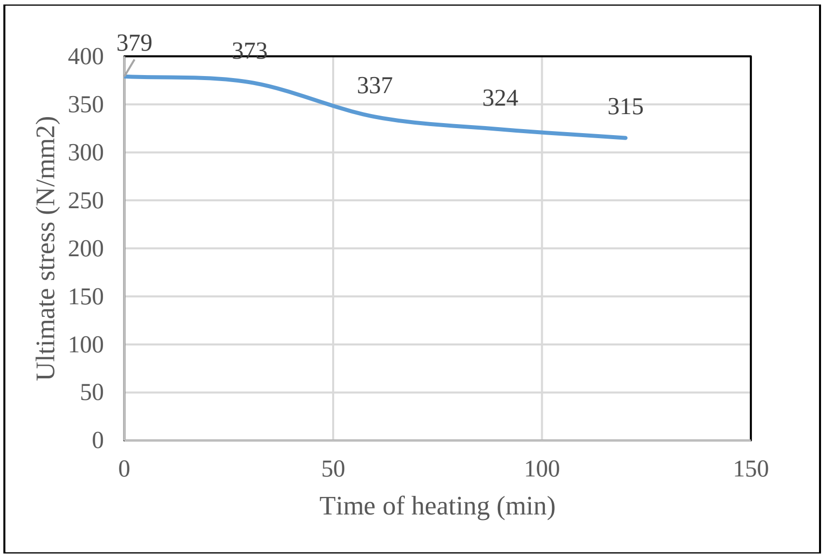
Figure 7. Stress –strain curve for T2TE400D30CA

3.1. Effect of heating time (400°C)

Unheated specimen gives a yield stress of 317 N/mm^2. The yield stress of specimen T2TE400D30CA was decreased to 313 N/mm^2. The reduction continuous in the other specimens with the increase of heating time as shown in Figure 8-a. Comparing to the yield stress of the reference specimen, the highest reduction in the yield stress was 21% (251 N/mm^2) and it was recorded to specimen T2TE400D120CA, which was heated for 120 minutes. The ultimate stress of the reference specimen was 379 N/mm^2. The ultimate stress of T2TE400D30CA decreased to 373 N/mm^2. The maximum drop in the ultimate stress was 17% (315 N/mm^2) and it was in the specimen that was heated for 120 minutes (T2TE400D120CA). Figure 8-b shows the effect of heating time on the ultimate stress of specimens heated to 400ºC and cooled in air. Table 3 presents the results of specimens heated to 400°C and cooled in water. The results indicate that the values of the yield stress and the ultimate stress decreased by increased the time of exposure of the specimen to heat. The percentage of elongation of all the specimens was close but greater than the elongation of the reference specimen. This indicates that there is an increase in the ductility of the specimens with heating to 400°C and cooling in water. The modulus of elasticity was decreased for all specimens.

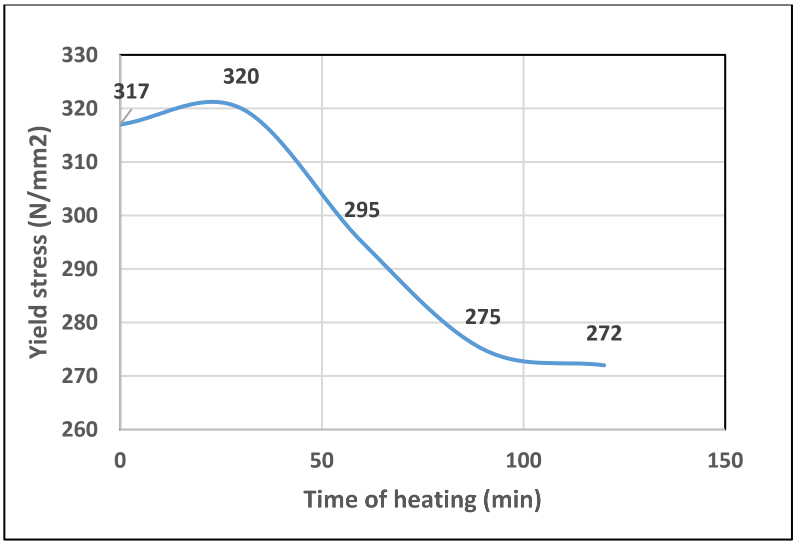


a) Yield stress

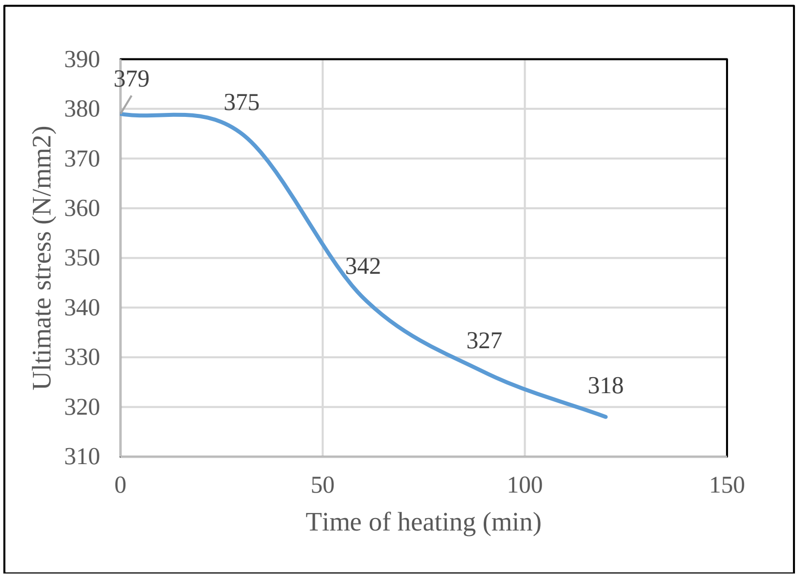


b) Ultimate stress

Figure 8. Yield and ultimate stress (specimens heated to 400°C and cooled in the air)



(a) Yield stress



(b) Ultimate stress

Figure 9. Yield and ultimate stress (specimens heated to 400°C and cooled in water)

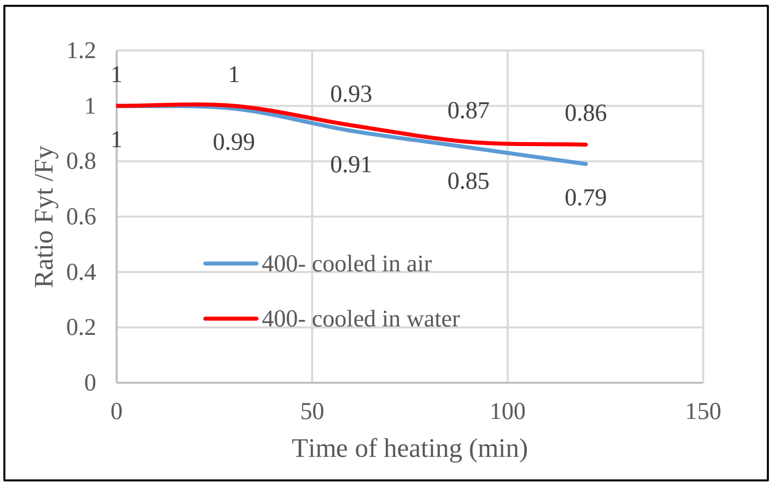
The specimen heated for 30 minutes shows a minor change in the yield stress. However, a clear reduction in the yield stress begins with increasing the heating time to 60 minutes. The yield stress dropped to 295 N/mm^2 (Figure 9-a). The drop continues to the last specimen T2TE400D120CW. It recorded a yield stress of 272 N/mm^2, which is equivalent to 86% of the reference specimen (Table 3). The ultimate stress of the specimens shows a slight reduction in the first specimen (T2TE400D30CW) about 5%, but the reduction amplified significantly by increasing the heating time to 60 minutes. The maximum reduction in the ultimate stress was about 20% comparing to the reference specimen and it was for the specimen that was heated to 120 minutes (Figure 9-b). The percentage of elongation was higher than the elongation of the reference specimen. The modulus of elasticity recorded a decrease in all specimens. The mechanical properties were decreased when the time of heating was increased with water-cooling. To find out the effect of cooling methods on the specimens heated to 400°C, the results of the specimens were compared. The ratio of yield stress of the specimens in both cooling methods to the reference specimen was very close with a slight increase in the water-cooled specimens (Figure 10-a). The increasing change was clear in the specimen T2TE400D120CW, after a heating for a period of one hundred and twenty minutes. On the other hand, the ratio of ultimate stress of the specimens to the reference specimen was not changed significantly for the specimens in the two cooling methods as show in Figure 10-b. For the elongation, the air-cooled specimens gave a higher elongation than the water-cooled specimens as can be seen in Figure 10-c. This means the air cooling can results in higher ductility than the water cooling. This is because water-cooling causes the specimens to harden more than the air-cooling [20].

Table 2: Results of specimens heated to 400°C and cooled in air

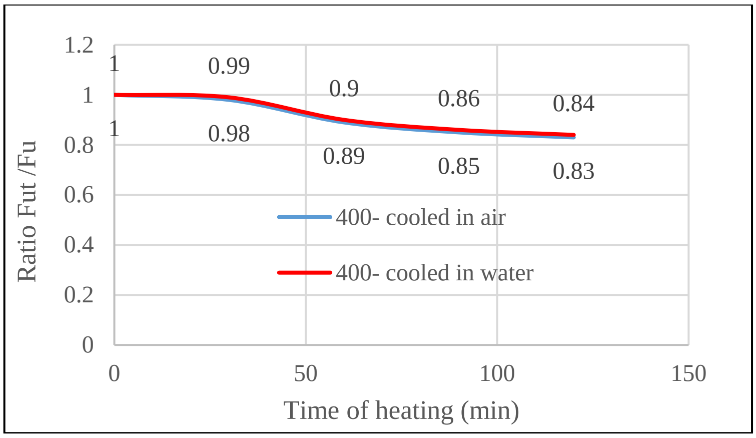
Specimens	**Modulus of elasticity (kN/mm^2)**	**Yield stress (N/mm^2)**	**^1F_y / ^2f_y**	**Ultimate stress (N/mm^2)**	**^3F_u / ^4f_u**	**F_u / f_y**	**Elongation E_L (%)**
T2TE40 Reference specimen	209.658	317	1	379	1	1.19	24
T2TE400CD30 CA	208.543	313	0.99	373	0.98	1.19	30
T2TE400CD60 CA	196.439	290	0.91	337	0.89	1.16	31
T2TE400CD90 CA	183.333	270	0.85	324	0.85	1.20	30
T2TE400CD120 CA	181.219	251	0.79	315	0.83	1.25	30
1 yield stress of heated specimen, 2 yield stress of reference specimen, 3 ultimate stress of heated specimen and 4 ultimate stress of reference specimen							

Table 3. Results of specimens heated to 400°C and cooled in water

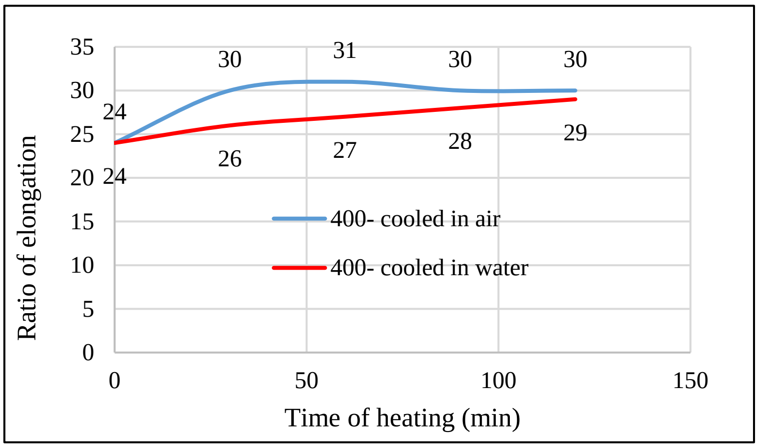
Specimens	**Modulus of elasticity (kN/mm^2)**	**Yield stress (N/mm^2)**	**^1F_y / ^2f_y**	**Ultimate stress (N/mm^2)**	**^3F_u / ^4f_u**	**F_u / f_y**	**Elongation E_L (%)**
T2TE40 Reference specimen	209,658	317	1	379	1	1.19	24
T2TE400CD30 CW	209.279	320	1	375	0.99	1.17	26
T2TE400CD60 CW	195,700	295	0.93	342	0.90	1.16	27
T2TE400CD90 CW	193.917	275	0.87	327	0.86	1.19	28
T2TE400CD120 CW	190.105	272	0.86	318	0.84	1.17	29
1 yield stress of heated specimen, 2 yield stress of reference specimen, 3 ultimate stress of heated specimen and 4 ultimate stress of reference specimen							



(a) Yield stress



(b) Ultimate stress

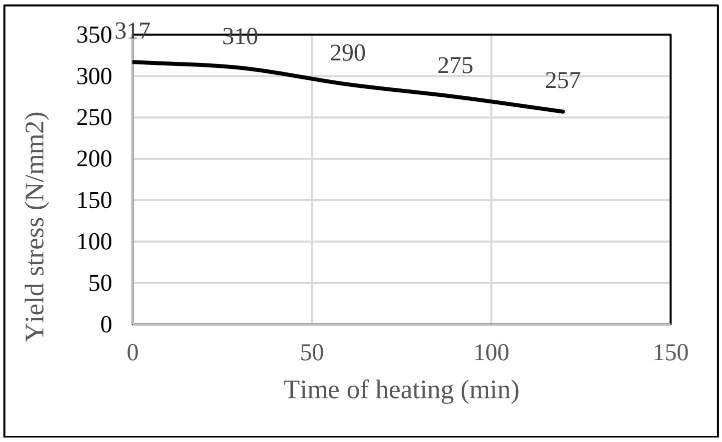


(c) Elongation

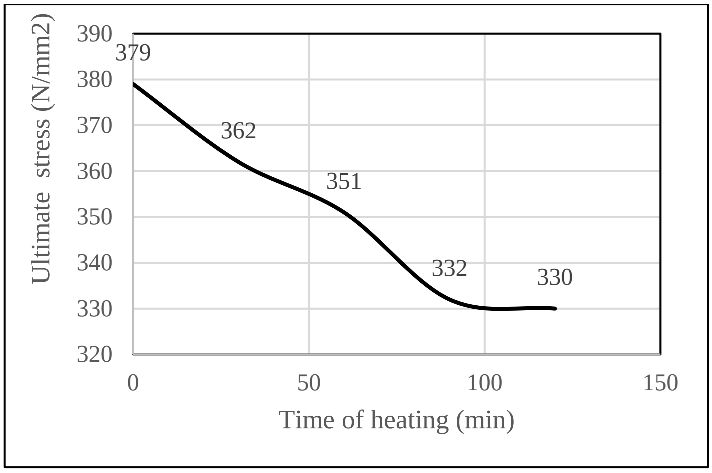
Figure 10. Effect of heating time and cooling method on yield and ultimate stress and elongation

3.2. Effect of heating time (700°C)

Table 4. shows the results of specimens heated to 700 °C and cooled in air. It is clear that increasing the heating time of the specimens leads to a decrease in the yield stress (Figure 11-a). The yield stress dropped from 317 N/mm^2 for reference specimen to 257 N/mm^2 (about 19%) for specimen heated for 120 minutes and cooled in air. The ultimate stress results are shown in Figure 11-b. The ultimate stress decreased from 379 N/mm^2 to 330 N/mm^2 (about 13%) by heating the specimen to 700°C for a duration of 120 minutes. The elongation was higher than the reference specimen. This means specimens become more ductile with increasing the heating time. The elastic modulus of elasticity gave minor change in all specimens (Table 4).



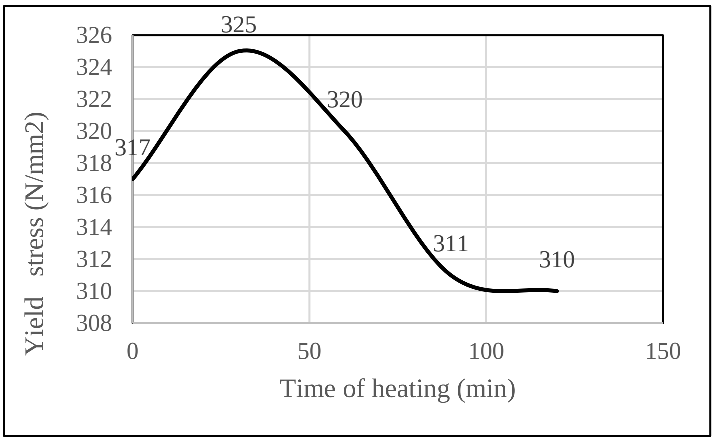
(a) Yield stress



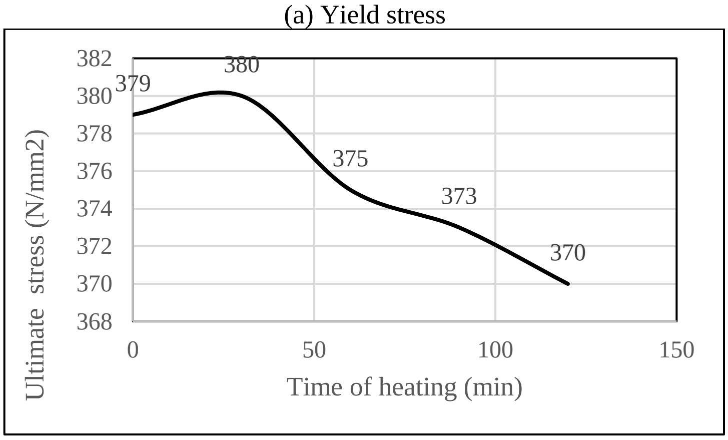
(b) Ultimate stress

Figure 11. Yield and ultimate stress for specimens (specimens cooled in air- 700°C)

The data in Table 5 is for specimens that are heated to 700°C and cooled in water. The effect of heating time on the yield stress is shown in Figure 12-a. Comparing to the reference specimen, the yield stress increased in the specimens that were heated for 30 and 60 minutes. Increasing the heating time to more than 60 minute results in decreasing the yield stress. For ultimate stress (Figure 12-b), the effect of heating duration is minor for specimens heated to 700°C and cooled in water. The elongation started to decrease until it becomes 58% of the reference specimen for T2TE700D120CW. This loss in ductility can be due to the hardening that occurs in steel after high temperatures and sudden cooling in water [21]. The modulus of elasticity also decreased with the increasing of heating time.



(a) Yield stress



(b) Ultimate stress

Figure 12. Yield and ultimate stress for specimens (specimens cooled in water 700°C)

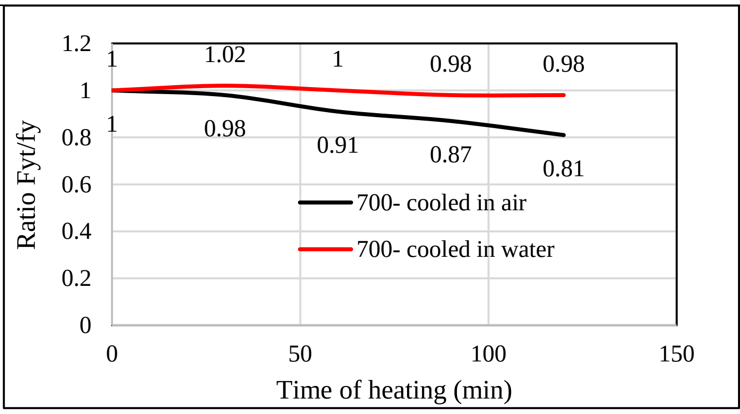
Figure 13 presents the effect of heating time and cooling method on yield and ultimate stress and elongation. The specimens cooled in water showed higher yield and ultimate stress (Figure 13 a and b). The difference in the strength increased with increasing the heating time. This means when the fire extends for a long time, it is recommended to cool the steel parts with water to prevent the drop in the strength which can reach 19%. However, in the elongation (Figure 13-c), the preference was to the specimens cooled in air. This means higher ductility can be obtained by air-cooling. The reason for this may be attributed to the state of hardening that appears on the steel after heating to a high temperature and cooling in water, due to the sudden and rapid change in temperature, which affects the crystal structure of the steel and the increase in the hardness [20].

Table 5: Results of specimens heated to 700°C and cooled in water

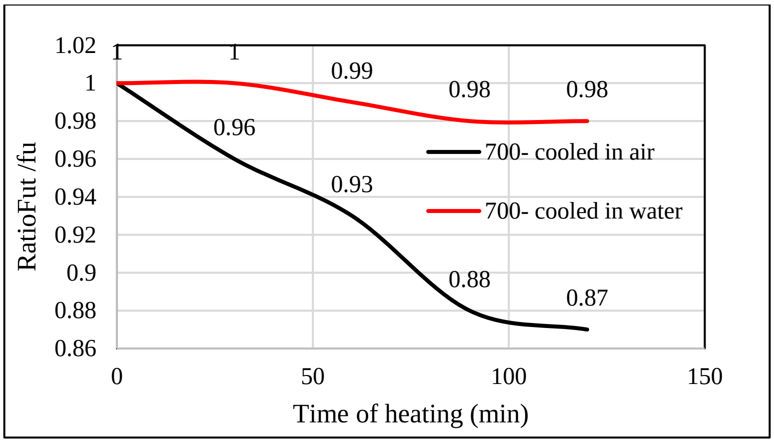
Specimens	**Modulus of elasticity (kN/mm^2)**	**Yield stress (N/mm^2)**	**^1F_y / ^2f_y**	**Ultimate stress (N/mm^2)**	**^3F_u/ ^4f_u**	**F_u / f_y**	**Elongation EL (%)**
T2TE40 Reference specimen	209,658	317	1	379	1	1.19	24
T2TE700D30CW	204,263	325	1.02	380	1	1.17	23
T2TE700D60CW	185,156	320	1	375	0.99	1.17	19
T2TE700D90CW	183,213	311	0.98	373	0.98	1.20	18
T2TE700D120CW	181.234	310	0.98	370	0.98	1.19	10
1 yield stress of heated specimen, 2 yield stress of reference specimen, 3 ultimate stress of heated specimen and 4 ultimate stress of reference specimen							

Table 4. Results of specimens heated to 700°C and cooled in air

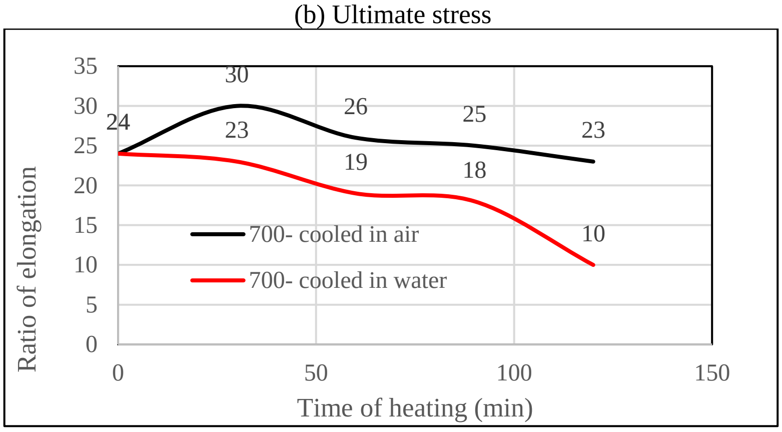
Specimens	Modulus of elasticity (kN/mm^2)	Yield stress (N/mm^2)	^1F_y / ^2f_y	Ultimate stress (N/mm^2)	^3F_u / ^4f_u	F_u / f_y	Elongation EL (%)
T2TE40 Reference specimen	209.658	317	1	379	1	1.19	24
T2TE700D30CA	209.334	310	0.98	362	0.96	1.17	29
T2TE700D60CA	211.500	290	0.91	351	0.93	1.21	26
T2TE700D90CA	208.307	275	0.87	332	0.88	1.20	25
T2TE700D120CA	211.340	257	0.81	330	0.87	1.28	23
1 yield stress of heated specimen, 2 yield stress of reference specimen, 3 ultimate stress of heated specimen and 4 ultimate stress of reference specimen							



(a) Yield stress



(b) Ultimate stress

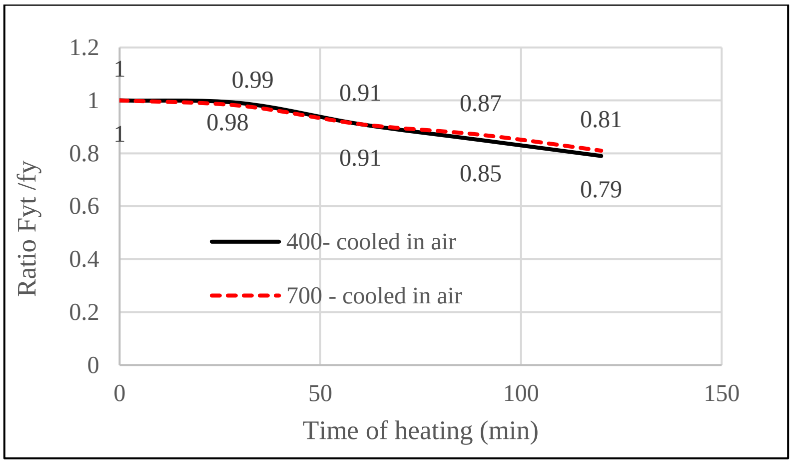


(c) Elongation

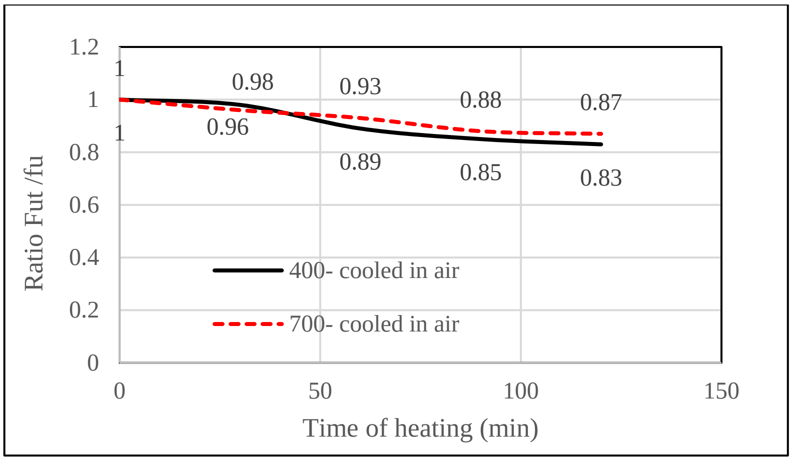
Figure 13. Effect of heating time and cooling method on yield and ultimate stress and elongation

3.3. Effect of heating temperature (air-cooling)

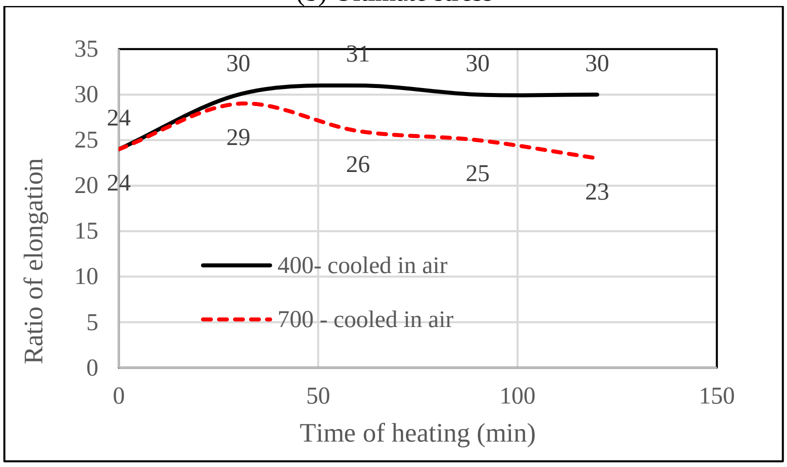
In this section and the next one, the aim is to present the effect of heating temperature on the mechanical properties of the steel by combining the data of specimens heated to 400°C and 700°C. Figure 14-a, reveals that the yield stress affected similarly in the two temperatures (400°C and 700°C). The ultimate stress observed in similar to the yield stress, the ultimate stress showed a steady reduction with the increase of heating time in both temperatures (Figure 14-b). The elongation ratio is shown in Figure 14-c. The specimens heated up to 400°C gave higher values, which is better in terms of ductility.



(a) Yield stress



(b) Ultimate stress

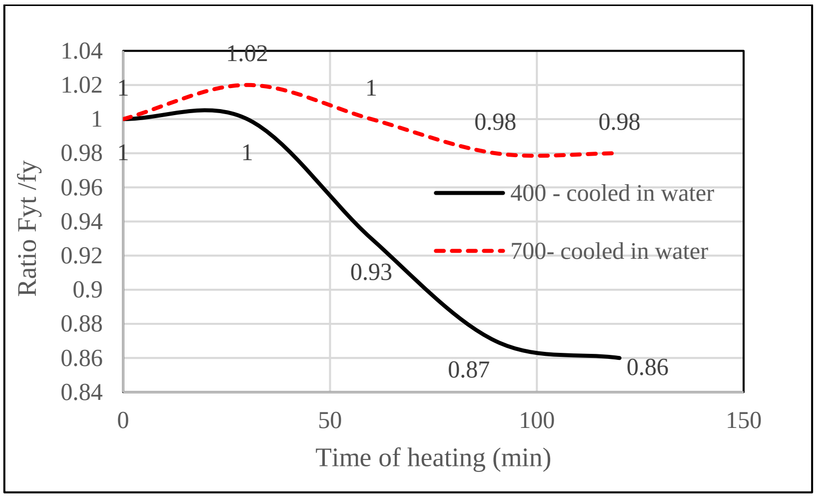


(c) Elongation

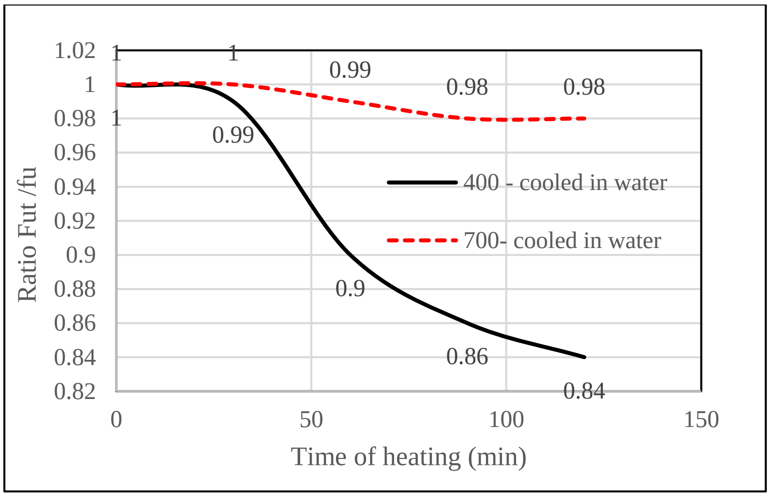
Figure 14. Effect of temperature and air-cooling on yield and ultimate stress and elongation

3.4. Effect of heating temperature (water-cooling)

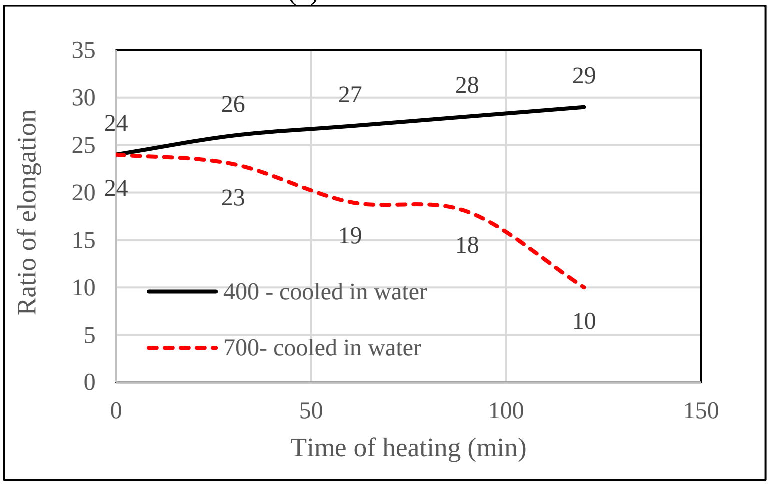
Figure 15-a and b show that there is an insignificant reduction in the yield and ultimate stress for specimens heated to 700ºC. However, a clear drop in the yield and ultimate stress for specimens heated to 400°C. The elongation of the specimens heated to 700 °C was significantly lower than the specimens heated to 400°C(Figure 15-c).



(a) Yield stress



(b) Ultimate stress



(c) Elongation

Figure 15. Effect of temperature and water-cooling on yield and ultimate stress and elongation

4. Conclusions

An experimental investigation was conducted in this study on the behaviour of carbon steel after elevated temperatures. The main conclusions of the study can be summarized as follows:

1. The physical change, especially after the coupons were exposed to high temperatures, was only in thickness and did not affect another dimension another.
2. Corrosion starts showing clearly in water-cooled specimens, that was heated to 700° C, whereas for specimens heated to 400° C no corrosion appears on the surface of specimens.
3. A clear reduction in the yield stress and ultimate strength can occur due to heating the steel to 400° C whether it was cooled in air or water. The maximum percentage of reduction in the yield strength and the ultimate strength are 21% and 16% respectively for the specimens cooled in air. For the water-cooled specimens, the decrease in the yield stress and the ultimate strength are 14% and 17% respectively. These ratios are after heating the specimens for 120 minutes.
4. Heating the carbon steel to 700° C can reduce the yield stress and ultimate strength 19% and 13% respectively for the specimens cooled in air. For the water-cooled specimens, the decrease in the yield stress and the ultimate strength was in significant. These ratios are after heating the specimens for 120 minutes. It is recommended to cool the carbon steel using water to avoid strength reduction.
5. There is no significant difference in the yield strength and ultimate strength of steel heated to 400 °C or 700°C and cooled in air.

6. The yield strength and the ultimate strength of steel heated to 700°C and cooled in water can be higher than that heated to 400°C and cooled in water.
7. The elongation of steel heated to 700°C and cooled in water can be lower than that heated to 400°C and cooled in water.

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