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MECHANICAL PROPERTIES OF STRUCTURAL STAINLESS STEELS

WŁAŚCIWOŚCI MECHANICZNE KONSTRUKCYJNYCH STALI NIERDZEWNYCH

Abstract

In the paper, the mechanical properties of structural stainless steels referred to in EN 1993-1-4 [6] used in the design of building structures and civil engineering works, are described. Some information about stainless steel behaviour at elevated temperatures is also given.

Keywords: *stainless steel*, *mechanical properties*, *EN 1993-1-4*, *EN 1993-1-2*

Streszczenie

W artykule opisano właściwości mechaniczne konstrukcyjnych stali nierdzewnych objętych normą EN 1993-1-4 [6], stosowanych w projektowaniu budowlanych obiektów inżynierskich. Podano również informacje na temat zachowania stali nierdzewnych w podwyższonych temperaturach.

Słowa kluczowe: *stal nierdzewna*, *właściwości mechaniczne*, *EN 1993-1-4*, *EN 1993-1-2*

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1. Introduction

The most important distinguishing feature of stainless steels is their greatly increased corrosion resistance in comparison to carbon steels. This is the result of applying chromium (Cr) as the main alloying component to a minimum quantity of 10.5% and limiting carbon (C) content to a maximum of 1.2%. The different chemical composition causes the formation of microstructures that usually do not occur in carbon steels and have a great influence on the physical and mechanical properties of stainless steel.

The paper describes mechanical properties (that are not material constants) of structural stainless steels covered by the European Standard EN 1993-1-4 [6].

2. Types, grades and designation of stainless steel

The main criterion of stainless steel classification is the microstructure, it is this that distinguishes different steels: ferritic; austenitic; austenitic-ferritic (so called duplex steels); martensitic; precipitation hardening. In building structures, designed according to EN 1993-1-4 [6], only ferritic, austenitic and austenitic-ferritic stainless steels with nominal yield strength f_y up to and including 480 N/mm² may be applied. Within the given microstructure, stainless steels can be additionally divided into grades of different chemical composition and physical, mechanical and technological properties.

The chemical compositions of particular grades of stainless steel are given in EN 10088 [12–16]. The composition ranges of main alloying elements for structural stainless steels listed in Table 2.1 EN 1993-1-4 [6] are given in Table 1.

T a b l e 1

Chemical composition ranges for structural stainless steels

Type of stainless steel	Chemical composition [wt%]			
	C (max)	Cr	Ni	Mo
Ferritic	0.03–0.08	10.50–18.00	0–1.00	–
Austenitic	0.02–0.08	16.50–21.00	6.00–26.00	0–7.00
Austenitic-ferritic	0.03	21.00–24.00	3.50–6.50	0.10–3.50

For the reason of description conciseness, the most popular in engineering practice is the stainless steel numbering designation system [11]. The structure of steel number is as follows: 1.*xxyy*, where: 1 – material group number (steel), *xx* – steel group number, *yy* – sequential number of steel grade:
- 1.40*yy* – stainless steels with less than 2.5% nickel (Ni), without molybdenum (Mo), niobium (Nb) and titanium (Ti),
- 1.41*yy* – stainless steels with less than 2.5% nickel (Ni), with molybdenum (Mo) but without niobium (Nb) and titanium (Ti),
- 1.43*yy* – stainless steels with min. 2.5% nickel (Ni), without molybdenum (Mo), niobium (Nb) and titanium (Ti),

– 1.44*yy* – stainless steels with min. 2.5% nickel (Ni), with molybdenum (Mo) but without niobium (Nb) and titanium (Ti),
– 1.45*yy* – stainless steels with special additions.

Cold worked hardened stainless steels should be additionally marked by specifying one of the following parameters: C*nnn* – cold worked hardened with a minimum tensile strength of *nnn* MPa [10]; CP*nnn* – cold worked hardened with a minimum 0.2% proof strength of *nnn* MPa [10] or hardness (no specifications for the designation of hardness levels of cold worked hardened steels in [10]). Some details are given in Table 2.

Table 2

Nominal values of the yield strength f_y and the ultimate tensile strength f_u,
for work hardened structural stainless steels to EN 10088 [6]

Type of stainless steel	0.2% proof strength level in the cold worked condition	f_y [N/mm^2]	Tensile strength level in the cold worked condition	f_u [N/mm^2]
Austenitic steels	CP350	350	C700	700
	CP500	500	C850	850
	CP700	700	C1000	1000

3. Mechanical properties of stainless steel

Supplementary provisions for the design of buildings and civil engineering works that extend and modify the application of EN 1993-1-1 [3], EN 1993-1-3 [5], EN 1993-1-5 [7] and EN 1993-1-8 [8] to austenitic, austenitic-ferritic and ferritic stainless steels are given in EN 1993-1-4 [6]. Indicated in [6] differences between mechanical and physical properties of carbon and stainless steels are important for structural safety. They include principal material properties (E, f_y) and also refer to stainless steel behaviour (e.g. σ–ε curve, behaviour during cold working or at elevated temperatures). These differences cannot be ignored during formulating and checking conditions of the ultimate and serviceability limit states in all design situations mentioned in EN 1990 [2].

3.1. Stress-strain behaviour

Stainless steels are characterized by a completely different stress-strain (σ–ε) curve than carbon steels. Unlike carbon steel, the stress-strain relationship of stainless steel is nonlinear (even in the elastic stage of material behaviour) with no explicit yield stress. Additionally, stainless steel σ–ε curves do not show a plateau before strain hardening which is typical of carbon steel (Fig. 1).

Nonlinearity of σ–ε curve is characterized by coefficient *n* defined as [1, 6]:

$$n = \frac{\log(0.05)}{\log(R_{p0.01} / f_y)} = \frac{\ln(20)}{\ln(f_y / R_{p0.01})} \tag{1}$$

where

$R_{p0,01}$ – the 0.01% proof stress,
f_y – the 0.02% proof stress.

According to [6], n may take the values from the range of 5–14 (see Table 4), the larger the coefficient n, the more the nonlinearity of the σ–ε curve. It means that the nonlinear elastic range of stainless steel behaviour, usually ignored in case of carbon steels, should be taken into account in the modelling of material behaviour, especially in the calculation of serviceability limit states (SLS) [6].

Stainless steels may be much more ductile than carbon grades which manifests as an ability to achieve large plastic strains in the range between yield strength and ultimate tensile strength. For example, elongation of austenitic stainless steel may be over 45%, while for structural carbon steel, it is around 25%.
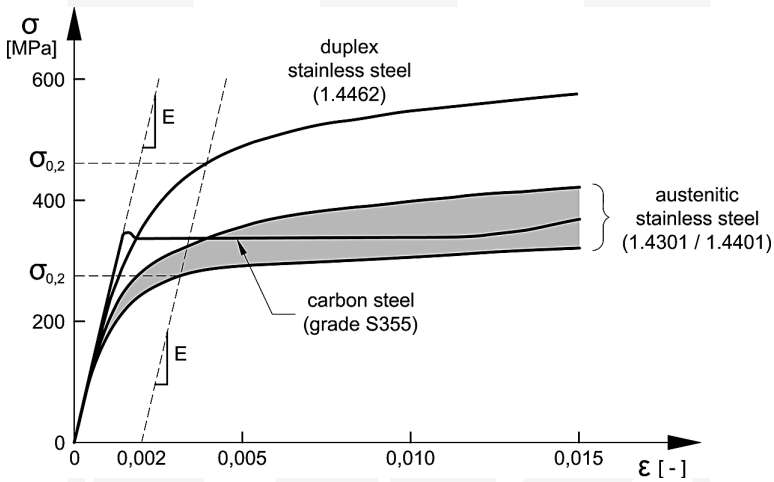
Fig. 1. Typical experimental stress-strain curves [1]

Plastic processing of stainless steel causes its work hardening which results in an increase in the yield strength, the ultimate strength and the hardness of the material. Further information about stainless steel work hardening is given in p. 3.4 of this paper. On the basis of numerous research investigations, it was shown that, in most cases, both cold and hot rolled material is characterized by higher strength in a direction transverse to the direction of rolling than in a longitudinal direction (see Table 3). It also has been found that stainless steel σ–ε curves do not show symmetry in case of compression and tension; in the annealed condition, σ–ε curves tend to be more nonlinear in tension than in compression [22]. Comparison of experimental values of mechanical properties of selected austenitic (1.4404) and austenitic-ferritic (1.4462) stainless steel grades allows us to notice that relative differences between values of the 0.2% proof strength due to anisotropy and asymmetry of stress-strain relationship do not exceed 5%. Anisotropy and asymmetry of stainless steel is the probable reason for increasing, in comparison with carbon steel, values of partial factors $\gamma_{M0} = 1,1$ and $\gamma_{M1} = 1,1$ recommended by EN 1993-1-4 [6]. Simultaneously, in design

**Representative values of stress-strain characteristics for materials
in the annealed condition [22]**

Stainless steel grade	Direction and character of stress	0.2% proof strength [N/mm²]	Modulus of elasticity [kN/mm²]	$\sigma_{0.01}/\sigma_{0.2}$	Index n
1.4404	LT	277	193	0.65	6.9
	LC	285		0.71	8.6
	TT	286	198	0.70	8.5
	TC	297		0.74	10.0
1.4462	LT	518	199	0.57	5.4
	LC	525		0.56	5.2
	TT	544	207	0.54	4.8
	TC	540		0.59	5.7
LT – Longitudinal tension, LC – Longitudinal compression, TT –Transverse tension, TC – Transverse compression.					

Values of coefficient n according to [6]

Steel grade	Coefficient n	
	Longitudinal direction	Transverse direction
1.4003	7	11
1.4016	6	14
1.4512	9	16
1.4301	6	8
1.4306		
1.4307		
1.4318		
1.4541		
1.4401	7	9
1.4404		
1.4432		
1.4435		
1.4539		
1.4571		
1.4462	5	5
1.4362		

calculations, the values of yield strength (the 0.2% proof strength) f_y and ultimate tensile strength f_u should be assumed constant for a particular grade, independently of the direction of rolling and loading [6].

For the design of stainless steel structures, especially in the case of material in the annealed condition, nonlinear stress-strain curve with strain hardening according to Annex C of EN 1993-1-4 [6] may be used to describe material behaviour. This spline function is a modification of the well-known Ramberg-Osgood formula:

$$
\varepsilon = \begin{cases}
\dfrac{\sigma}{E} + 0.002\left(\dfrac{\sigma}{f_y}\right)^n & \text{for} \quad \sigma \le f_y \\[4mm]
0.002 + \dfrac{f_y}{E} + \dfrac{\sigma - f_y}{E_y} + \varepsilon_u\left(\dfrac{\sigma - f_y}{f_u - f_y}\right)^m & \text{for} \quad f_y < \sigma \le f_u
\end{cases}
\tag{2}
$$

where

n – the coefficient depending on rolling direction according to (1); it also may be taken from Table 4 or calculated from measured values,

E_y – the tangent modulus of stress-strain curve at the yield strength, defined as $E_y = E/(1 + 0.002n\, E/f_y)$,

ε_u – the ultimate strain, corresponding to the ultimate strength f_u; it may be obtained from approximation $\varepsilon_u = 1 - f_y/f_u$, but $\varepsilon_u \le A$ where A is the elongation after fracture defined in [13–16],

m – the coefficient that may be determined as $m = 1 + 3.5\, f_y/f_u$.

Figure 2 shows nonlinear stress-strain curves for a longitudinal (solid lines) and a transverse (dashed lines) rolling direction, determined from formula (2), for the most popular grades of ferritic, austenitic and duplex stainless steels. To better demonstrate differences between stress-strain relationships for different rolling directions in the elastic range, stress-strain curves from Fig. 2 were drawn for limited range of strains (Fig. 3).
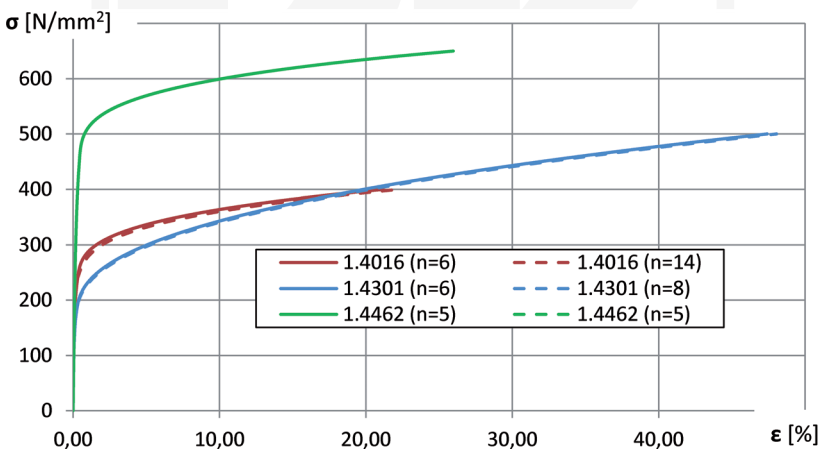

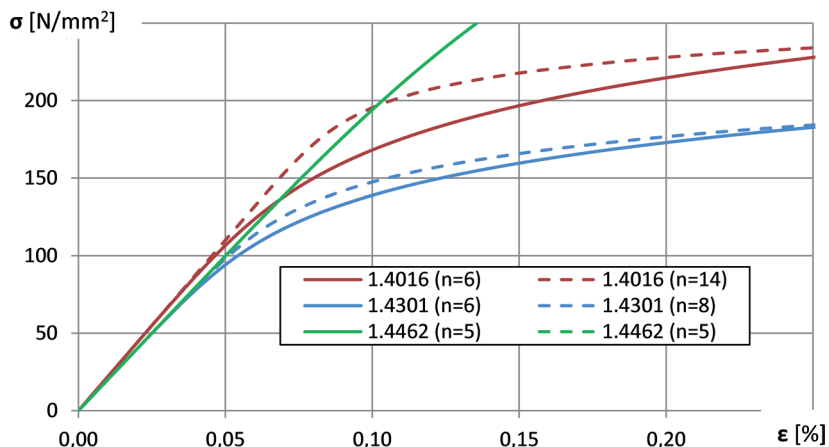Fig. 2. Stress-strain curves for different types of stainless steel

Fig. 3. Stress-strain curves for different types of stainless steel (limited strain range)

3.2. Influence of chemical composition and microstructure on mechanical properties of stainless steel

Mechanical properties of structural stainless steels significantly depend on their microstructure [1, 20, 21, 22] that is a derivative of both the chemical composition of the alloy and its heat treatment.

Austenitic and ferritic stainless steels have quite low yield strength: 175–300 MPa and 240–260 MPa, respectively, while in the case of the most common carbon steels it is 235(215) MPa for S235 grade and 355(335) for S355 grade, depending on element thickness.
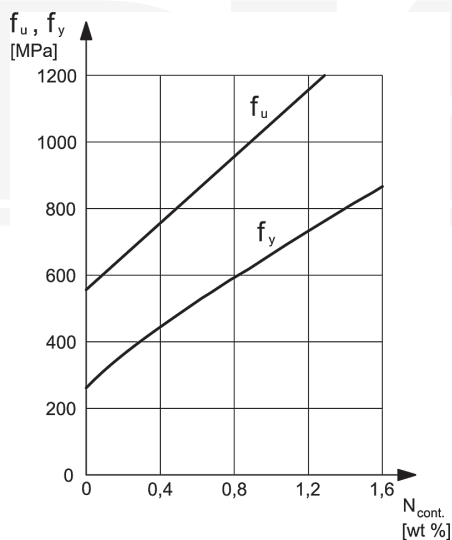

Fig. 4. Effect of nitrogen on the strength of austenitic stainless steels [17]

Austenitic-ferritic stainless steels are characterized by the highest yield strength from among all stainless steel types (even more than two times higher than for some austenitic grades).

The increasing of yield strength and tensile strength of austenitic stainless steels is mostly related to their high content of carbon (C) and nitrogen (N) which are alloying elements that improve these properties. If the nitrogen (N) content is increased from 0.05% to 0.20%, an increase of yield strength from 270MPa to 340MPa will be achieved [17]. Figure 4 shows the influence of nitrogen (N) content on yield strength and ultimate tensile strength of austenitic steels.

The strength of ferritic stainless steels increases with increasing carbon (C) content in the alloy; the influence of chromium (Cr) content on the strength of this type of stainless steel in negligible. At the same time, attainment of good ductility of ferritic steel requires a very low content of carbon (C) and nitrogen (N). High content of chromium (Cr) reduces ductility of ferritic stainless steels.

T a b l e 5

Mechanical properties of stainless steel in the annealed condition at room temperature [16]

Type of stainless steel	Grade of stainless steel	Hardness HB[1] max	0.2% proof strength $R_{p0,2}$ [MPa] min.	Tensile strength R_m [MPa]	Elongation after fracture A [%] (long.)
Ferritic	1.4003	100	260	450–600	20
	1.4016	100	240	400–630	20
Austenitic	1.4307	215[2]	175	500–700[2]	45
	1.4306	215[2]	180	460–680[2]	45
	1.4311	230[2]	270	550–760[2]	40
	1.4301	215[2]	190	500–700[2]	45
	1.4541	215[2]	190	500–700[2]	40
	1.4404	215[2]	200	500–700[2]	40
	1.4406	250[2]	280	580–800[2]	40
	1.4401	215[2]	200	500–700[2]	40
	1.4571	215[2]	200	500–700[2]	40
	1.4432	215[2]	200	500–700[2]	40
	1.4435	215[2]	200	500–700[2]	40
	1.4439	250[2]	280	580–800[2]	35
	1.4539	230[2]	230	530–730[2]	35
	1.4547	260[2]	300	650–850[2]	35
	1.4529	250[2]	300	650–850[2]	40
Austenitic--ferritic	1.4462	270	450	650–880	25
	1.4362	260	450	600–830	25

[1] Only for guidance
[2] The maximum HB-values may be raised by 100 HB or the tensile strength value may be raised by 200 MPa and the minimum elongation value may be lowered to 20% for sections and bars of ≤ 35 mm thickness having a final cold deformation and for hot formed sections and bars of ≤ 8 mm thickness.

Table 5 summarizes the basic mechanical properties of a max. 160 mm thick section made of structural stainless steels.

According to Table 5, the 0.2% proof strength $R_{p0.2}$ is about 25–50% of the tensile strength R_m for structural austenitic steels, 40–60% for structural ferritic steels and 50–75% for structural austenitic-ferritic steels.

The effect of alloying elements and microstructure on the strength of austenitic and austenitic-ferritic stainless steel may be estimated (with an uncertainty of approximately 20 MPa) from the following regression equations [20]:

$$R_{p0.2} = 120 + 210\sqrt{N + 0.02} + 2Mn + 2Cr + 14Mo + 10Cu + (6.15 - 0.054\delta)\delta +$$
$$+ (7 + 35(N + 0.2))d^{-1/2} \quad [MPa] \tag{3}$$

$$R_{p1.0} = R_{p0.2} + 40 \quad [MPa] \tag{4}$$

$$R_m = 470 + 600(N + 0.02) + 14Mo + 1.5\delta + 8d^{-1/2} \quad [MPa] \tag{5}$$

where

N, Mn, etc.	–	the level of the alloying elements [wt %],
δ	–	the ferrite content [%],
d	–	the grain size [mm].

Ferritic and austenitic-ferritic stainless steels have good ductility of similar orders of magnitude. Excellent ductility characterizes austenitic stainless steels, their elongation is about two times larger than in the case of ferritic or duplex structural steels and can reach 35–45% (Table 5).

The hardness of iron alloys, including stainless steels, is dependent on their chemical composition which is shown in Fig. 5.
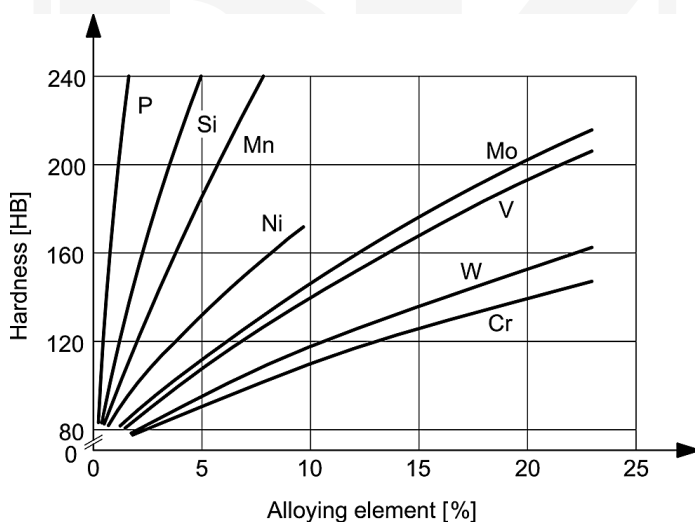

Fig. 5. Influence of substitutional elements on hardness of iron alloys [21]

The hardness of stainless steel differs between steel types (Table 5); the lowest value is for ferritic grades (~100 HB) and the highest – for austenitic-ferritic grades (250–260 HB).

3.3. Strain rate sensitivity

Strain rate sensitivity is more distinct in the case of stainless steels than in the case of carbon steels. Figure 6 illustrates the strain rate effect on the stress-strain curves of selected stainless steel grades.

It can be seen that higher values of strength and lower rupture strain are achieved at higher strain rates. In the design of blast walls made of stainless steel, where predominant loading is accompanied by a high strain rate, the design strength is customarily multiplied by a strain rate enhancement factor to utilize the increase in strength at higher strain rates [22].

Curve	Strain rate [sec^{-1}]
1	10^{-4}
2	10^{-2}
3	50
4	140
5	502

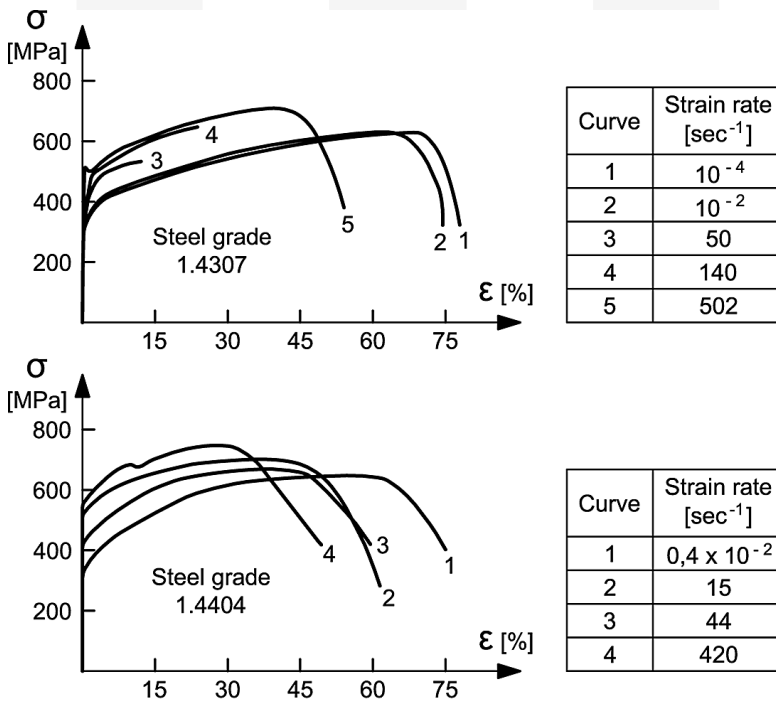| Curve	Strain rate [sec^{-1}]
1	$0{,}4 \times 10^{-2}$
2	15
3	44
4	420

Fig. 6. Strain rate effect on grades 1.4307 and 1.4404 [22]

It should be also noted that the obtained results are influenced by the loading procedure. Constant stress rates usually give higher value of proof stresses than constant strain rates. The influence of the strain rate disappears at temperatures above 200°C – this is shown in Fig. 7 for stainless steel grade 1.4401.

The minimum values of stainless steel strength given in EN 10088 [13–16] are determined on the basis of tensile testing according to ISO 6892-1 [18]. In this international standard, two methods of testing speeds are available - based on strain rates (method A) and

based on stress rates (method B). During discussions concerning the speed of testing in the preparation of ISO 6892:1998, it was decided to recommend the use of strain rate control in future revisions [18].
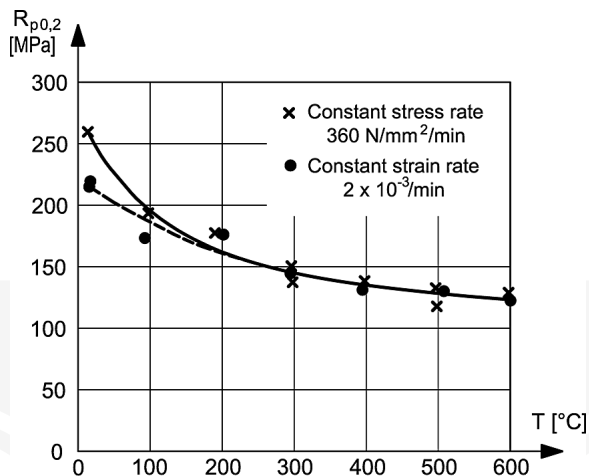

Fig. 7. Effect of loading procedure on the 0.2% proof stress [22]

The recommendations of method A given in [18] are aimed at minimizing the effect of strain rate variations and thus minimizing the measurement uncertainty of the test results. During determination of the upper yield strength R_{eH} or proof strength properties R_p (plastic extension) and R_t (total extension), the strain rate should be kept as 0.00025 s^{-1} (recommended) with a relative tolerance of ±20%, up to and including the determination of R_{eH} or R_p or R_t [18]. For the determination of the lower yield strength R_{eL}, maintaining the same value of strain rate is recommended until discontinuous yielding has ended [18]. To determine the tensile strength R_m and percentage elongation after fracture A, after determination of the required yield/proof strength properties, the strain rate shall be changed to 0.0067 s^{-1} (recommended) with a relative tolerance of ±20% [18].

3.4. Effect of cold working and heat treatment

One of the properties of stainless steel is its ability to harden to a higher rate than carbon steel. Structural stainless steel consistent with [6], i.e. steels with a ferritic, austenitic or austenitic-ferritic microstructure can only be hardened (i.e. made stronger) by cold working and cannot be strengthened by heat treatment. It was noticed that, because of work hardening, Bauschinger's effect occurs also for stainless steels [1, 22]. In general, cold working may cause increases of proof strengths and also ultimate tensile strength and a decrease of elongation. Figure 8 shows how cold working affects proof strengths, ultimate tensile strength and elongation after fracture of austenitic stainless steel grade 1.4307 and austenitic-ferritic grade 1.4462.

Cold working also intensifies the anisotropy and asymmetry of the stainless steel stress-strain relationship. The degree of asymmetry and anisotropy depends on the steel grade, the

level of cold working and the manufacturing route. Figure 9 compares stress-strain curves for stainless steel grade 1.4318, cold worked to strength level C850 ($R_m = 850 – 1000$ MPa) [13, 15], illustrating the differences caused by the change of direction and the character of the acting load.
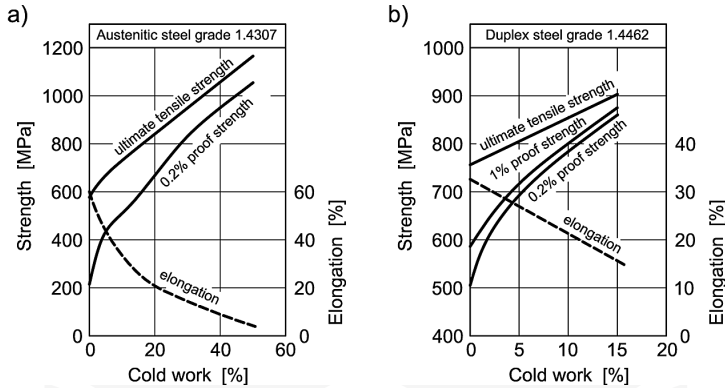

Fig. 8. Effect of cold working on a sample of stainless steel: a) austenitic grade 1.4307
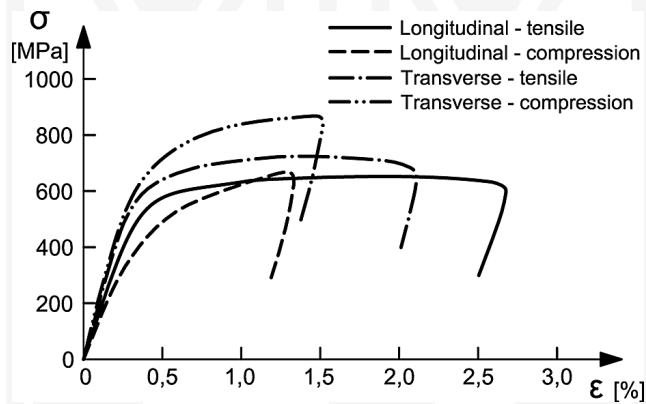b) austenitic-ferritic grade 1.4462 [22]

Fig. 9. Typical stress-strain curves for austenitic stainless steel grade 1.4318,
cold worked to strength level C850 for transverse compression [23]

The work hardening of stainless steel may be caused by cold rolling (most often it is an intended effect) or by the fabrication process of the structural member (most often it is an unintended effect), or a combination of both. The 0.2% proof strength for the cold formed corners of the cross-section is around 20%-100% (usually 50%) higher than for flat parts of the cross-section [22, 23]. This is a local effect depending on the cross-section geometry. It has also been found that the degree of work hardening depends on the manufacturing methods. For example, if a rectangular hollow section is cold formed from annealed material in two stages (first the circular hollow section is fabricated and then it is shaped into a rectangular hollow section) a moderate increase in the strength of the flat parts and

a large increase in the strength of the corners is observed. In cases where the rectangular hollow section is fabricated by direct bending from a flat sheet, the strength of the flat parts is essentially unchanged, while the strength increase in the corners is large (but not as large as the enhancement with the indirect fabrication method) [22].

The stainless steel rate of work hardening (strength enhancement) depends on the steel microstructure and the alloy composition. For ferritic stainless steels, the work hardening is limited, while the rate of the work hardening of austenitic and austenitic-ferritic stainless steels is larger. Nickel (Ni), manganese (Mn), nitrogen (N), copper (Cu) and carbon (C) tend to reduce the rate of the work hardening, while most other alloying elements will increase it.

Rules for the use of stainless steel in the work hardened condition are given in Annex B of EN 1993-1-4 [6]. These rules may be applied only if the properties of work hardened steel are maintained during the fabrication and execution of the structure and during the whole design life of the structure. In the design of stainless steel structures [6], increased nominal values of yield strength f_y and ultimate tensile strength f_u may be adopted only for material delivered in the cold worked conditions specified in EN 10088 (type of process route 2H) [13–16]. Rules given in EN 1993-1-4 [6] are applicable only for material up to grade C700 and CP350, i.e. for work hardened structural stainless steel with an ultimate tensile strength f_u not higher than 700 MPa or with a yield strength f_y not higher than 350 MPa. In the case of higher grades, rules of [6] may only be applied if the structure is designed with cross-section resistance without local or global instability. In all other cases, stainless steel structures should be designed by testing according to Section 7 of [6]. Taking advantage of work hardening during the fabrication of structural components also requires verification by full size tests in accordance with [6].

Welding or heat treatment of cold worked stainless steel makes it partially or fully annealed. Steel microstructure gets back to its original form and steel strength decreases to original value (before cold working). Heat treatment like annealing or softening also reduces stainless steel anisotropy. Stainless steels are generally supplied in an annealed (softened) condition and mechanical properties given in EN 10088 [13–16] relate to steel in this condition. According to recommendations of EN 1993-1-4 [6], welding or heat treatment of products made of work hardened stainless steel should not be done unless it can be proved by testing that the execution of the structure will not reduce the mechanical properties below the values to be adopted.

3.5. Toughness

Toughness of stainless steel is diverse and changes with the steel microstructure and temperature. In Fig. 10, toughness of different stainless steel types and their changes with temperature are compared. As mentioned before, martensitic steels are not permitted for use in the design of building structures [6] due to, among other things, their low toughness (Fig. 10). It can be seen that, for all stainless steel types, toughness increases as the temperature increases and the largest quantitative differences relate to the low-temperature range.

Ferritic and austenitic-ferritic stainless steels are characterized by a change of behaviour from tough to brittle at a specific temperature (the so-called transition temperature) from the range of around –60°C to 0°C. Such a phenomenon is not observed in the case of austenitic stainless steels. The transition temperature of ferritic steels increases with increases
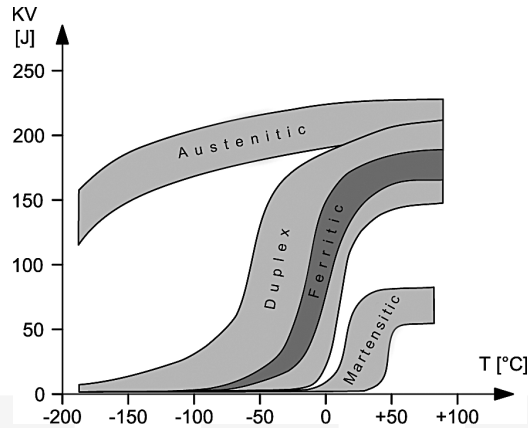
Fig. 10. Toughness for different types of stainless steels, where KV is the impact energy
(Charpy V-Notch) [20]

in the carbon (C) and nitrogen (N) contents (steel becomes brittle at higher temperatures). The toughness of ferritic stainless steels is also strongly dependent on the grain size and metallurgical purity of the alloy. Coarse-grained ferritic stainless steels at room temperature often have very low toughness (at the level of 10 J/cm^2), therefore, after proper finishing of plastic processing, ferritic stainless steels should not be heated up to temperatures of fast grain growth, i.e. higher than 900°C. In the case of austenitic-ferritic stainless steels, a higher transition temperature is the effect of an increase in the ferrite content. Transition temperature of this stainless steel type is usually below −50°C and the lower value of impact strength is about 30 J. Austenitic stainless steels have very good toughness at all temperatures and because of a lack of toughness transition, are preferable for low temperature applications [19, 20].

3.6. Fatigue

Fatigue is the process of initiation and propagation of cracks in structure caused by cyclic loading. Initiation and propagation of fatigue cracks depend on stress amplitude, number of load cycles and its duration. Number of load cycles to structure failure (lifetime) increases with decreasing load amplitude (Fig. 11).

In table 6, fatigue properties (S_0 – load amplitude), determined for ferritic, austenitic and austenitic-ferritic stainless steels and a lifetime of 10^6–10^7 load cycles, with their tensile strength R_m are compared.

Analyses were conducted at two levels of loading asymmetry cycle coefficient ($R = 0$ and $R = -1$).

Stainless steel fatigue strength may change dependent on environment conditions. Figure 12 shows how an aggressive environment may affect the fatigue strength of stainless steel; lower pH denotes more aggressive conditions (equivalent grades according to EN 10027-2 [11] are given in brackets). Fatigue strength was determined at 40°C for rotating bending stress at 100 Hz. Tests were made in air and in 3% NaCl at various pH levels [20]. The fatigue strength of all the analyzed grades decreases with environment aggressiveness.
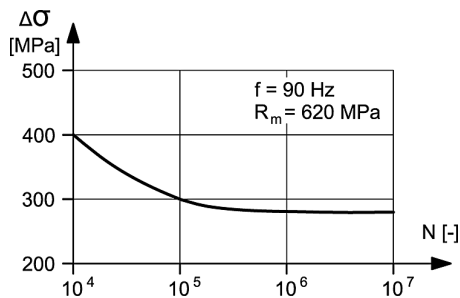
Fig. 11. S-N curve (Wöhler curve) for austenitic stainless steel grade 316HMo
(equivalent grade: 1.4435) [20]

Table 6

**Fatigue properties of stainless steels, relationship between tensile strength
and fatigue strength [20]**

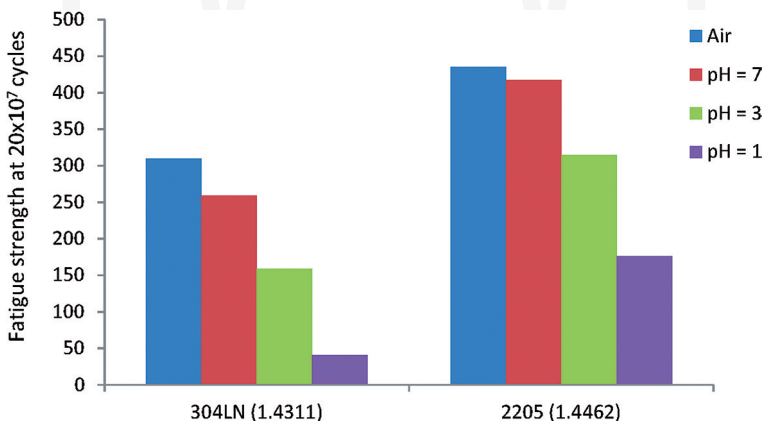| Type of stainless steel	S_0/R_m		Permissible stress level
	Stress ratio		
	$R = -1$	$R = 0$	
Ferritic	0.70	0.47	Yield strength[*)]
Austenitic	0.45	0.30	Yield strength[*)]
Austenitic-ferritic	0.55	0.35	Yield strength[*)]
[*)] the value depends on stainless steel grade			

Fig. 12. Effect of environment aggressiveness on fatigue strength for selected stainless
steel grades [20]

Proper detailing of structural elements helps prevent stress concentration and increases stainless steel fatigue strength. For that reason, sharp changes in cross-section, misalignments and eccentricities, partial penetration welds, intermittent welding and fillet welds should be avoided.

According to EN 1993-1-4 [6] fatigue strength of stainless steel structures should be determined on the basis of recommendations given in EN 1993-1-9 [9].

3.7. Properties of stainless steel at elevated temperatures

Steel is a non-combustible material, but in some cases, the effect of elevated temperatures on its mechanical properties must be taken into account. Behaviour of stainless steel structure at elevated temperatures is essential in the design for accidental situation of fire exposure.

Recommendations for structural fire design are given in EN 1993-1-2 [4]. The methods presented in [4] are also applicable to stainless steel members and sheeting within the scope of EN 1993-1-4 [6]. Properties of stainless steel at elevated temperatures are specified in Annex C of [4]. The stress-strain relationship for this type of steel at elevated temperatures is presented in Fig. 13.
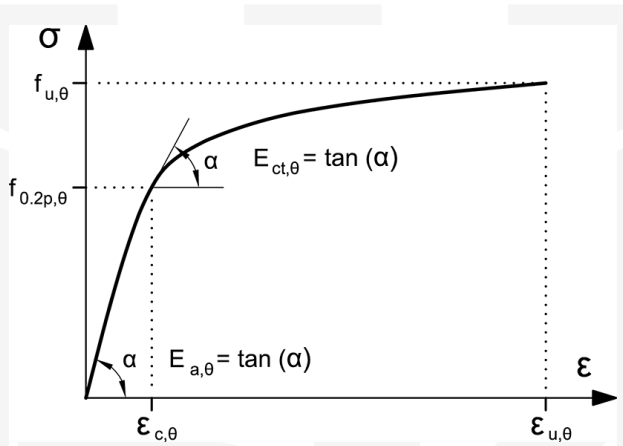

Fig. 13. Stress-strain relationship for stainless steel at elevated temperatures [4]

Symbols used in Fig. 13 are as follows:

$f_{u,\theta}$ – tensile strength,
$f_{0.2p,\theta}$ – the proof strength at 0.2% plastic strain,
$E_{a,\theta}$ – the slope of the linear elastic range,
$E_{ct,\theta}$ – the slope of proof strength,
$\varepsilon_{c,\theta}$ – the total strain at proof strength,
$\varepsilon_{u,\theta}$ – the ultimate strength.

Important parameters in the design of stainless steel structures exposed to fire are reduction factors applied to the stress-strain relationship for steel at elevated temperatures.

These reduction factors are defined as follows [4]:

– reduction factor for the modulus of elasticity (slope of linear elastic range at temperature θ, relative to slope at 20°C)

$$k_{E,\theta} = E_{a,\theta} / E_a, \tag{6}$$

– reduction factor for the yield strength (proof strength at temperature θ, relative to yield strength at 20°C)

$$k_{0.2p,\theta} = f_{0.2p,\theta} / f_y, \tag{7}$$

– reduction factor for the tensile strength (tensile strength at temperature θ, relative to tensile strength at 20°C)

$$k_{u,\theta} = f_{u,\theta} / f_u. \tag{8}$$

Analogously, as in the case of carbon steel, the reduction factor for the effective yield strength can also be determined:

$$k_{y,\theta} = f_{y,\theta} / f_y. \tag{9}$$

Stainless steel effective yield strength $f_{y,\theta}$ may be calculated using the correction factor $k_{2\%,\theta}$ given in Annex C of EN 1993-1-2 [4]:

$$f_{y,\theta} = f_{0.2p,\theta} + k_{2\%,\theta}(f_{u,\theta} - f_{0.2p,\theta}). \tag{10}$$

Reduction factors for the slope of the linear elastic range $k_{E,\theta}$ according to (6) and for effective yield strength $k_{y,\theta}$ according to (9), determined for stainless steel selected grades (1.4330 – ferritic, 1.4301 – austenitic, 1.4462 – duplex) and for carbon steel, are compared in Fig. 14–15 (20–1200°C) and in Table 7 (600–1100°C).

Table 7

Reduction factors for the determination of stiffness and strength at elevated temperatures [4]

Steel temp. [°C]	Reduction factor for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$				Reduction factor for the effective yield strength $k_{y,\theta} = f_{y,\theta}/f_y$			
	1.4003	1.4301	1.4462	carbon steel	1.4003	1.4301	1.4462	carbon steel
600	0.7600	0.7600	0.7600	0.3100	0.575	0.718	0.647	0.470
700	0.7100	0.7100	0.7100	0.1300	0.270	0.590	0.441	0230
800	0.6300	0.6300	0.6300	0.0900	0.167	0.424	0.325	0.110
900	0.4500	0.4500	0.4500	0.0675	0.142	0.237	0.133	0.060
1000	0.2000	0.2000	0.2000	0.0450	0.110	0.110	0.043	0.040
1100	0.1000	0.1000	0.1000	0.0225	0.055	0.050	0.022	0.020

As it can be seen, reduction of stainless steel modulus of elasticity depends on steel temperature. In comparison with value of Young's modulus at 20ºC, this reduction varies from 24% at 600°C to 90% at 1100°C. It should be noted, that reduction of carbon steel modulus of elasticity is higher – 69% at 600°C and 97.75% at 1100°C. Effective yield strength of stainless steel at a temperature of 600ºC is equal to 57.5%–71.8% of yield strength value at a temperature of 20°C. At a temperature of 1100°C effective yield strength decreases to 2.2%–5.5% of its value at a temperature of 20°C. In the case of carbon steel, reduction of effective yield strength in temperature range 600°C to 900°C is greater than in the case of stainless steel. In temperature range 1000–1100°C effective yield strength reduction is greater for carbon steel and duplex stainless steel than for
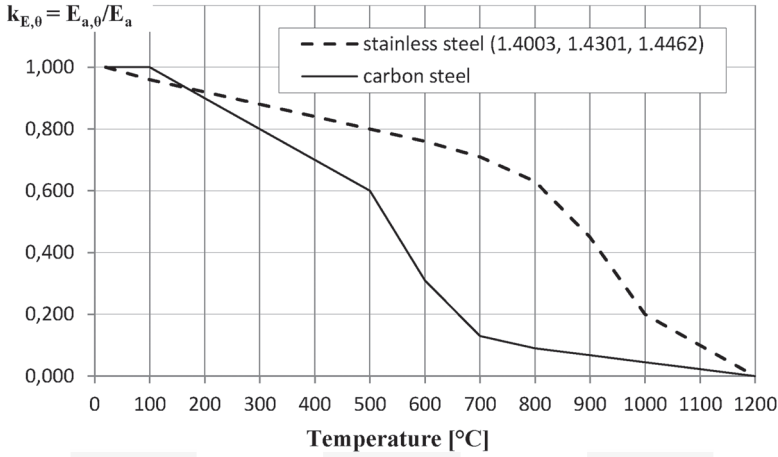
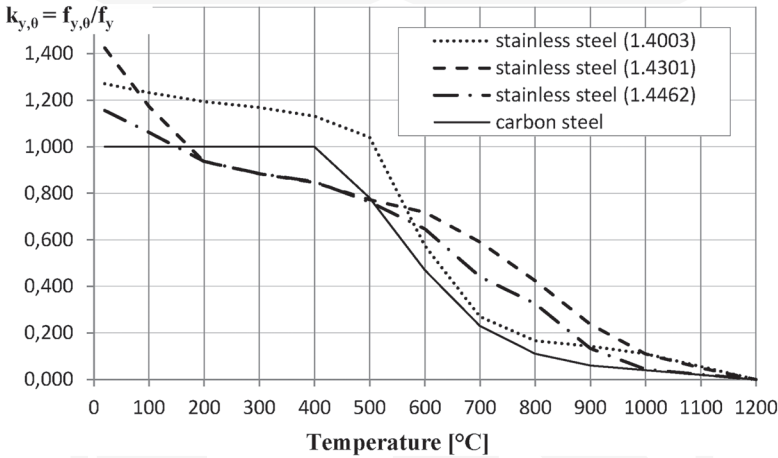Fig. 14. Reduction factor $k_{E,\theta}$ for the slope of linear elastic range

Fig. 15. Reduction factor $k_{y;\theta}$ for the effective yield strength

ferritic and austenitic stainless steels. Summarizing, in the structural design for accidental situation of fire exposure, reduction of stiffness at temperatures above 200°C and reduction of resistance at temperatures above 500°C is lower for analyzed stainless steel grades than for carbon steel.

The strength of stainless steel at elevated temperatures is also described by its creep strength, which is its ability to resist distortion over a long-term exposure to high temperature. Creep strength is usually measured by creep-rupture strength, i.e. the stress value that causes specimen rupture after 100 000 hours of exposure (basic value). If deformation is of greater concern, then the design may be based on creep deformation strength, i.e. the stress value that causes specimen strain of 1% after 100 000 hours of exposure. Figure 16 shows how the strengths of stainless steels change with increasing temperature.
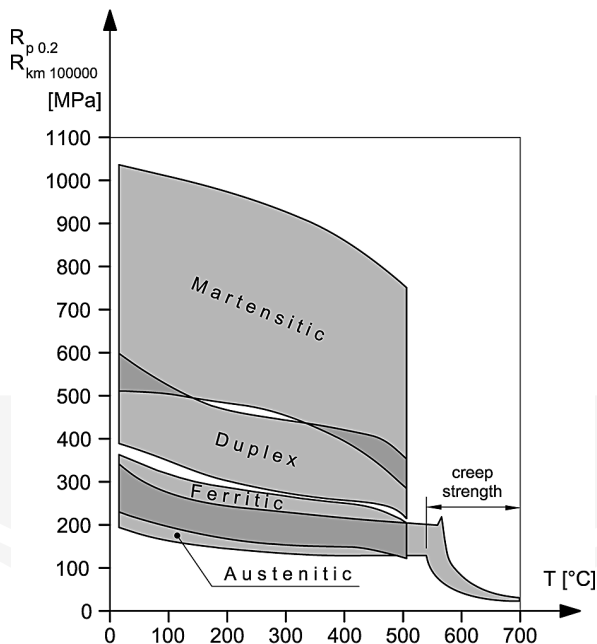
Fig. 16. Elevated temperature strength of stainless steels, including nonstructural
type – martensitic [20]

Ferritic stainless steels keep quite high strength up to temperatures of around 500°C, but at higher temperatures where deciding is creep strength – low for this type of stainless steel – their application is usually limited. Furthermore, at temperatures above 350°C, embrittlement of these steels may occur.

Austenitic-ferritic stainless steels at temperatures of up to 500°C have higher strength than all other stainless steels, but their creep strength is low (Fig. 16). The disadvantage of this stainless steel type, as in the case of ferritic grades, is the risk of embrittlement at temperatures above 350°C, so this is usually the upper limit of their service temperature.
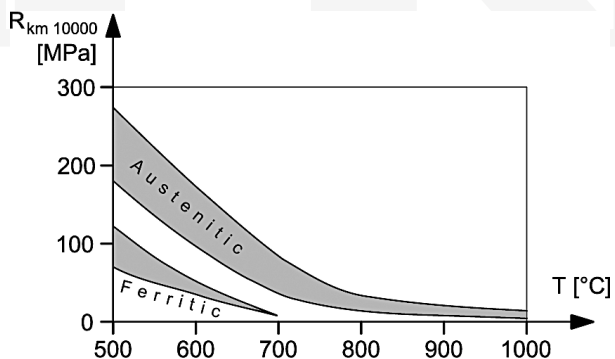

Fig. 17. Creep strength of ferritic and austenitic stainless steels [20]

The strength of most austenitic structural stainless steels at temperatures 0–500°C is lower than in the case of other stainless steels (Fig. 16) while at higher temperatures, they are characterized by superior creep strength – Fig. 16 and Fig. 17.

The coefficient of thermal expansion α, the thermal conductivity k, and the specific heat c, are physical not mechanical properties. The response of the mechanical model of stainless steel structure strongly depends on these thermal quantities, they are briefly described below.

The coefficient of thermal expansion α and thermal conductivity k are the properties that take significantly different values depending on the microstructure of stainless steel, they also distinguish stainless steel from carbon steel.

Values of coefficient of thermal expansion α between 20°C and 100°C for ferritic and austenitic-ferritic stainless steel are similar to that of carbon steel, but austenitic structural grades may have an almost 40% higher coefficient of thermal expansion than carbon steel [12]. High thermal expansion of austenitic stainless steels is the reason for large thermal stresses and distortions. The thermal elongation of austenitic stainless steel referred to in EN 1993-1-4 [6], may be determined according to Annex C of EN 1993-1-2 [4]; it monotonically increases with increasing steel temperature.

The thermal conductivity k of stainless steel is lower than the thermal conductivity of carbon steel which is related to a high chromium content in stainless steels. At temperature of 20°C the lowest thermal conductivity has austenitic stainless steel (12––15 W/m·K). The highest thermal conductivity at the same temperature has ferritic stainless steel (25 W/m·K) [12]. By comparison, carbon steel thermal conductivity k at 20°C is about 53 W/m·K. The thermal conductivity of stainless steel increases with increasing temperature [4].

The specific heat c of ferritic stainless steels (430–460 J/kg·K) is similar to those of carbon steels (440 J/kg·K), while most austenitic and duplex grades have around 15% larger specific heat [12]. Stainless steel specific heat is a monotonically increasing function of temperature; its value may be calculated according to Annex C of EN 1993-1-2 [4].

4. Conclusions

Stainless steels may have different mechanical properties depending on their chemical content and microstructure. In the design of buildings and civil engineering works, only ferritic, austenitic and austenitic-ferritic (duplex) stainless steels are approved for use [6]. Austenitic stainless steels are the most common type. These steels are characterized by good strength and ductility and can be harden by cold working. Ferritic stainless steels do not have as good ductility as austenitic grades, but the strength of some ferritic grades (Table 2.1 of [6]) is higher than that of austenitic ones. Austenitic-ferritic (duplex) stainless steels combine properties of austenitic and ferritic steels. They have higher strength than austenitic grades, but lower ductility. Ferritic and duplex stainless steels can be hardened only by cold working.

Differences between the behaviour and properties of carbon and stainless steels are specified in EN 1993-1-4 [6] and should be taken into account in the design of building

structures. One of these differences refers to the stress-strain curve: for stainless steel, it is nonlinear, even in the elastic stage of material behaviour, with no explicit yield stress and not showing a plateau before strain hardening. Another characteristic is that the modulus of elasticity depends upon the steel grade.

Mechanical, physical and technological properties of stainless steel, its behaviour during cold working and heat treatment, or at elevated temperatures, defines the scope of applications of this kind of steel. In comparison with popular carbon steel grades (S235 and S355), structural stainless steels are generally characterized by higher strength, higher ductility, a higher work hardening rate, lower thermal conductivity, and most of all, higher corrosion resistance. Unfortunately, with all these advantages, stainless steel is about four times more expensive than carbon steel. The high price of stainless steel may be compensated by lower steel consumption due to higher strength, lower costs of structure maintenance due to lack of anticorrosive coatings and the long life cycle of structure. Therefore, choosing between cheaper carbon steel and more expensive stainless steel should be preceded by a wider analysis of the total investment costs and not only the costs of building materials.

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