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Research paper I Оригинални научни рад
DOI 10.7251/STP2215053M
ISSN 2566-4484

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THE EFFECT OF THERMAL TREATMENT ON MECHANICAL AND DEFORMATION PROPERTIES OF STEEL REINFORCEMENT

Abstract

Presented research was intentioned to clarify the effects of thermal treatment (ageing) of reinforcing steel products on their mechanical and deformation properties. In order to determine the effect of temperature, samples were exposed to room temperature (reference samples) and a temperature of 100 °C in duration of 30, 60 and 120 minutes, respectively. Tests were conducted on bars, coils and welded fabrics. After the thermal treatment, samples were exposed to tensile testing. The duration of the ageing treatment did not significantly affect measured properties of the tested products. Still, longer ageing process increased the yield stress of samples taken from coils by 7%, while the welded fabrics reached optimum values of yield stress and elongation after ageing of 60 minutes.

Keywords: steel reinforcement, σ-ε diagram, yield stress, maximum stress, elongation.

UTICAJ POSTUPKA STARENJA NA MEHANIČKO-DEFORMACIONA SVOJSTVA ČELIKA ZA ARMIRANJE BETONA

Сажетак

Истраживање је имало за циљ да се испита утицај поступка старења челика за армирање бетона на његова механичка и деформациона својства. Да би се одредио ефекат температуре на предметна својства арматурног челика, узорци су излагани собној температури (контролни узорци) или температури од 100°Ц у трајању од 30, 60 и 120 мин, респективно. Испитивања су обављена на шипкама, котуровима арматурним мрежама. Узорци су излагани аксијалном затезању. Трајање третмана старења није значајно утицало на карактеристике испитиваних производа. Ипак, дуже трајање старења котурова доводи до повећања напона течења од 7%, док су код арматурних мрежа оптималне вредности напона течења и издужења измерене након старења од 60 мин.

Кључне ријечи: арматурни челик, σ-ε дијаграм, напон течења, максимални напон, издужење.

1. INTRODUCTION

Among all steel products used in construction, the steel reinforcement represents a very important group of products, since it is one of the mostly used materials in the world (as a part of reinforced concrete).

Important properties of reinforcing steel, such as tensile strength, yield stress, hardness, ductility and plasticity can be improved with changes in the chemical composition of steel, through alloying, changing of the size of the metal grains, etc., but also through different treatments in the secondary production phase (thermal treatments, rolling, drawing, extruding, and so on) [1].

Thermal treatments are defined as processes that include heating of products up to the critical temperature, holding this temperature for a defined period of time, and then cooling the product in a prescribed way and velocity. One of the mostly applied ways of improvement of properties is thermal treatment of steel, usually referred to as ageing. In simple terms, cold deformation controls the number of dislocations, as well as the size and the number of polycrystal grains in the metal, while thermal treatment and alloying influence the size and the shape of the grains, number of spot defects, as well as the fineness and distribution of different phases of metal alloys. These methods for steel improvement are mutually intermixed and can give similar effects.

After the production in the steel mill, the steel is reshaped through rolling and/or drawing into wires, coils and bars (smooth or ribbed) with different diameters. Bars or coils prepared in this way, may be used as final products, that are shipped directly to the construction site, or as half products that are further used in production of welded fabrics (steel meshes) and lattice girders. Standard SRPS EN 10080 recognizes the following products for concrete reinforcement [2]:

- Bars, coils (rod, wire) and de-coiled products,
- Sheets of factory-made machine-welded fabric, and
- Lattice girders.

Standard SRPS EN 10080 (*Steel for the reinforcement of concrete - Weldable reinforcing steel – General*) defines the testing methods for different reinforcement products, as shown in Table 1. Most of the tests should be performed on the samples exposed to ageing. Ageing is defined as heating of the specimens to the temperature of 100 °C, holding this temperature ±10 °C during one hour ± 15 minutes and then cooling in still air to room temperature, with no air flow.

Having in mind that the European norm EN 10080 was accepted in Serbia as active standard in 2008 and that for the reinforced steel used on domestic construction sites there are no published data on the effect of ageing on steel properties, large experimental testing regarding this topic has been conducted.

Table 1. Conditions of testing the mechanical properties [2]

Manufacturing and delivery conditions of the product	Conditions of testing (test pieces)
Produced in straight lengths by hot rolling	As delivered a) or aged b)
Produced in straight lengths by cold working	Aged b)
Produced as coil and delivered de-coiled	Aged b)
Produced and delivered as coil	Straightened and aged b)
Welded fabric	Aged a), b), b)
Lattice girders	Aged a), b), b)

a) Aged, in case of dispute.

b) Aged means: Heating of the test piece to 100 °C, maintaining at this temperature ± 10 °C for a period of 1 h ± 15 min and then cooling in still air to room temperature. The method of heating is left to the discretion of the manufacturer.

c) Or as delivered when the constituents are produced in straight lengths by hot rolling.

2. LITERATURE REVIEW

Elghazouli at al. [3] have tested properties of reinforcing bars with 6 mm, 8 mm and 10 mm in diameter, exposed to the tensile stresses in different temperatures and stress conditions, with special attention paid to the temperature influence on ductility of steel. These tests were performed in order to analyse the behaviour of reinforced concrete slabs exposed to fire.

The types of the tested reinforcing bars are shown in Table 2.

Table 2. Types of the tested reinforcing bars [3]

Applied production procedure	Sample mark	Description
Hot rolling	P10	Smooth bar Ø 10 mm
	D10	Ribbed bar Ø 10 mm
	P6	Smooth bar Ø 6 mm
Cold rolling	D6	Ribbed bar Ø 6 mm
	D8	Ribbed bar Ø 8 mm

The following test conditions were applied:

- Tensile test at room temperature,
- Tensile test at the constant (increased) temperature and raising stress,
- Tensile test at the raising temperature and constant stress,
- Testing of retained properties (laying of samples on constant temperature in duration of at least 30 min, slow cooling to the room temperature, and then tested with increasing stress).

Stress-strain diagrams of all samples tested at room temperature are shown in Figure 1. Bars acquired through hot rolling production process show clearly detectable yield stress, which is not the case for the cold rolled bars.

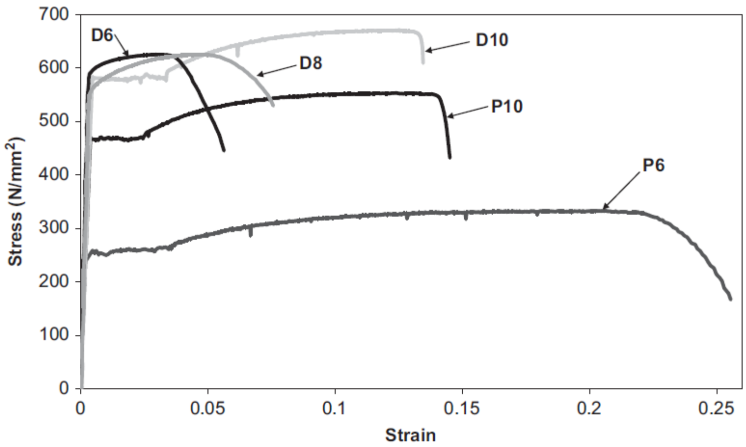

Figure 1. *Results of tensile test in room temperature [3]*

In the case when samples were aged (heated up to the determined temperature with holding the temperature for duration of 30 min, and then slowly cooled down to the room temperature), and then tested using tensile test, the stress-strain diagrams presented in Figures 2 and 3 were recorded.

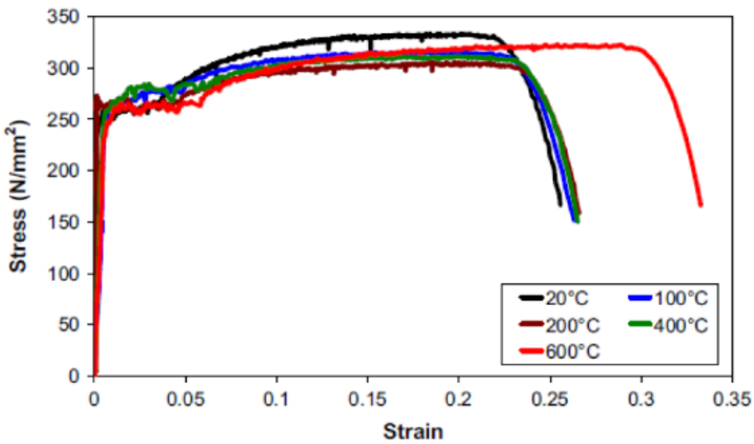

Figure 2. *Stress-strain diagram for sample P6 exposed to ageing on different temperatures [3]*

As it can be noticed in Figure 2, hot rolled bar P6 had clearly detectable yield stresses. Apart from the case when samples were exposed to the temperature of 600 °C, the increase in temperature led to the reduction of tensile strength, while yield stresses and elongation at maximum force were unchanged. Large increase in total elongation at maximum force was noted only for sample aged at the temperature of 600 °C.

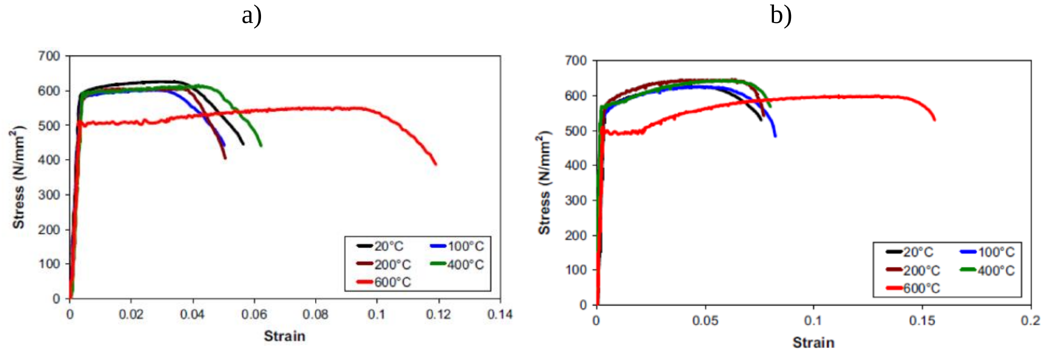

Figure 3. *Stress-strain diagram for sample D6 (a) and sample D8 (b) exposed to ageing on different temperatures [3]*

Different behaviour was noticed for cold shaped bars. Yield stresses of these bars were clearly detectable only on samples aged at the temperature of 600°C (Figure 3). This is a consequence of the loss of the cold deformation effects at very high temperatures, when these bars tend to behave similarly as hot rolled products. At the temperature of 600°C, the increase in total elongation at maximum force values was noticed for all the samples. At temperatures up to the 400°C, no significant changes in strength, ductility and stiffness of these samples were noted.

In another research conducted by Ahmad [4], the reinforcing bars of nominal diameter Ø20 mm were exposed to tensile tests, after ageing on the temperatures of 200 °C, 300 °C, 400 °C, 500 °C, 600 °C and 700 °C in duration of 30 min, 1 hour and 2 hours. After ageing, the samples were cooled to room temperature, and then tested.

The results of this study are shown in Table 3.

Table 3. Tensile tests results on reinforcing bars [4]

Type of specimen	Temperature (°C)	Duration (hours)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
Control	25 °C	0	684.2	764.3	25
Heated	200 °C	0.5 1 2	573.0 573.2 573.2	726.1 745.2 738.8	25 28 32
Heated	300 °C	0.5 1 2	554.1 567.0 560.5	719.8 719.8 732.5	35 33 28
Heated	400 °C	0.5 1 2	579.6 579.6 560.5	745.2 745.2 732.5	28 29 25
Heated	500 °C	0.5 1 2	600.0 598.0 579.0	758.0 764.3 732.5	18 29 28
Heated	600 °C	0.5 1 2	541.4 560.5 573.2	719.8 719.8 726.1	20 26 30
Heated	700 °C	0.5 1 2	465.0 484.1 452.2	598.7 595.1 582.2	32 33 35

It was shown that large scale reduction of mechanical properties (yield stress, tensile strength) was noticed only for samples tested on temperature of 700°C [4]. The length of the ageing process did not affect the obtained results.

Topçu and Karakurt [5] have tested hot rolled smooth reinforcing bars designated as S220 and ribbed bars designated as S420. Samples were aged at temperatures of 20 °C, 100 °C, 200 °C, 300 °C, 500 °C, 800 °C and 950 °C in duration of 3 h. After the exposure, samples were cooled down in air, to the room temperature, and then exposed to the tensile test.

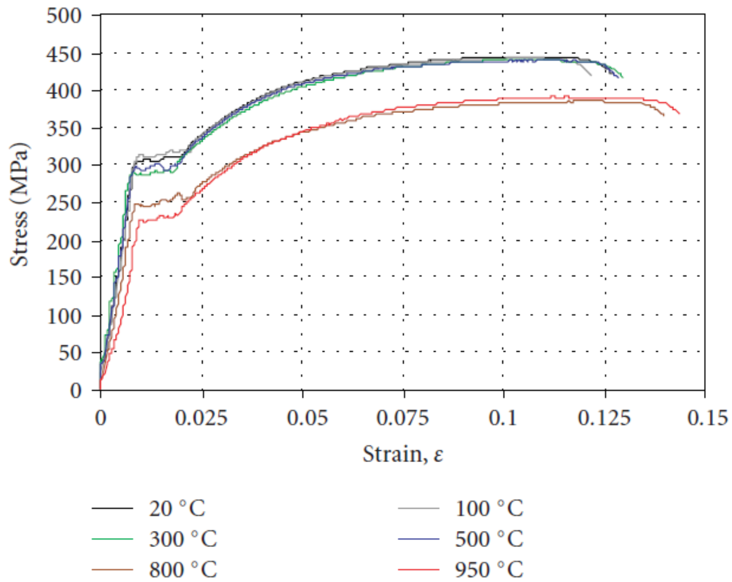

Figure 4. *Stress-strain diagram for reinforcing steel S220 aged on different temperatures [5]*

It was shown that the temperatures up to 500°C did not have greater influence on mechanical properties of steel S220. Significant reduction in strength and yield stress, and increase in ductility, were noticed at temperatures of 800°C and 950°C in both types of reinforcing steel products (as shown in Figure 4).

3. METHODOLOGY

The goal of the presented research was to determine the influence of the ageing defined according to the relevant standard SRPS EN 10080, on the mechanical and deformation properties of different reinforcing steel products. Having in mind that this standard defines that ageing of the samples should be performed at the temperature of 100±10°C, in duration of 1 h ± 15 min, this was one of the methods applied. In order to understand the influence of the duration of ageing process on the same properties, additional ageing methods in duration of 30 min and 2 hours were considered. The testing was conducted on the reinforced steel bars and coils (declared quality B500B) and reinforcing welded fabrics (declared quality B500A). Bars and coils were produced by hot rolling, while fabrics were prepared by spot welding of cold drawn bars.

Three samples for each type of reinforcing steel were chosen (bars, coils, fabrics), designated as „a“, „b“ and „c“, every sample 1000 mm long. Each of the samples was cut in 4 parts, making new samples of 250 mm in length. Parts obtained in this way were marked as 1, 2, 3 and 4. All the parts, marked with number 4, are shown in Figure 5. Bars and coils were tested in diameter of 10 mm, while fabric type Q221 had 6.5 mm bars in both directions.

All the samples for one type of product were taken from the same heat, in order to avoid differences in chemical composition and treatment of the samples. Each of the 4 parts marked 1-4 was exposed to one of the treatments, as shown in Table 4.

All the samples were tested using the tensile test with measurements of force and elongation until breakage. In this way, it was possible to form stress-strain diagrams for all the tested samples. These diagrams were used for analysis of the ageing effects on the values of yield stress, tensile strength and total elongation at maximum force. The testing was performed in the Laboratory of building materials, Faculty of Civil engineering University of Belgrade, using universal testing machine produced by „Shimadzu“, with range 0-300 kN and electrical extension meter produced by EDX, with maximum opening of 25 mm, and base length of 100 mm.

Table 4. Designation of the testing samples

Treatment	Marking of the samples		
	Bars	Coils	Fabrics
No ageing	š-a-1, š-b-1, š-c-1	k-a-1, k-b-1, k-c-1	m-a-1, m-b-1, m-c-1
30 min at T=100°C	š-a-2, š-b-2, š-c-2	k-a-2, k-b-2, k-c-2	m-a-2, m-b-2, m-c-2
1 h at T=100°C	š-a-3, š-b-3, š-c-3	k-a-3, k-b-3, k-c-3	m-a-3, m-b-3, m-c-3
2 h at T=100°C	š-a-4, š-b-4, š-c-4	k-a-4, k-b-4, k-c-4	m-a-4, m-b-4, m-c-4

Figure 5. *Samples of bars, coils and welded fabrics that were prepared for the ageing at the temperature of 100°C in duration of 2 h*

4. TESTING RESULTS AND DISCUSSION

Measured values of stress (σ) and strain (ε) acquired on the samples exposed to tensile testing are presented in Figures 6-8. It can be seen that σ-ε diagrams of reinforcing bars and coils, obtained by hot rolling, have clearly detectable yield stresses. However, stress-strain diagrams of welded fabrics (obtained through cold drawing) show that yield stress is not clearly defined for these products.

As it was expected, due to their ductility classes, elongation at maximal force was significantly lower for the samples taken from wired fabrics. Depending on the thermal treatment, elongations for the bars were between 10.3 and 10.7%, for coils between 9.8% and 9.9% and for fabrics between 2.6% and 3.1%. This is the consequence of the different production technologies. Cold drawing leads to uniform direction of the crystal grains and irreversible changes in crystal lattice, that influences increase in tensile strength and hardness of steel, and decrease in its ductility [6].

Ageing of the bar and coil samples at the temperature of 100°C in duration of 1 h and 2 h, led to mild increase of tensile strength and yield stress, when compared to the untreated samples, and samples aged in the duration of 30 minutes. For samples taken from coils, the highest influence of the treatment was noticed on the yield stress, which was increased by 7%, while tensile strength remained unchanged. The ductility of these samples (total elongation at maximum force), was reduced with the prolongation of the thermal treatment (see Table 5). However, if individual results of measured elongations are observed, for the samples designated as „a“, „b“ and „c“, both for bars and coils, the correlation between these values and the duration of the ageing process could not be determined.

When samples taken from the welded fabrics are considered, the differences in yield stresses and tensile strengths were very small. The lowest values of these stresses (R_{eH}=612.9 MPa and R_m=638.8 MPa), together with the highest values of total elongation at maximum force (A_{gt}=3.1%) were reached on samples aged for one hour. On the contrary, samples aged for 2 hours showed the highest values of measured stresses (R_{eH}=632.4 MPa and R_m=655.4 MPa) and lowest elongations.

For coils and fabrics, the ratio between tensile strength and yield stress decreased with the prolonging of the thermal treatment. For reinforcing bars, it was not possible to determine correlation between these two parameters.

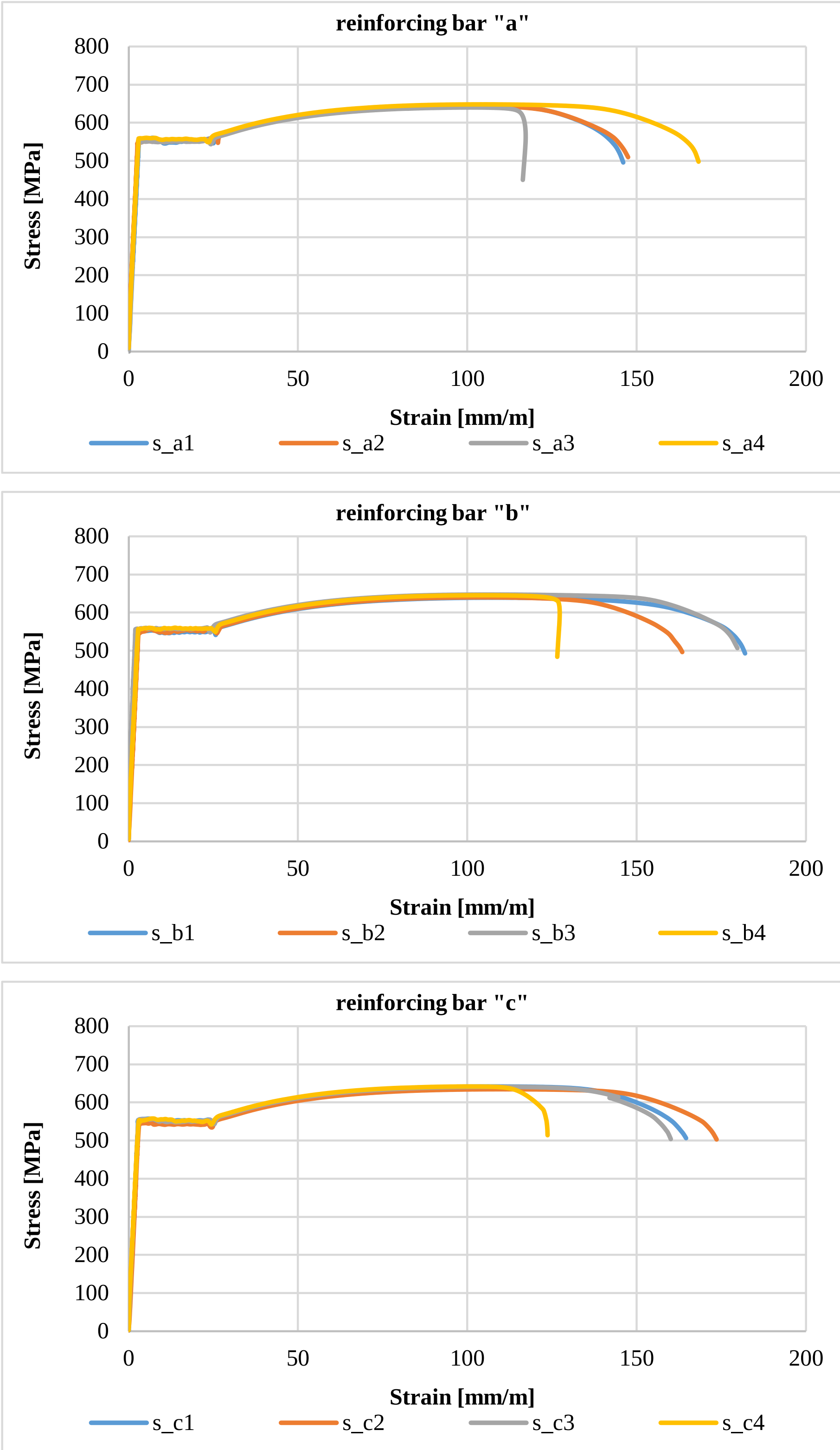

Figure 6. *Stress-strain diagrams for reinforcing bars tested after different thermal treatments*

The highest discrepancy of results, regarding all the measured parameters, was obtained for the samples taken from the welded fabrics. This may be the consequence of their production method, but this could be confirmed only after testing of larger number of samples for this type of product in the future.

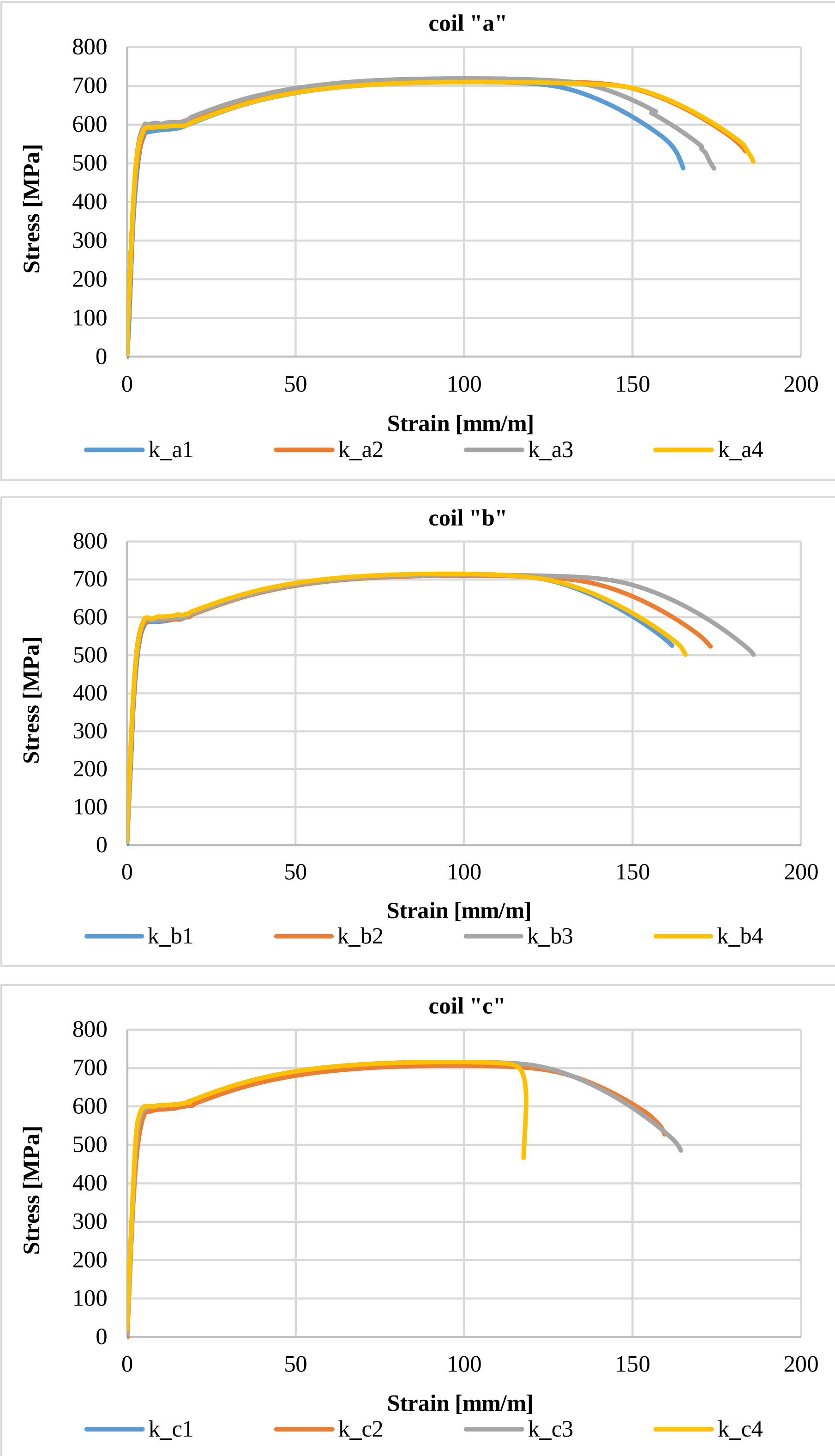

Figure 7. *Stress-strain diagrams for reinforcing coils tested after different thermal treatments*

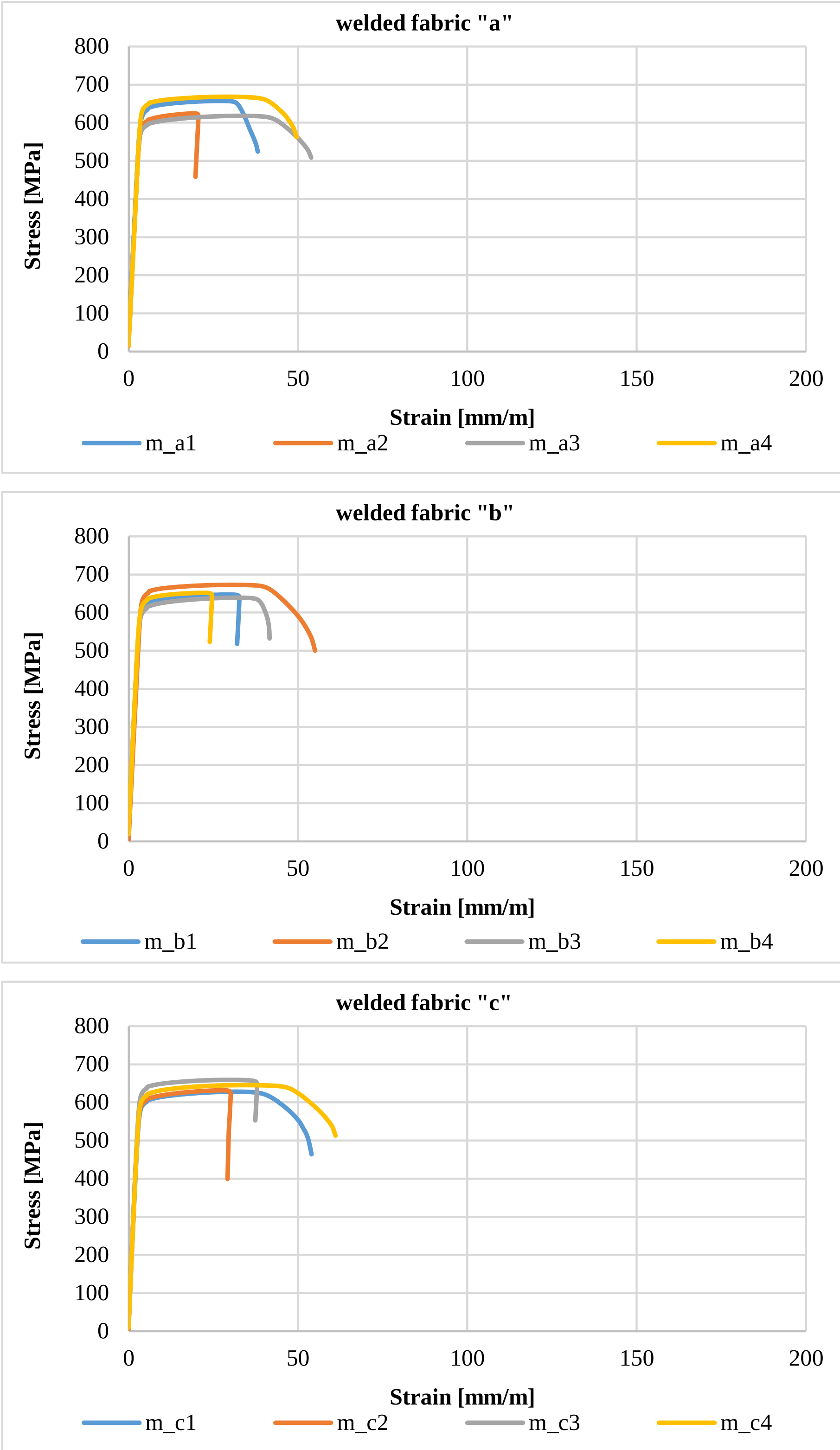

Figure 8. *Stress-strain diagrams for welded fabrics tested after different thermal treatments*

Table 5. Average values (standard deviations) of measured stress and strain on tested samples

Sample treatment	R_{eH} (MPa)	R_m (MPa)	R_m/R_{eH}	A_{gt} (%)	
No treatment	555.2 (2.99)	641.4 (2.49)	1.155	10.68 (0.23)	bars
Ageing for 30 min at 100°C	550.2 (3.99)	639.5 (4.11)	1.162	10.45 (0.31)	
Ageing for 1h at 100°C	554.9 (4.25)	642.7 (4.17)	1.158	10.57 (0.33)	
Ageing for 2h at 100°C	557.9 (2.70)	645.0 (3.23)	1.156	10.30 (0.21)	
No treatment	569.1 (5.38)	712.9 (2.69)	1.253	9.83 (0.42)	coils
Ageing for 30 min at 100°C	576.9 (5.77)	710.5 (3.69)	1.232	9.92 (0.45)	
Ageing for 1h at 100°C	590.3 (4.05)	715.6 (3.57)	1.212	9.80 (0.32)	
Ageing for 2h at 100°C	587.6 (8.97)	713.2 (3.10)	1.214	9.79 (0.70)	
No treatment	619.6 (17.23)	644.3 (14.85)	1.040	2.93 (0.57)	fabrics
Ageing for 30 min at 100°C	619.5 (27.40)	643.2 (26.02)	1.038	2.58 (0.91)	
Ageing for 1h at 100°C	612.9 (21.79)	638.8 (20.49)	1.042	3.14 (0.72)	
Ageing for 2h at 100°C	632.4 (15.43)	655.4 (11.71)	1.036	2.85 (0.51)	

5. CONCLUSION

The presented research was planned and performed in order to discuss the requirement of the standard SRPS EN 10080, prescribing that the reinforcing steel samples should be exposed to thermal treatment (ageing at the temperature of 100°C in duration of 1 hour). The duration of the ageing treatment was varied (30 min, 1 h and 2 h), as well as the type of the product treated (bars, coils and welded fabrics). After the treatment, samples were exposed to the tensile testing. Based on the acquired results, the following conclusions can be drawn:

- The most noticeable effect on the stress-strain diagram shape, was influenced by the production technology of the final products. Bars and coils were produced using the hot rolling procedure and thus showed pronounced yield stress and higher ductility, when compared to cold drawn wires applied in the welded fabrics production.
- Different duration of the thermal treatment at the temperature of 100°C did not show significant influence on the stress and elongation values. When compared to the reference samples, measured differences were not significant. This is in accordance with the findings in the literature, that greater changes in mechanical and deformation properties are noticeable when samples are exposed to temperatures higher than 400°C.
- Nevertheless, it was noticed that longer ageing process increased the yield strength of samples taken from coils. This parameter was increased by 7% when the ageing lasted for 1 h and 2 h. For welded fabrics, ageing in the duration of 1 hour, gave the optimal results for this type of product, reducing their mechanical properties and increasing their ductility. This is important due to the fact that production procedure of this steel reinforcement type generally has the opposite effect.

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