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Research paper

Post-fire properties of bolt steel, quenched and tempered in the production process

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Abstract: The article presents results of a static tensile test of standardized machined test pieces of round cross-section made of 32CrB3 alloy steel, quenched and tempered in the production process, subjected to environmental actions simulating an extraordinary fire situation. The tests were aimed at assessing the impact of simulated fire conditions on the residual mechanical properties of the analysed steel used to produce grade 8.8 steel construction bolts. The tests involved variants of the maximum temperature applied in the soaking process, exposure time to specific thermal conditions, and the cooling method. The specimens were soaked at temperatures of 600°C, 650°C, 700°C, 750°C, 800°C, 900°C, and 1000°C for periods of 30′, 60′, 120′ and 240′, respectively, and varied cooling methods were applied during the tests. The first batch of specimens, after soaking, was cooled naturally, left to cool down freely at ambient temperature. In the case of the second batch, the specimens were rapidly cooled by immersion in water until they cooled completely, thus simulating the effect of an intensive firefighting operation. The analysis relates to variability of values of the following post-fire parameters obtained in the static tensile test: ultimate tensile strength – $f_{u,\theta,\mathrm{post}}$, yield point – $f_{y,\theta,\mathrm{post}}$, modulus of elasticity – $E_{a,\theta,\mathrm{post}}$, ultimate strain at maximum force – $\varepsilon_{u,\theta,\mathrm{post}}$, strain at fracture – $\varepsilon_{f,\theta,\mathrm{post}}$, percentage elongation after fracture – $A_{5,\theta,\mathrm{post}}$, and percentage reduction of area – $Z_{\theta,\mathrm{post}}$, depending on the temperature and soaking time, as well as the cooling method applied. The results were compared with those reported in the literature. The values of retention factors and recovery factors were determined.

Keywords: cooling method, exposure time, high-strength steel bolt, recovery factor, residual post-fire mechanical properties, retention factor

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1. Introduction

There is no doubt that knowledge of the post-fire mechanical properties of construction materials is an issue of key importance in the process of expert assessment of the possibility of further safe operation of building structures, that have experienced this type of incident, and managed to survive it relatively intact. Depending on the construction material, the size of these parameters may depend on numerous factors, which undoubtedly include the temperature reached during the fire, the exposure time to the specific thermal conditions, and the method of cooling the heated structure. In the case of steel structures or composite steel-concrete structures, bolts are one of the key elements determining the structural safety, as they enable the assembly of complete load-bearing systems from individual transport elements delivered directly to the construction site from the plant. Intensive technological development in the field of materials engineering observed in recent decades, has resulted in considerable progress in this area. Newer steel grades have entered the market, characterized by previously unknown properties, which are obtained as a result of numerous operations in the production process – starting from the selection of the desired chemical composition of the raw material, up to suitable mechanical or heat treatment of the finished product. This development in the field of materials engineering, the possibility of modifying the chemical composition, and changes in the production technology have made it impossible to expect the same way of response to extraordinary thermal actions from all varieties or types of steel, and therefore – to predict the level of degradation of the properties given to products in the production process. High-strength bolts (HSB), to which this paper is directly devoted, are a product particularly exposed to the impact of high temperatures, because the properties obtained by them in the production process become degraded to varying degrees in the case of exceeding the original tempering temperature, the threshold values related to the parameters of the transformation phase (Ac_1 and Ac_3, respectively), and finally the quenching temperature, after which the original properties of the charge material, resulting only from the designed chemical composition, are actually restored. Prolonged subjecting to an elevated temperature, especially after the end of the austenitization process, may lead to unnatural grain growth, which translates into a deterioration of important strength parameters. Fast cooling of steel during firefighting operations may lead to repeated – complete or incomplete – hardening in uncontrolled conditions, which ultimately results in increased susceptibility of steel to brittle fracture, lower deformability and, therefore, less predictable behaviour under load. These issues were described in detail by, among others, Maślak et al. [1] or Król et al. [2]. The issue of predicting the post-fire mechanical properties of bolt steels, due to such aspects as the complexity of processes used in their production – from the design of the chemical composition of the raw material up to adequately designed production processes – is neither an easy nor an obvious job. Based on the classification resulting from the standards [3,4], also adopted by the author of [5], depending on the yield point characteristic of a given steel, structural steels can be divided into the following subgroups: NSS – normal structural steel grades (NSS) ($f_y \leq 420$ MPa), high-strength structural steel grades (HSS) ($420 < f_y \leq 700$ MPa), and very high-strength structural steel grades (VHSS) ($700 < f_y \leq 960$ MPa). And although this classification does not refer directly to fastening materials, it gives an idea that without

thorough research, supported by knowledge in the field of materials engineering, it is basically impossible to give a clear answer to the question how, as a result of actions accompanying the fire phenomenon, the properties of bolt steel will change, which in its initial state (delivered in the form of wire rod, as raw material for the production of bolts) corresponds to the NSS subgroup according to the above-presented classification, after quenching reaches parameters typical of VHSS, while after tempering fits into the values corresponding to HSS.

The scientists have strived for many years to understand and describe in analytical terms the variability of post-fire properties of materials, important from the point of view of their functional usefulness. Their scientific curiosity has led to the development of numerous publications and this paper focuses on those from among them, in which an attempt was made to describe the results obtained with appropriately fit regression curves. When examining the literature devoted to the research on the topic in question, attention should be paid to the work of Kodur et al. [6], in which the authors conducted comprehensive tests of the thermal and mechanical properties of bolts, based on standardized American A325 steel specimens, used for the production of grade 8.8 steel bolts. Although it provides the results of percentage reduction of area and percentage elongation after fracture, which is rare in the available literature, these are the values obtained in tests conducted at elevated temperatures, so they do not refer to the post-fire situation. The paper [7] presents the results of post-fire tests of grade 8.8 steel bolts made of SAE10B38 and SAE10B21 steel, which differ in their chemical composition, including quite significantly in the percentage of carbon content. The authors applied only slow natural cooling of specimens inside a furnace chamber and the tests were carried out on complete bolt assemblies, consisting of entire bolts, washers and nuts. The obtained results were presented in the form of relationships describing the reduction values of the residual modulus of elasticity, yield point, and ultimate strength as a function of the maximum temperature obtained in the soaking test. Tests with the use of bolts made of the same steel grades as presented in [7] were carried out by Daryan and Katebdari [8] who, unlike their predecessors, used standardized machined specimens and diverse rate of cooling in air. The results, as before, were presented in the form of relationships describing the level of permanent degradation of the modulus of elasticity, yield point, and ultimate strength as a function of the soaking temperature. Both in [7] and [8], the specimens were soaked at the set temperature for only 15 minutes. A significant impact of the cooling speed on the mechanical properties of high-strength bolts was noticed by, among others, Lou et al. [9] who subjected bolt assemblies consisting of M20/120 grade 8.8 steel bolts and nuts, immediately after soaking for a period of 60 minutes, to accelerated cooling in water and natural cooling in air. The results of static tensile tests and static shear tests, taking into account the conditions of a natural fire (including the cooling phase and the post-fire state), were presented, among others, for class 8.8 bolts by Hanus et al. [10], and for class 10.9 bolts by Mushahary et al. [11]. They confirmed that the cooling phase of the structure may be crucial from the point of view of the safety of connections. An attempt to organize post-fire test results available in the literature (mainly relating to various types of structural steels) and to formulate universal prediction formulas on basis thereof was made, as ones among the first, by Maraveas et al. [12], who presented in their paper relationships concerning, inter alia, cold-worked and heat-treated (HT) steels, initially pointing out to the lack of considerable differences in the degradation method between these

two groups of steel. In [13] they modified their viewpoint, clearly differentiating the formulas recommended for cold-worked steels from those recommended for heat-treated (HT) steels, and finally in their next work [14], they provided prediction formulas dedicated to high-strength bolts, mostly based on the results presented by Lou et al. [9]. It is impossible to ignore the work of Wang et al. [15], who presented an extensive testing program devoted to the assessment of post-fire properties of various grades of high-strength steel, quenched and tempered (QT) in the production process. Standardized specimens were soaked in the temperatures ranging from 100°C to 1200°C for a period of 30 to 240 minutes and cooled at various pace in water, air, and inside the furnace chamber. The work presented different variants of prediction formulas calibrated for respective mechanical properties, determined standardly in a static tensile test and varied depending on the method of cooling members, as a function of the temperature and time of fire exposure, and the tempering temperature used in the production process. At the same time, the formulas previously proposed by Tao et al. [16], which is the result of the work of a team working in a similar composition, in the same centre, were developed and supplemented. Relatively comprehensive tests on standardized specimens, made of Chinese GLG650 steel bars with strength parameters like those of grade 8.8 steel bolts, as well as similar chemical composition, were conducted by Chen et al. [17], who applied variant cooling methods after thermal exposure, both in air and water. As a result of their experiments, they proposed polynomial prediction curves. Finally, one cannot disregard the work of Katebdari et al. [18], who, based on previous test results presented in [8] and additionally supplemented with bolts of smaller diameters, attempted to build predictive models with the use of computer simulations and the meta-heuristic algorithms of Gene Expression Programming (GEP).

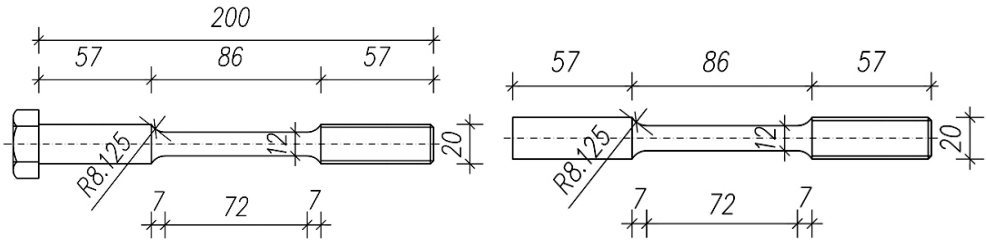
This article presents the results of own research on the impact of various environmental conditions occurring in an extraordinary situation of a real fire on the values of typical parameters obtained in a static tensile test: ultimate tensile strength – $f_{u,\theta,\mathrm{post}}$, yield point – $f_{y,\theta,\mathrm{post}}$, Young's modulus of elasticity – $E_{a,\theta,\mathrm{post}}$, ultimate strain at maximum force – $\varepsilon_{u,\theta,\mathrm{post}}$, strain at fracture – $\varepsilon_{f,\theta,\mathrm{post}}$, percentage elongation after fracture – $A_{5,\theta,\mathrm{post}}$,and percentage reduction of area – $Z_{\theta,\mathrm{post}}$. Values of retention factors and recovery factors were determined. The results obtained were compared with those reported in the literature. They undoubtedly indicate, that knowledge about the residual properties of various grades and types of steel is still incomplete and insufficiently documented.

2. Experimental study

2.1. Test specimens and methods

The post-fire mechanical properties of bolt steel described in this paper were tested by means of a classic static tensile test conducted at ambient temperature, consisting in breaking specimens of standardized shape and dimensions, made in accordance with [19], Figs. 1(a) and 1(b) from M20/200 grade 8.8 steel construction bolts. The test specimens were made from bolts delivered in factory condition and then subjected to heat treatment in accordance with the selected conditions of a simulated fire, by soaking them in batches in an electric furnace at

respective temperatures of: 600°C, 650°C, 700°C, 750°C, 800°C, 900°C, and 1000°C, for the time specified in applicable technical and construction regulations [20], corresponding to the fire endurance classes of members of the main load-bearing structure of buildings, i.e. 30′, 60′, 120′ and 240′. There was a doubt, whether the adopted shape of test pieces is appropriate for screws quenched and tempered in the production process and would not affect the test results. Analysis of the microstructure of screws in as-delivered state, presented in [2], did not show significant differences in the microstructure image, confirming the homogeneity of the material along the entire width of the bolt shank.



(a) Laying out of the specimen along the length of the bolt

(b) Approximate shape and dimensions of the specimen prepared for testing

Fig. 1. Standardized machined test piece of round cross-section, made based on the recommendations of the standard [19]

The correctness of the specimens was also confirmed by provisions of [21], specifying the mechanical and physical properties of bolts, screws and studs made of carbon or alloy steel, tested at an ambient temperature range of 10 to 35°C. In the case of 8.8 grade bolts, the standard specifies two alternative methods of conducting tests: a tensile strength test of machined test pieces, which should be carried out in accordance with [19] and a tensile strength test of full-size bolts, with only the former being recommended for determining the full package of mechanical properties of the material. The soaking temperatures were selected based on the results of previous tests of entire bolt assemblies, reported in [22], following the principle that the range of analysed temperatures is limited only to values exceeding the tempering temperature.

The specimens were placed into the furnace chamber previously heated to the desired temperature, kept in these conditions for 6–10 minutes, adopting based on the works [23, 24] the estimated heating rate of the specimens at approximately 100°C/min, after which the soaking time measurement was started. Following such thermal exposure, some of the specimens were removed from the furnace and left to naturally cool at ambient temperature (air-cooling/specimen symbol: AC), which was supposed to correspond to the situation of a free of interference, natural end of fire, resulting either from a lack of oxygen or a lack of flammable substances. The second batch of specimens was shock-cooled by immersion in water (water-cooling/specimen symbol: WC), where they were kept until they completely cooled, which was intended to simulate the conditions of an intensive firefighting operation. In each series, for statistical reasons, 3 specimens were tested, which made up a total of 171 specimens, including 84 specimens cooled in air, 84 specimens cooled in water, and 3 specimens in the initial state, treated as reference. Apart from the reference specimens in the initial state (IS-20),

the remaining specimens were marked according to the X/Y/Z scheme, where X denotes the cooling method, Y – the soaking temperature, and Z – the time of soaking in set thermal conditions (for example, AC/600/120 means a specimen cooled in air, after soaking at 600°C for 120 minutes). Before starting the tests, after cleaning the specimen surfaces from scale and degreasing them, markers showing an original gauge length of the specimen were applied. Proportional 5d gauge specimens with an original gauge length of 60 mm were used in the tests. The specimens were prepared with the use of bolts made of chromium alloy steel with the addition of boron, designated as 32CrB3, the chemical composition of which is presented in Table 1, according to the manufacturer's declaration of conformity. The bolts were made of smooth wire rod in the cold forging process and then, in order to obtain the expected mechanical properties corresponding to strength of grade 8.8 steel, they were heat-treated by quenching in oil at a temperature of approx. 850–860°C and tempering at a temperature of approx. 550°C.

Table 1. Chemical composition of the 32CrB3 bolt steel

Steel designation	**Chemical composition [%]**										
32CrB3	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo	Sn
	0.31	0.84	0.13	0.012	0.013	0.74	0.08	0.15	0.025	0.018	0.010
	V	Ti	B	Zn	Ce	N	Al_m	Ca	As	Nb	Sb
	0.004	0.047	0.002	0.028	0.62	0.0114	0.022	0.0023	0.007	0.001	0.002

2.2. Test setup and procedures

The bolt tests were performed using a universal testing machine Instron 8802, with a load range of up to 250 kN and a force measurement accuracy of ±0.5%, controlled by the Bluehill 2 software, and a video extensometer made by Instron, designed for longitudinal and transverse measurements, with a field of view of 25 × 200 mm and position accuracy measurement of 1 μm. The tests were carried out using the displacement control method, assuming a constant strain rate of 2 mm/min, until the fracture of the specimen. In line with the recommendations contained in [19], it was assumed that the change in the strain rate during the test is unjustified, because it may lead to, difficult to interpret, distortions of the tensile curve. The specimens were mounted directly in the grip jaws of the testing machine, using clamps. During the tests, the following parameters were automatically recorded: the force corresponding to the conventional 0.2 yield point, the maximum force applied to a given specimen during the test, the accompanying ultimate strain – ε_u, the load value at the moment of specimen fracture, and the size of percentage strain at fracture – ε_f. Based on the knowledge of these values and the measurements of the gauge diameter and length of the specimens before and after the test, the percentage elongation after fracture – A_5, and the percentage reduction of area – Z were determined. Young's modulus was also determined automatically using the "E-Modulus" algorithm implemented in the Bluehill 2 software, based on the recorded $\sigma - \varepsilon$ curve.

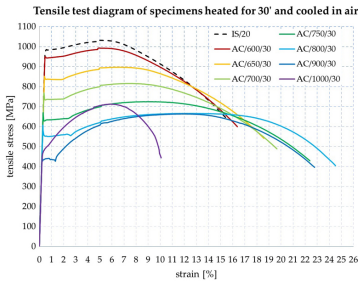
2.3. Experimental results and discussion

2.3.1. Stress-strain curves

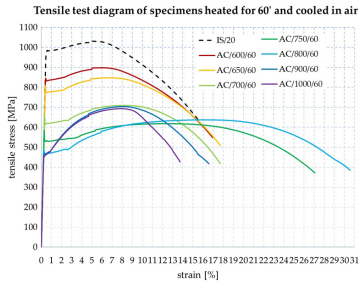
Recorded stress-strain curves, presented in Figs. 2(a)–(h), show the impact of a range of factors on the nature of behaviour of the tested specimens depending on the set temperature value, soaking time, and the adopted cooling method. The diagrams were prepared for average values of the results obtained for each of the three specimens in each series. Detailed analysis of the tensile curves presented in Figs. 2(a)–(h) indicates that in the area of temperatures exceeding the tempering temperature, up to 700°C (i.e. lower than the temperature when the allotropic transformation begins – Ac_1 which, based on the chemical composition, the simulations carried out in the "JmatPro" software, and available Internet sources, is estimated at the level of 741–745°C), the level of dispersion of carbides in the sorbitol decreases as a result of their coalescence, which results in a noticeable decrease in strength and yield point, with a simultaneous increase in ductility. This process is proportional to the soaking time applied – the longer the time, the greater the reduction in strength, regardless of the cooling method applied. The situation changes at a temperature of 750°C, at which the specimen steel undergoes microstructural reconstruction associated with the phase transformation and the process of complete loss of structure and properties obtained as a result of quenching begins. In the temperature range lower than Ac_3– the temperature at which the austenitization process ends (which, using the method similar to Ac_1, was estimated at approximately 805–810°C), the exposure time to fire conditions and the heating rate become key factors.

Soaking at temperatures exceeding Ac_1leads to the creation of a range of ferritic-austenitic structures, which, depending on the rate of subsequent cooling, may result in the end in various combinations of ferritic-pearlitic structures with different proportions and dispersion of respective phases, and therefore characterized by completely different mechanical properties. This was confirmed by research of, among others, Peng et al. [25], who conducted tests on SN490C steel specimens using a metallurgical microscope.

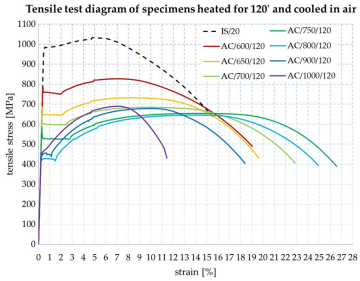
In the case of the bolts soaked at 750°C and 800°C and cooled in water, the effect of repeated hardening becomes visible, manifesting itself in a significant increase in strength with a simultaneous noticeable decrease in the ductility of the material. It should be noted, however, that in the case of the temperature of 750°C, this effect is noticeable only in the case of longer soaking periods (120′ and 240′). As the phase transformation of steel has not yet taken place to a full extent, this effect is still incomplete at this temperature. The observed phenomenon results from the strict dependence of the rate of transformation of pearlite into homogeneous austenite on the speed at which the material is being soaked. This may explain the irregularities observed in the tests in terms of mechanical properties and the behaviour of specimens under load, as well as some apparent inconsistency of results in this temperature range. Referring this to the conditions of a simulated fire, the rate of pearlitic transformation will, in practice, depend on the fire intensity. The higher the heating rate, the higher the temperature range in which the transformation of pearlite into austenite takes place and the quicker the rate of this transformation. At first, austenite within individual grains is non-homogeneous, because in areas where cementite was present in the structure of the material, the carbon content is higher and the austenite homogenizes only after some time. It



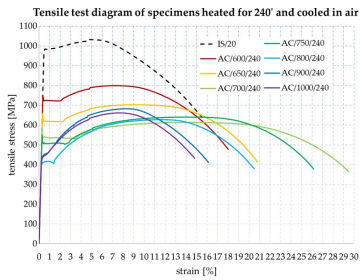
(a) 30′ of soaking time, specimens cooled in air



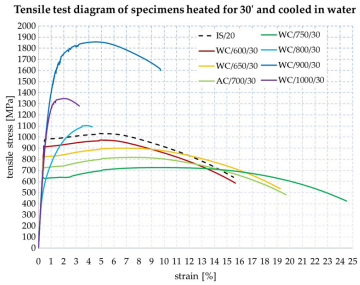
(b) 60′ of soaking time, specimens cooled in air



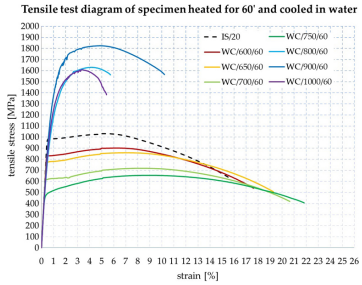
(c) 120′ of soaking time, specimens cooled in air



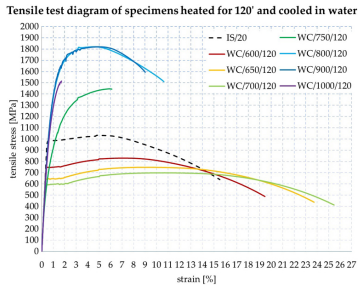
(d) 120′ of soaking time, specimens cooled in air



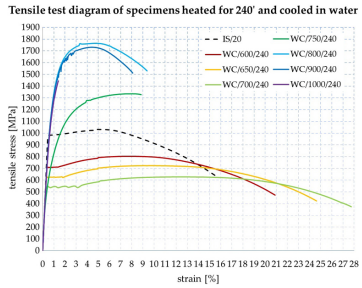
(e) 30′ of soaking time, specimens cooled in water



(f) 60′ of soaking time, specimens cooled in water



(g) 120′ of soaking time, specimens cooled in water



(h) 120′ of soaking time, specimens cooled in water

Fig. 2. Tensile test diagrams for varied soaking time, cooling methods, and temperature conditions

ought to be mentioned that the transformation of pearlite into austenite takes place nominally at 727°C only in the case of very slow heating. In the case of faster heating, it is shifted towards higher temperatures. For example, at a temperature of 750°C, the transformation of pearlite into austenite will begin after a few seconds, after several dozen seconds we will obtain inhomogeneous austenite with carbide remnants, which will dissolve in austenite solution after approximately two hours, at which point only inhomogeneous austenite will be present. The end of its homogenization at this temperature requires a much longer soaking period and this time cannot be precisely determined based on the available literature, but in general, it may take up to several hours. Just to illustrate, at a temperature of 800°C, the transformation of pearlite into austenite begins almost immediately, we will obtain heterogeneous austenite with carbide remnants after a few seconds, and it will dissolve in austenite after less than 2 minutes, while the entire homogenization process will be completed within 1 hour. At higher temperatures (900–1000°C), the entire transformation process will take a maximum of a couple of minutes [26]. Soaking at 900°C and cooling in water leads to complete re-hardening of the specimens and the related increase in strength and decrease in ductility resulting from the complete martensitic transformation in the steel. Both an increase in the soaking time and temperature to 1000°C lead to a decrease in the strength, which is the result of overheating of the steel, excessive growth of austenite grains, and in consequence – the coarse-grained structure of the resulting martensite and considerable structural stresses in the steel.

2.3.2. Method of presenting results

The results of research on the degree of dependence of the post-fire mechanical properties of bolt steel on the temperature, soaking time, and cooling method were presented by deriving inspiration from the formula proposed in the works [5] and [24]. The measure of reduction of the i-th material property after fire exposure is the so-called retention factor (respectively: $R_{Ea,\theta,\text{post}}$, $R_{y,\theta,post}$, $R_{u,\theta,\text{post}}$, $R_{\varepsilon u,\theta,\text{post}}$, $R_{\varepsilon f,\theta,\text{post}}$, $R_{A5,\theta,post}$, and $R_{Z,\theta,\text{post}}$, defined as the quotient of the value of a specific property after going through a complete thermal cycle, consisting of soaking up to the temperature θ[°C] and then cooling, according to the adopted method, and the value of the same property determined for a reference specimen, not exposed to fire. In the case of structural steels, the value of the retention factor can be also identified (in relation to some values to which it is applicable) with the product of the standard reduction factor [27] (respectively: $k_{E,\theta}$,$k_{y,\theta}$, $k_{u,\theta}$or $k_{b,\theta}$), defined as for a fire situation, and a corresponding new factor, hereinafter referred to as the recovery factor: $r_{E,\theta}$, $r_{y,\theta}$, $r_{u,\theta}$ or $r_{b,\theta}$, according to the idea presented on the example of the factors defined for the modulus of elasticity in Eq. 2.1.

$$R_{Ea,\theta,\text{post}} = \frac{E_{a,\theta,\text{post}}}{E_{a,20}} = \frac{E_{a,\theta}}{E_{a,20}} \cdot \frac{E_{a,\theta,\text{post}}}{E_{a,\theta}} = k_{E,\theta} \cdot r_{E,\theta,\text{post}} \tag{2.1}$$

Since factors $k_{E,\theta}$, $k_{y,\theta}$, $k_{u,\theta}$ cannot be applied in the case of bolts, because according to [28] they only refer to the steel from which the structure's bar members are made, from a formal point of view, for bolts it is only possible to determine the value of the recovery factor $r_{b,\theta,\text{post}}$, by using the values of the retention factor $R_{u,\theta,\text{post}}$ obtained in the tests and the values of the reduction factor of bolt strength $k_{b,\theta}$ given in [27], in line with Eq. 2.2. This is due to the fact that the reduction factor $k_{b,\theta}$ is used to determine the design resistance of bolts to tension,

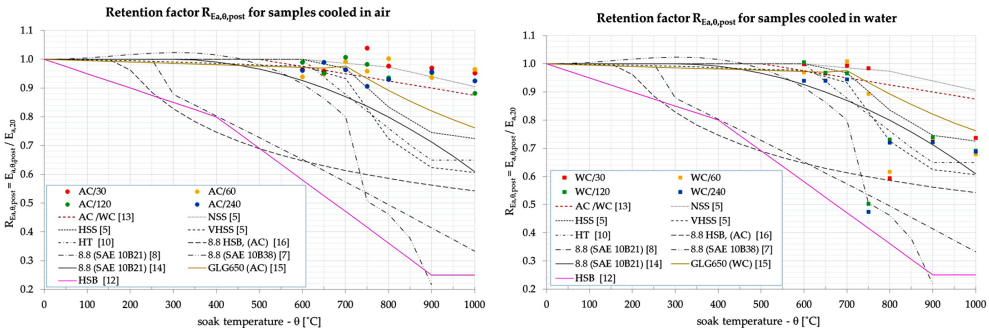
shear or pressure, the values of which are determined in accordance with [2–5], based on the knowledge of the parameter f_{ub}.

$$R_{u,\theta,\text{post}} = \frac{f_{u,\theta,\text{post}}}{f_{u,20}} = \frac{f_{ub,\theta}}{f_{ub,20}} \cdot \frac{f_{ub,\theta,\text{post}}}{f_{ub,\theta}} = k_{b,\theta} \cdot r_{b,\theta,\text{post}} \tag{2.2}$$

The retention factor takes values less than 1.0 if a given parameter after fire exposure reaches values lower than the reference values determined on the specimen in the initial state and greater than 1.0 if the situation is reverse. The recovery factor may have values higher than 1.0 when the value of a given i-th property measured on a specimen cooled after a fire is greater than the same property determined in a fire situation.

2.3.3. Modulus of elasticity

The values of retention factors for the modulus of elasticity obtained in the tests are presented in the form of coloured points in Figs. 3(a)–(b) and are provided in Table 2. For comparison, the diagrams also include prediction curves taken from the cited bibliographic sources. A detailed analysis of the results shows that in the case of the specimens cooled in air, there are basically no significant decreases in the Young's modulus values determined on the specimens after they have cooled down. The lowest recorded value reaches 88.3% of the initial value and refers to the specimens soaked for 120 minutes at 1000°C.



(a) Samples cooled in air (b) Samples cooled in water

Fig. 3. Retention factors for modulus of elasticity – $R_{Ea,\theta,\text{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

In the case of the specimens cooled in water, the greatest reduction in the Young's modulus value concerns the specimens heated for 120′ and 240′ at 750°C, and 30′ and 60′ at 800°C. In this case, the Young's modulus value is approximately 47.4–61.3% of the original value. This may be related to the unclear state of the internal structure of the material obtained after incomplete hardening, as mentioned in subsection 2.3.1.

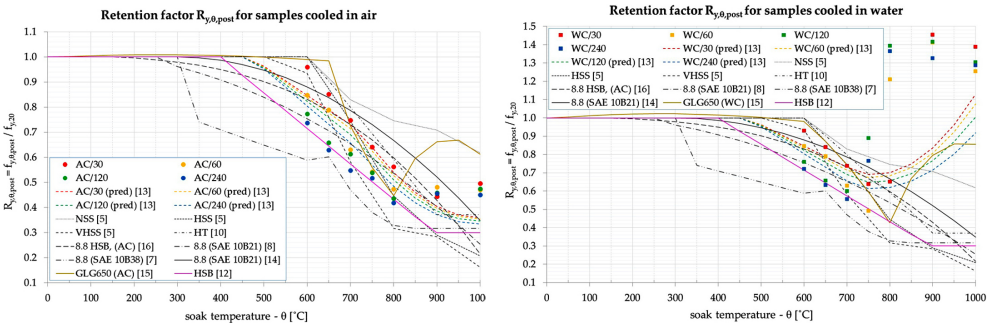
It should be noted, that the prediction curves presented in Figs. 3(a)–(b), in general significantly underestimate the Young's modulus values, especially in the case of specimens cooled in air.

Table 2. Retention factor values for modulus of elasticity – $R_{Ea,\theta,\text{post}} = E_{a,\theta,\text{post}}/E_{a,20}$

Temp. [°C]	Retention factor values for modulus of elasticity (E_a), after the thermal exposure lasting . . .							
	. . . 30 minutes		. . . 60 minutes		. . . 120 minutes		. . . 240 minutes	
	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	0.965	0.998	0.940	0.970	0.990	1.006	0.962	0.940
650	0.960	0.996	0.948	0.941	0.952	0.969	0.990	0.939
700	0.964	0.994	1.007	1.009	0.992	0.965	0.964	0.944
750	1.039	0.983	0.983	0.893	0.959	0.503	0.906	0.474
800	0.977	0.593	0.936	0.616	1.002	0.731	0.930	0.720
900	0.971	0.723	0.937	0.726	0.954	0.739	0.957	0.721
1000	0.952	0.736	0.966	0.678	0.883	0.691	0.925	0.688

2.3.4. Yield point

The values of the retention factors for the yield point, determined based on the test results, are shown in Figs. 4(a)–(b) and are provided in Table 3.



(a) Samples cooled in air (b) Samples cooled in water

Fig. 4. Retention factors for yield point – $R_{y,\theta,\text{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

A detailed analysis of the results shows that in the case of specimens cooled in air, there are basically no anomalies in the obtained values. Measured values, as expected, gradually decrease along with an increase in the soaking temperature and time, and the prediction curves are relatively consistent with the obtained results.

Table 3. Retention factor values for yield point – $R_{y,\theta,\text{post}} = f_{y,\theta,\text{post}}/f_{y,20}$

Temp. [°C]	Retention factor values for yield point (f_y), after the thermal exposure lasting ...							
	... 30 minutes		... 60 minutes		... 120 minutes		... 240 minutes	
	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	0.960	0.930	0.848	0.845	0.773	1.761	0.737	0.722
650	0.852	0.841	0.789	0.790	0.659	0.657	0.630	0.633
700	0.747	0.738	0.630	0.630	0.612	0.601	0.548	0.556
750	0.641	0.638	0.542	0.492	0.538	0.889	0.517	0.766
800	0.562	0.652	0.473	1.210	0.437	1.394	0.418	1.365
900	0.443	1.454	0.481	1.413	0.459	1.416	0.456	1.327
1000	0.496	1.388	0.471	1.255	0.474	1.304	0.451	1.288

In the case of specimens cooled in water, a clear inconsistency of the results obtained for respective soaking times is noticeable at a temperature of 750°C, while in the case of a temperature of 800°C, with a soaking time longer than 30′, the results clearly increase, which is due to the strengthening of the material as a result of its hardening. The obtained values are up to approx. 45% higher than the reference value. Prediction curves for specimens cooled in water in the temperature range higher than 750°C clearly underestimate the measured values.

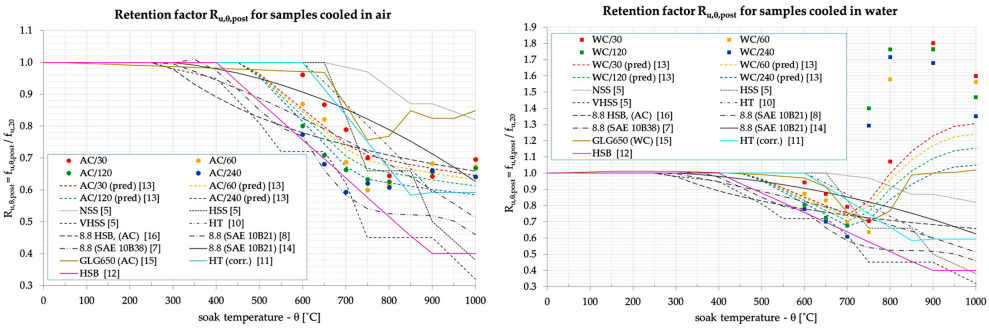
2.3.5. Ultimate tensile strength

The values of the retention factors for ultimate tensile strength are shown in Figs. 5(a)–(b) and are provided in Table 4. They reflect a similar trend as in the case of the yield point, with the only difference that in the case of specimens cooled in water, they are characterized by slightly greater diversity between the values for the temperature range 800–1000°C. The values obtained after soaking at 1000°C are lower than in the case of soaking at 800°C, which may be the result of unnatural growth of the austenite grain during soaking, which ultimately resulted in the formation of coarse-grained martensite after hardening of the specimen. Nevertheless, it should be noted that the level of strengthening of the material is significant.

After hardening the breaking strength increased in some cases by over 70%, and even – in the case of specimens heated at 900°C for 30′ – it reached a value that was 80% higher from the reference value.

2.3.6. Ultimate strain

The values of the retention factors for the ultimate strain (associated according to [3] with $f_{u,\theta,\text{post}}$, are shown in Figs. 6(a)–(b) and are provided in Table 5. As a result of soaking, the ductility and thus the deformability of the material increases until the temperature exceeds the



(a) Samples cooled in air (b) Samples cooled in water

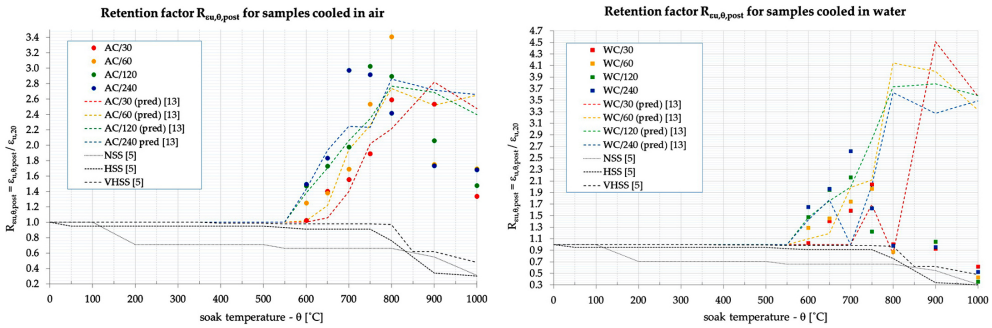
Fig. 5. Retention factors for ultimate tensile strength – $R_{u,\theta,\mathrm{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

Table 4. Retention factors for ultimate tensile strength – $R_{u,\theta,\mathrm{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

Temp. [°C]	**Retention factor values for ultimate tensile strength (f_u), after the thermal exposure lasting . . .**							
	. . . 30 minutes		**. . . 60 minutes**		**. . . 120 minutes**		**. . . 240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	0.961	0.943	0.870	0.873	0.801	0.803	0.774	0.777
650	0.868	0.872	0.822	0.832	0.709	0.724	0.681	0.701
700	0.790	0.791	0.688	0.696	0.663	0.676	0.594	0.608
750	0.701	0.703	0.599	0.636	0.633	1.400	0.620	1.293
800	0.644	1.071	0.618	1.579	0.626	1.764	0.608	1.715
900	0.642	1.801	0.683	1.768	0.657	1.763	0.661	1.679
1000	0.695	1.598	0.673	1.563	0.669	1.467	0.642	1.351

level when the Ac_1 phase transformation begins. In the case of specimens cooled in air, the observed deformations exceed the values determined for reference specimens by even more than three times.

After exceeding the Ac_1 value, the material is still ductile and its deformations exceed the values specified for the reference specimen, however, this deformability decreases because the structure of the material has been rebuilt as a result of the phase transformation and its properties no longer correspond to those given to it in the heat treatment process at the production stage. Cooling in water of the specimens heated above the temperature at which



(a) Samples cooled in air (b) Samples cooled in water

Fig. 6. Retention factors for ultimate strain – $R_{\varepsilon u,\theta,\text{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

the Ac_1 phase transformation begins results in a decrease in ductility, even to the level of approximately 27% of the original value – the material becomes brittle. In the case of specimens cooled in air, the prediction curves marked with coloured lines proposed by Wang et al. [15], quite well reflect the trend of how the results are shaped in the entire specified area.

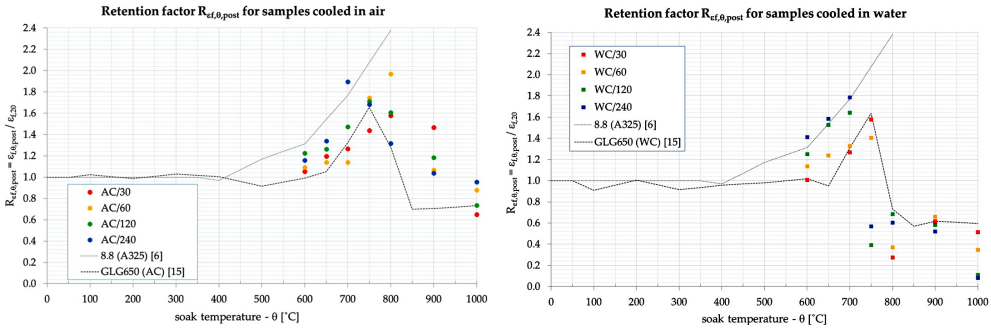
Table 5. Retention factor values for ultimate strain – $R_{\varepsilon u,\theta,\text{post}} = \varepsilon_{u,\theta,\text{post}}/\varepsilon_{u,20}$

Temp. [°C]	**Retention factor values for ultimate strain (ε_u), after the thermal exposure lasting ...**							
	... 30 minutes		**... 60 minutes**		**... 120 minutes**		**... 240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	1.027	1.027	1.250	1.285	1.473	1.473	1.494	1.646
650	1.402	1.402	1.381	1.452	1.729	1.944	1.833	1.965
700	1.556	1.583	1.692	1.744	1.979	2.160	2.973	2.619
750	1.890	2.042	2.535	1.965	3.027	1.223	2.917	1.625
800	2.590	0.792	3.410	0.875	2.896	0.979	2.417	0.979
900	2.535	1.000	1.750	1.042	2.063	1.048	1.735	0.952
1000	1.340	0.615	1.694	0.688	1.479	0.354	1.681	0.265

Unfortunately, as regards specimens cooled in water, in the range of temperatures exceeding 800°C, they are completely different from the obtained results. In this range, a much better approximation is the curves marked with black lines proposed by Molkens et al. [5].

2.3.7. Strain at fracture

The values of the retention factors for the strain at fracture are shown in Figs. 7(a)–(b) and are provided in Table 6. Following the initial increase, the total deformability of the specimen, after soaking at a temperature exceeding Ac_1, shows a decreasing trend, regardless of the chosen cooling method. It is much larger in the case of specimens cooled in water, which is a natural consequence of hardening of the material.



(a) Samples cooled in air (b) Samples cooled in water

Fig. 7. Retention factors for strain at fracture – $R_{\varepsilon f,\theta,\mathrm{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

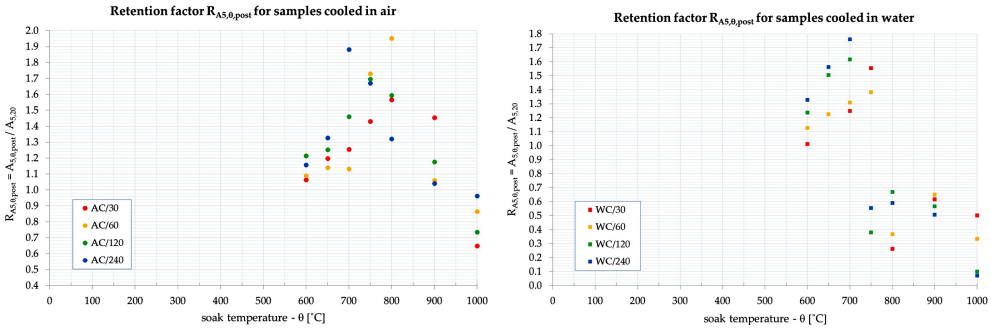
Table 6. Retention factor values for strain at fracture – $R_{\varepsilon f,\theta,\mathrm{post}} = \varepsilon_{f,\theta,\mathrm{post}}/\varepsilon_{f,20}$

Temp. [°C]	Retention factor values for strain at fracture (ε_f), after the thermal exposure lasting . . .							
	. . . 30 minutes		. . . 60 minutes		. . . 120 minutes		. . . 240 minutes	
	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	1.056	1.009	1.091	1.135	1.227	1.252	1.160	1.411
650	1.198	1.238	1.139	1.240	1.264	1.528	1.339	1.586
700	1.267	1.269	1.140	1.328	1.473	1.642	1.898	1.786
750	1.440	1.578	1.743	1.406	1.711	0.393	1.685	0.569
800	1.578	0.274	1.968	0.370	1.607	0.684	1.319	0.605
900	1.466	0.618	1.068	0.658	1.184	0.581	1.039	0.522
1000	0.650	0.515	0.879	0.348	0.736	0.109	0.956	0.082

Nevertheless, it should be noted that in the case of specimens cooled in air, although their deformability after overheating at a temperature of 1000°C drops below the reference value, it still remains at a relatively decent level, while in the case of specimens cooled in water it decreases to practically zero. The presented prediction curves, in terms of their specificity, correspond quite well to the trends of the research results.

2.3.8. Percentage elongation after fracture – A_5

The values of the retention factors for percentage elongation – A_5 are shown in Figs. 8(a)–(b) and are provided in Table 7.



(a) Samples cooled in air (b) Samples cooled in water

Fig. 8. Retention factors for percentage elongation – $R_{A5,\theta,\text{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

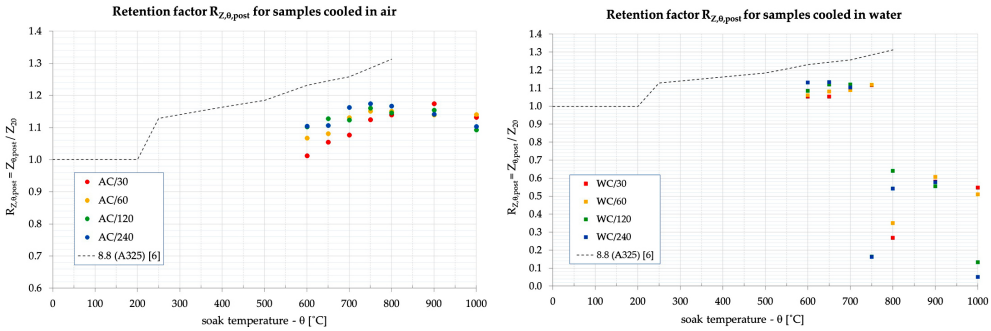
Table 7. Retention factor values for percentage elongation after fracture – $R_{A5,\theta,\text{post}} = A_{5,\theta,\text{post}}/A_{5,20}$

Temp. [°C]	**Retention factor values for percentage elongation after fracture (A_5), after the thermal exposure lasting**							
	. . . 30 minutes		**. . . 60 minutes**		**. . . 120 minutes**		**. . . 240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	1.063	1.022	1.089	1.137	1.214	1.247	1.157	1.338
650	1.198	1.234	1.140	1.235	1.253	1.516	1.328	1.572
700	1.255	1.258	1.133	1.318	1.460	1.647	1.881	1.772
750	1.430	1.565	1.773	1.394	1.696	0.390	1.670	0.565
800	1.566	0.272	1.951	0.377	1.595	0.680	1.321	0.600
900	1.455	0.626	1.061	0.661	1.176	0.576	1.041	0.517
1000	0.648	0.513	0.865	0.345	0.735	0.110	0.962	0.082

In a natural way, they do not differ from the results obtained for strain at fracture, presented in subsection 2.3.7. Minor differences result only from the fact that the other ones refer to the total length of a test piece, while these ones refer to its original gauge length.

2.3.9. Percentage reduction of area – Z

The values of the retention factors for the reduction of area – Z are shown in Figs. 9(a)–(b) and are provided in Table 8.



(a) Samples cooled in air (b) Samples cooled in water

Fig. 9. Retention factors for percentage reduction of area – $R_{Z,\theta,\text{post}}$; (a) for samples cooled in air, (b) for samples cooled in water

Table 8. Retention factor values for percentage elongation after fracture – $R_{Z,\theta,\text{post}} = Z_{\theta,\text{post}}/Z_{20}$

Temp. [°C]	**Retention factor values for percentage reduction of area after fracture (Z), after the thermal exposure lasting**							
	. . . 30 minutes		**. . . 60 minutes**		**. . . 120 minutes**		**. . . 240 minutes**	
	Cooled in air (AC)	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**	**Cooled in air (AC)**	**Cooled in water (WC)**
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	1.013	1.054	1.068	1.062	1.103	1.085	1.105	1.133
650	1.055	1.055	1.081	1.081	1.128	1.121	1.107	1.133
700	1.078	1.090	1.131	1.090	1.123	1.120	1.163	1.104
750	1.125	1.117	1.151	1.120	1.161	0.165	1.175	0.164
800	1.140	0.269	1.151	0.351	1.146	0.641	1.168	0.542
900	1.175	0.583	1.140	0.608	1.154	0.556	1.141	0.578
1000	1.132	0.548	1.140	0.512	1.093	0.133	1.104	0.052

Values higher than 1.0 mean that the specimen after fracture reduced its area by more than the reference specimen (i.e. the fracture area is smaller therein), and, consequently, the nature of its failure was more plastic. Values lower than 1.0 indicate a decrease in the ductility of the material, whereas in the case of significantly lower values – a brittle or nearly brittle method of failure. The prediction curves marked in Figs. 9(a)–(b) generally overestimate the obtained results.

2.3.10. Recovery factor

Table 9 shows the calculated values of the recovery factor – $r_{b,\theta,\text{post}}$, related to the standard [27] reduction factor of the bolt strength in a fire situation – $k_{b,\theta}$.

Table 9. Recovery factor related to strength reduction factor for bolts ($k_{b,\theta}$) – $r_{b,\theta,\text{post}} = f_{ub,\theta,\text{post}}/f_{ub,20} = f_{u,\theta,\text{post}}/f_{u,20}$

Temp. [°C]	Recovery factor values related to strength reduction factor for bolts ($k_{\mathbf{b},\theta}$)							
	... 30 minutes		... 60 minutes		... 120 minutes		... 240 minutes	
	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)	Cooled in air (AC)	Cooled in water (WC)
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
600	4.370	4.285	3.955	3.968	3.641	3.652	3.518	3.533
650	5.426	5.448	5.135	5.200	4.431	4.526	4.255	4.379
700	7.897	7.915	6.876	6.959	6.632	6.764	5.936	6.080
750	8.397	8.424	7.178	7.622	7.584	16.768	7.429	15.489
800	9.618	15.990	9.219	23.563	9.336	26.329	9.074	25.601
900	19.465	54.584	20.704	53.569	19.916	53.432	20.028	50.890
1000	$\to \infty$	$\to \infty$	$\to \infty$	$\to \infty$	$\to \infty$	$\to \infty$	$\to \infty$	$\to \infty$

Obtained values higher than 1.0 indicate that the ultimate strength values measured on specimens cooled after a fire are higher than the ultimate strength assumed when verifying the strength of connecting members in a fire situation, in accordance with the rules specified in [27].

3. Concluding remarks

The article presents the results of a static tensile test of standardized specimens of grade 8.8 steel bolts, quenched and tempered in a production process, previously subjected to the environmental conditions of a simulated fire. The research was aimed at determining the impact of the soaking temperature, exposure time to the set thermal conditions and cooling method on the characteristic mechanical properties of bolt steel after a fire. Based on the results obtained and the observations made, the following concluding remarks can be drawn:

– below the tempering temperature used in the bolts production process, any fluctuations or discrepancies in the values of individual parameters are negligible and should be treated as a measurement error,
– if the fire temperature exceeds the tempering temperature applied in the production process, each of the above-mentioned factors (temperature, time, and cooling method) independently have a significant impact on the post-fire residual mechanical properties

and the behaviour of bolt steel under loading. The detailed results of the performed experimental tests have been presented and discussed in Chapter 2.2, as well as visualized in Figs. 2–9, where they are also compared with the results reported in the literature,

– the impact of thermal conditions during thermal soaking becomes visible when the soaking temperature is close to (in case of long thermal exposition) or higher than the tempering temperature applied in the production process. Also the time of exposure to thermal conditions noticeably affects the values of the experimentally determined post-fire properties (as indicated by the scattering of dots and squares in Figs. 3–9). The cooling method has less impact when the soaking temperature is lower than the Ac_1 austenitization temperature. After this value is exceeded, the influence of the cooling method begins to play a significant role, both from the point of view of the capacity as well as ductility parameters. Cooling in water leads to the re-quenching of the specimens, which results in an increased strength, combined with reduced plasticity/ductility, due to the formation of a brittle martensitic structure of the steel. In view of the foregoing, the method of carrying out a firefighting operation may have a crucial effect on the safety of building in fire. Rapid cooling increases susceptibility of the bolts to brittle fracture, which can lead to a sudden construction disaster without the occurrence of the intermediate phase, which is usually a natural warning sign for rescue teams and other people in a fire-engulfed building,
– analysis of the level of fit and the multitude of prediction curves proposed in the literature, at this stage of research, leads to the reflection that there are no universal solutions and it is difficult to develop a perfect model that would be equally well suited to all bolts classified in a given strength class. To create it, a much larger population of results for each of the strength classes of bolts available on the market would be needed,
– imperfections in the fit of the predictive models to the test results may be due to, for example, differences in the chemical composition of the charge materials used to produce the tested bolts, as well as – varying depending on the chemical composition of the raw material – heat treatment parameters (quenching and tempering),
– certain differences in the course of the presented prediction curves may result from the fact that some of them were adjusted to the test results of complete bolt assemblies (and not standardized specimens) and the specimens were fastened to the grip jaws of the testing machine with the use of washers and nuts. This method of fastening is more flexible than clamping them directly into the machine's jaws, which may result in some discrepancies in the results. This conclusion is also based on author's personal observations and experience,
– the comparative analysis of the results obtained with the prediction curves presented in the literature at this stage casts a doubt on whether it is reasonable to develop such models, as they seem to be precise only in relation to a specific, numerically limited set of results,
– when assessing the research results from the perspective of the post-fire safety of bolted connections, it is worth noting that the obtained values ??of the recovery factor, which are higher than 1.0 indicate, that the ultimate strength values ??measured on specimens

cooled after a fire are higher than the ultimate strength assumed when verifying the strength of connecting members in a fire situation,
– the research presented herein is of a practical nature with great application potential for engineering practice. The obtained test results, supplemented with microstructure analysis, as well as hardness and impact tests, can be helpful for the purpose of assessing structures that have survived a fire without any major damage, in the context of the possibility of reusing selected elements, and those that have been damaged by fire. In the latter case, the results can be used to recreate a fire development scenario and to estimate maximum values of fire temperatures in a situation where they have not been measured by firefighting and rescue services.

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References

[1] M. Maślak and G. Żwirski, "Zmiany strukturalne w stali konstrukcyjnej wywołane epizodami jej nagrzewania i stygnięcia podczas pożaru" ("Changes in Structural Steel Microstructures Following Heating and Cooling Episodes in Fires"), *Bezpieczeństwo i Technika Pożarnicza*, vol. 48, no. 4, 2017, pp. 34–52, doi: 10.12845/bitp.48.4.2017.2.

[2] P.A. Król and M. Wachowski, "Effect of Fire Temperature and Exposure Time on High-Strength Steel Bolts Microstructure and Residual Mechanical Properties", *Materials*, vol. 14, no. 11, art. no. 3116, 2021, doi: 10.3390/ma14113116.

[3] PN-EN 1993-1-1: 2006-06 Eurokod 3: Projektowanie konstrukcji stalowych – Część 1–1: Reguły ogólne i reguły dla budynków (Design of steel structures – Part 1–1: General rules and rules for buildings). Warszawa: PKN, 2006.

[4] PN-EN 1993-1-12: 2008-12 Eurokod 3: Projektowanie konstrukcji stalowych – Część 1–12: Reguły dodatkowe rozszerzające zakres stosowania EN 1993 o gatunki stali wysokiej wytrzymałości do S 700 włącznie (Design of steel structures – Part 1–12: Additional rules for the extension of EN 1993 up to steel grades S 700). PKN, 2008.

[5] T. Molkens, K.A. Cashell, and B. Rossi, "Post-fire mechanical properties of carbon steel; and safety factors for the reinstatement of steel structures", *Engineering Structures*, vol. 234, art. no. 111975, 2021, doi: 10.1016/j.engstruct.2021.111975.

[6] V. Kodur, S. Kand, and W. Khaliq, "Effect of temperature on thermal and mechanical properties of steel bolts", *Journal of Materials in Civil Engineering (ASCE)*, vol. 24, no. 6, pp. 765–774, 2012, doi: 10.1061/(ASCE)MT.1943-5533.0000445.

[7] V. Kodur, M. Yahyai, A. Rezaeian, M. Eslami, and A. Poormohamadi, "Residual mechanical properties of high strength steel bolts subjected to heating-cooling cycle", *Journal of Constructional Steel Research (ASCE)*, vol. 131, pp. 122–131, 2017, doi: 10.1016/j.jcsr.2017.01.007.

[8] A.S. Daryan, and H. Ketabdari, "Mechanical properties of steel bolts with different diameters after exposure to high temperatures", *Journal of Materials in Civil Engineering (ASCE)*, vol. 31, no. 10, 2019, doi: 10.1061/(ASCE)MT.1943-5533.0002865.

[9] G.-B. Lou, S. Yu, R. Wang, and G.-Q. Li, "Experimental study on mechanical properties of high-strength bolts after fire", *Proceedings of the Institution of Civil Engineers. Structures and Buildings*, vol. 165, no. 7, 2012, pp. 373–383, doi: 10.1680/stbu.11.00015.

[10] F. Hanus, G. Zilli, and J.-M. Franssen, "Behaviour of grade 8.8 bolts under natural fire conditions – Test and model", *Journal of Constructional Steel Research*, vol. 67, no. 8, pp. 1292–1298, 2011, doi: 10.1016/j.jcsr.2011.03.012.

[11] S.K. Mushahary, K.D. Singh, and S.A. Jayachandran, "Tensile and shear strength of 10.9 grade bolts in heating and cooling fire", *Journal of Constructional Steel Research*, vol. 197, art. no. 107503, 2022, doi: 10.1016/j.jcsr.2022.107503.

[12] C. Maraveas and Z. Fasoulakis, "Post-fire mechanical properties of structural steel", presented 8^{th} National Steel Structures Conference, Tripoli, Greece, 2014.

[13] C. Maraveas, Z. Fasoulakis, and K.D. Tsavdaridis, "Mechanical properties of High and Very High Strength Steel at elevated temperatures and after cooling down", *Fire Science Reviews*, vol. 6, no. 3, 2017, doi: 10.1186/s40038-017-0017-6.

[14] C. Maraveas, Z. Fasoulakis, and K.D. Tsavdaridis, "Post-Fire Assessment and Reinstatement of Steel Structures", *Journal of Structural Fire Engineering*, vol. 8, no. 2, pp. 181–201, 2017, doi: 10.1108/JSFE-03-2017-0028.

[15] X-Q. Wang, Z. Tao, and Md K. Hassan, "Post-fire behavior of high-strength quenched and tempered steel under various heating conditions", *Journal of Constructional Steel Research*, vol. 164, art. no. 105785, 2020, doi: 10.1016/j.jcsr.2019.105785.

[16] Z. Tao, X.Q. Wang, and B. Uy, "Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures", *Journal of Materials in Civil Engineering (ASCE)*, vol. 25, no. 9, pp. 1306–1316, 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000676.

[17] Z. Chen, J. Lu, H. Liu, and X. Liao, "Experimental study on the post-fire mechanical properties of high-strength steel tie rods", *Journal of Constructional Steel Research*, vol. 121, pp. 311–329, 2016, doi: 10.1016/j.jcsr.2016.03.004.

[18] H. Katebdari, A.S. Daryan, and N. Hassani, "Predicting post-fire mechanical properties of grade 8.8 and 10.9", *Journal of Constructional Steel Research*, vol. 162, no. 105735, 2019, doi: 10.1016/j.jcsr.2019.105735.

[19] PN-EN ISO 6892-1:2020-05 Metale – Próba rozciągania – Część 1: Metoda badania w temperaturze pokojowej (Metallic materials – Tensile testing – Part 1: Method of test at room temperature). PKN, 2022.

[20] "Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions which should be met by buildings and their location", *Journal of Laws of the Republic of Poland*, 2022, item 1225 (in Polish).

[21] PN-EN ISO 898-1:2013-06 Własności mechaniczne części złącznych wykonanych ze stali węglowej oraz stopowej – Część 1: Śruby i śruby dwustronne o określonych klasach właściności – Gwint zwykły i drobnozwojny (Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property class – Coarse thread and fine pitch thread). PKN, 2013.

[22] P.A. Król, "Post-fire behavior and residual capacity of high-strength grade 8.8 steel bolts", *Archives of Civil Engineering*, vol. 70, no. 3, pp. 85–100, 2024, doi: 10.24425/ace.2024.150972.

[23] K. Maciejewski, Y. Sun, O. Gregory, and H. Ghonem, "Time-dependent deformation of low carbon steel at elevated temperatures", *Materials Science and Engineering: A*, vol. 534, pp. 147–156, 2012, doi: 10.1016/j.msea.2011.11.053.

[24] M. Maślak, K. Pancikiewicz, M. Pazdanowski, M. Stankiewicz, P. Woźniczka, and P. Zajdel, „Quantification of the Post-Fire Strength Retention Factors for Selected Standard Duplex and Lean Duplex Stainless Steel Grades", *Materials*, vol. 17, no. 2, 2024, doi: 10.3390/ma17020371.

[25] P-C. Peng, J-H. Chi, and J-W. Cheng, "A study on behavior of steel structures subjected to ire using non-destructive testing", *Construction and Building Materials*, vol. 128, pp. 170–175, 2016, doi: 10.1016/j.conbuildmat.2016.07.056.

[26] S. Rudnik, *Metaloznawstwo*, wyd. 4. Warszawa: Wydawnictwo Naukowe PWN, 1998.

[27] PN-EN 1993-1-2 Eurokod 3 Projektowanie konstrukcji stalowych – Część 1–2: Reguły ogólne – Obliczanie konstrukcji z uwagi na warunki pożarowe (Design of Steel Structures – Part 1–2: General Rules – Structural Fire Design). PKN, 2007.

[28] PN-EN 1993-1-8 Eurokod 3 Projektowanie konstrukcji stalowych – Część 1–8: Projektowanie węzłów (Design of Steel Structures – Part 1–2: Design of joints). PKN, 2006.

Po-pożarowe właściwości mechaniczne stali śrubowej, ulepszanej termicznie przez hartowanie i odpuszczanie w procesie produkcyjnym

Słowa kluczowe: czas ekspozycji, metoda chłodzenia, rezydualne właściwości mechaniczne, śruby o podwyższonej wytrzymałości, współczynnik odzysku, współczynnik retencji

Streszczenie:

W artykule zaprezentowano wyniki statycznej próby rozciągania próbek znormalizowanych wykonanych ze stali stopowej o symbolu 32CrB3, ulepszonej termicznie w procesie produkcyjnym, poddanych oddziaływaniom środowiskowym symulującym nadzwyczajną sytuację pożaru. Celem badań było dokonanie oceny wpływu symulowanych warunków pożarowych na rezydualne właściwości mechaniczne analizowanej stali, stosowanej do wytwarzania śrub budowlanych klasy 8.8. W badaniach wariantowano wartości maksymalnej temperatury w procesie wygrzewania, czas ekspozycji na dane warunki termiczne i zastosowany sposób chłodzenia. Próbki wygrzewano w temperaturze 600°C, 650°C, 700°C, 750°C, 800°C, 900°C i 1000°C przez okres odpowiednio 30′, 60′, 120′ i 240′, w badaniach dodatkowo uwzględniono zróżnicowany sposób chłodzenia. Pierwszą partię próbek, po wygrzaniu, studzono w sposób naturalny, pozwalając im ostygnąć swobodnie w warunkach temperatury otoczenia. W przypadku drugiej partii, śruby wystudzono w sposób gwałtowny, przez zanurzenie w wodzie aż do całkowitego wystudzenia, symulując tym samym efekt intensywnie prowadzonej akcji ratunkowo-gaśniczej. Analizie poddano zmienność wartości typowych parametrów po-pożarowych, możliwych do uzyskania w statycznej próbie rozciągania: nośności na rozciąganie – $f_{u,\theta,\mathrm{post}}$, granicy plastyczności – $f_{y,\theta,\mathrm{post}}$, modułu sprężystości podłużnej Younga – $E_{a,\theta,\mathrm{post}}$, odkształcenia granicznego przy maksymalnej sile – $\varepsilon_{u,\theta,\mathrm{post}}$, odkształcenia w chwili zerwania – $\varepsilon_{f,\theta,\mathrm{post}}$, wydłużenia względnego po zerwaniu – $A_{5,\theta,\mathrm{post}}$ oraz przewężenia względnego – $Z_{\theta,\mathrm{post}}$, w zależności od temperatury i czasu wygrzewania oraz zastosowanej metody chłodzenia. W każdej z serii przebadano po 3 próbki, celem weryfikacji poprawności i powtarzalności uzyskanych wyników. Uzyskane wyniki porównano z wynikami raportowanymi w literaturze. Wyznaczono wartości współczynników retencji oraz współczynników odzysku.

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