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PHYSICAL AND TECHNOLOGICAL PROPERTIES OF STRUCTURAL STAINLESS STEEL

WŁAŚCIWOŚCI FIZYCZNE I TECHNOLOGICZNE KONSTRUKCYJNYCH STALI NIERDZEWNYCH

Abstract

The paper summarizes microstructures and, associated with them, the physical and technological properties of structural stainless steel covered by EN 1993-1-4 [4]. Recommendations of the code [4] concerning the modelling of stainless steel properties are also described.

Keywords: stainless steel, physical and technological properties, EN 1993-1-4

Streszczenie

W artykule opisano struktury wewnętrzne i związane z nią właściwości fizyczne i technologiczne konstrukcyjnych stali nierdzewnych zgodnych z EN 1993-1-4 [4]. Podano również zalecenia zwarte w [4], dotyczące modelowania właściwości stali nierdzewnej.

Słowa kluczowe: stal nierdzewna, właściwości fizyczne i technologiczne, EN 1993-1-4

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1. Introduction

Stainless steels, due to their appropriate chemical composition, are resistant to corrosion. Their diverse chemical composition and relatively high content of chemical components (e.g. by comparison with alloy steels) [7–11] cause that different microstructures may arise during alloy solidification. Physical and technological properties of the alloy strongly depend on its microstructure. Usually, the stainless steel microstructure contains one or two principal phases which determine the physical, mechanical and anticorrosive properties of steel. It should be noted that, if there is no proper control of the alloy chemical composition or the production technology, phases other than principal may occur in stainless steel microstructure. These additional phases may have a negative impact on properties of stainless steel. There are some methods that allow for determining which stainless steel phases will exist for a given alloy composition and temperature so it can be pointed out what kind of thermal treatments are needed to obtain the required microstructure of stainless steel. For complicated alloy systems, it is very difficult to determine analytically which phase may occur for given chemical composition and temperature. For this reason, most published phase diagrams enabling the calculations of existing phases are experimentally derived [15].

Stainless steel may be marked in accordance with two designation systems, one of which being the numbering system consistent with [6], according to which:

- 1.40xx – stainless steels with less than 2.5% nickel (Ni), without molybdenum (Mo), niobium (Nb) and titanium (Ti),
- 1.41xx – stainless steels with less than 2.5% nickel (Ni), with molybdenum (Mo) but without niobium (Nb) and titanium (Ti),
- 1.43xx – stainless steels with at least 2.5% nickel (Ni), without molybdenum (Mo), niobium (Nb) and titanium (Ti),
- 1.44xx – stainless steels with at least 2.5% nickel (Ni), with molybdenum (Mo) but without niobium (Nb) and titanium (Ti),
- 1.45xx – stainless steels with special additions.

Two last numbers (xx) specify subsequent grades within the group of stainless steels.

In this paper, microstructure and physical and technological properties of structural stainless steels covered by European Standard EN 1993-1-4 [4] are described.

2. Chemical composition and microstructure of stainless steel

The term ‘stainless steel’ concerns a chemically diverse group of iron-base (Fe) alloys. In these kinds of alloys, the main element of chemical composition, besides iron (Fe), is chromium (Cr) that provides appropriate corrosion resistance. According to EN 10088-1 [7], stainless steel should contain at least 10.5% of chromium and not more than 1.20% of carbon (C). Proper alloy chemical composition guarantees formation of appropriate microstructure of stainless steel and, related with it, required physical, mechanical and technological properties of stainless steel. Chemical compositions of structural stainless steel is given in Fig. 1 and in Fig. 2 [7].

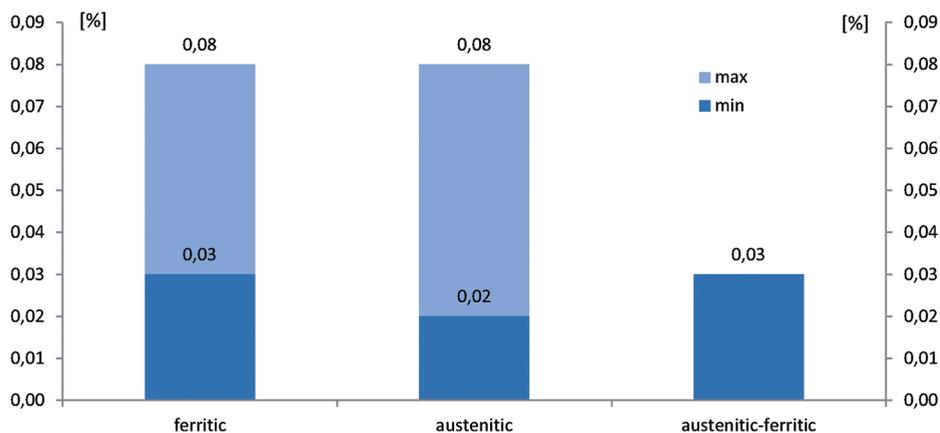


Fig. 1. The range of maximum carbon (C) content for different stainless steel categorie

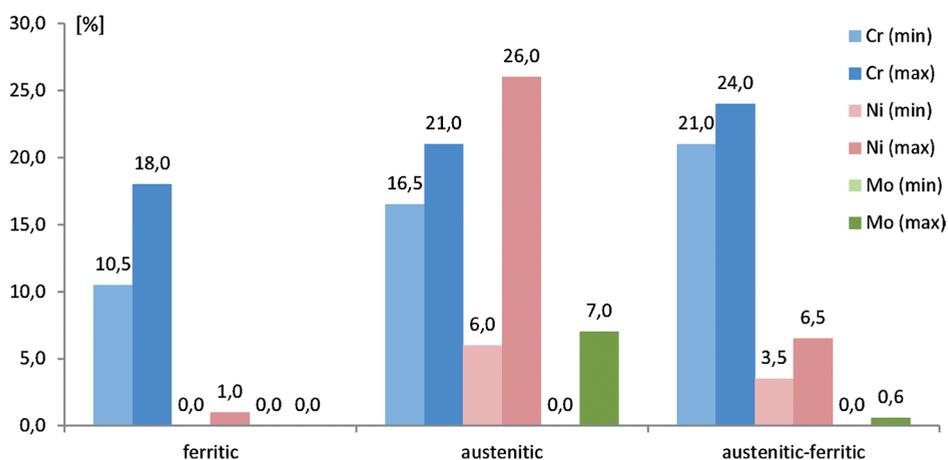


Fig. 2. The range of main alloying element content for different stainless steel categories

During alloy solidification, the diverse chemical composition of stainless steel causes the possible occurrence of three principal phases: martensite; ferrite; austenite. The content of these phases in steel microstructure determines the properties of the particular categories and grades of stainless steel [13–15], is described below. According to the current European Standard for the design of buildings and civil engineering works made of stainless steel [4], as structural steels, only steels with a ferritic, austenitic or austenitic-ferritic microstructure can be used. Austenitic-ferritic steels are also called duplex steels.

The principal property of stainless steels, according to the definition included in [7], is their resistance to corrosion resulting from high (min. 10.5%) chromium (Cr) content. The chromium (Cr) content enables the formation of a thin passive film on the element surface, protecting stainless steel elements from corrosion. Chromium (Cr) is also the main alloying element that promotes the ferritic microstructure of stainless steel. Silicon (Si),

aluminum (Al), molybdenum (Mo), wolfram (W), niobium (Nb) and titanium (Ti) have a similar influence on stainless steel microstructure. Additionally, titanium (Ti) enhances toughness and corrosion resistance and silicon (Si) increases the oxidation resistance of ferritic stainless steel. The formation of a stable ferritic microstructure is not favoured by the presence of carbon (C) and nitrogen (N), their content in ferritic stainless steels is limited to 0.025% (C) and 0.015% (N) [7]. Moreover, the presence of carbon (C) and nitrogen (N) strongly decreases toughness and corrosion resistance of this category of stainless steel.

The main alloying element that promotes the austenitic microstructure of stainless steel is nickel (Ni). Its content in austenitic stainless steel, according to [7], is not less than 3.0%, while for structural grades specified in Table 2.1 of EN 1993-1-4 [4] – min. 6.0%. Nickel (Ni) increases the ductility and toughness of stainless steel, enhances corrosion resistance in acid environments and resistance to stress corrosion, but it also reduces the rate of work hardening during cold deformation. Other elements that promote an austenitic microstructure are carbon (C) and copper (Cu). Carbon (C) increases strength, but may decrease resistance to corrosion. According to [7], in austenitic stainless steels, the content of carbon (C) is limited to 0.020%. Copper (Cu) increases corrosion resistance in some acid environments. Nitrogen (N) is another austenite former – it also enhances resistance to localized corrosion, especially in the presence of molybdenum (Mo). Manganese (Mn) can have an influence on the balance between austenite and ferrite in stainless steel microstructure. Depending on alloy temperature, it may be an austenite former (at low temperatures) or a ferrite former (at high temperatures). Manganese (Mn) improves hot ductility it is used to deoxidize molten steel and, as it increases the solubility of nitrogen (N), it is also used to obtain a higher nitrogen content and enhance strength and resistance to corrosion. The addition of titanium (Ti), as well as the addition of niobium (Ni), increases resistance to the intergranular corrosion of austenitic stainless steels, it also improves mechanical properties at high temperatures.

With regard to stainless steel microstructure, alloying elements can be divided into ferrite and austenite stabilizers, which are those which promote a ferritic microstructure and those which promote an austenitic microstructure [13], see Table 1.

Table 1

Classification of alloying elements

Ferrite stabilizers	Austenite stabilizers
Iron (Fe)	Nickel (Ni)
Chromium (Cr)	Nitrogen (N)
Molybdenum (Mo)	Carbon (C)
Silicon (Si)	Manganese (Mn)
Niobium (Nb)	Copper (Cu)
Aluminum (Al)	
Titanium (Ti)	
Wolfram (W)	

Based on this classification, a Schaeffler-Delong diagram, which illustrates the effect of the alloying elements on stainless steels microstructure, was developed (Fig. 3).

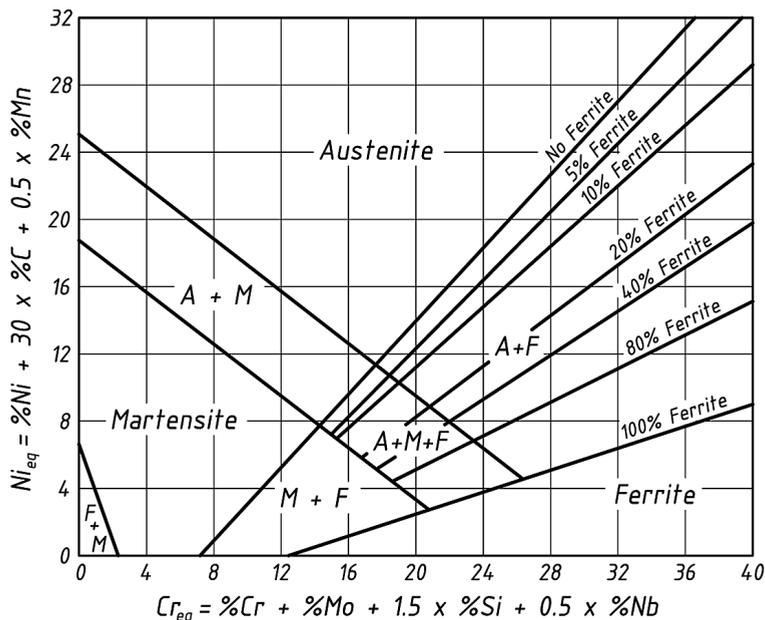


Fig. 3. Schaeffler-Delong constitution diagram for stainless steel [15]

If the austenite stabilizers ability to promote the formation of austenite is related to that for nickel, and the ferrite stabilizers likewise compared to chromium, it becomes possible to calculate the total ferrite and austenite stabilizing effect of the alloying elements in the steel [14]. This gives the so called chromium Cr_{eq} and nickel Ni_{eq} equivalents, defined as below [15]:

$$Cr_{eq} = \%Cr + \%Mo + 1.5\%Si + 0.5\%Nb, \quad (1)$$

$$Ni_{eq} = \%Ni + 30\%C + 0.5\%Mn. \quad (2)$$

Chromium equivalent Cr_{eq} (1), presented on the horizontal axis of the Schaeffler-Delong diagram, shows how to select an appropriate content of chromium (Cr), molybdenum (Mo), silicon (Si) and niobium (Nb) to obtain a chromium-like effect. Nickel equivalent Ni_{eq} (2), presented on the vertical axis of the Schaeffler-Delong diagram, performs the same function for nickel (Ni) and austenite formers. On the basis of the Schaeffler-Delong diagram, for the given values of Cr_{eq} and Ni_{eq} , some information about the joint effect of alloying elements on the microstructure of stainless steel can be found.

Originally, the Schaeffler-Delong diagram was developed for weld metal, but it transpires that it can also provide useful information for wrought and heat treated material. It should be noted that the Schaeffler-Delong diagram presented in Fig. 3 is not the only one which has been published. In specialist literature, several different diagrams with slightly different equivalents, phase limits or general layout can be found. They are the results of conducted research and discussions [14].

3. Influence of stainless steel microstructure on its properties

Both principal phases of structural stainless steel, i.e. ferrite and austenite, differ in properties, and their percentage in microstructure has a definite influence on steel properties.

Ferrite is a solid solution of carbon (C) in alpha iron (α -Fe) with a body-centered cubic (BCC) crystal structure (Fig. 4a). It is relatively soft and plastic, it has higher electrical and thermal conductivity and lower thermal expansion than austenite. The strength of ferrite decreases with temperature to a greater degree than happens in the case of austenite but in spite of this, ferritic stainless steel is great high-temperature material.

Austenite is a solid solution of carbon (C) in gamma iron (γ -Fe) with a face-centered cubic (FCC) crystal structure (Fig. 4b). It has good toughness, even in low temperatures. Austenite has lower stacking fault energies than ferrite which results in higher work-hardening rates. Ferrite and austenite alloys with a similar content of alloying elements have a similar yield strength, but austenitic alloys are more ductile and have higher work-hardening rates and higher tensile strengths [15]. Austenite, in contrast to ferrite, is nonmagnetic.

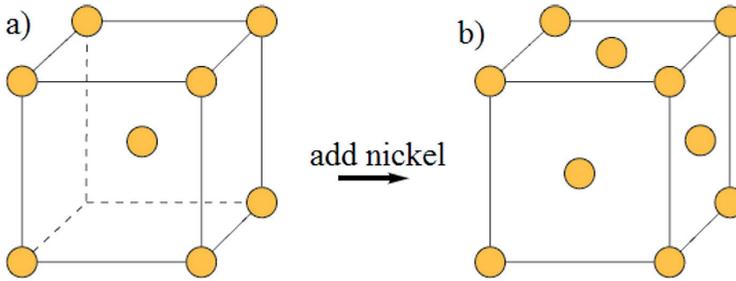


Fig. 4. Iron crystalline structure: a) in ferrite, b) in austenite [12]

The formation of the diphase (austenitic-ferritic) microstructure of stainless steel is the result of appropriate alloy chemical composition, i.e. a balance between ferrite and austenite formers, and steel thermal treatment. Melted steel solidifies to complete ferrite structure and then, at a temperature of about 1000°C (depending on alloy chemical composition), some ferrite grains transform into austenite, at lower temperatures further changes in the equilibrium ferrite-austenite balance occur. The austenite/ferrite phase balance in stainless steel microstructure can be estimated with multivariable linear regression [12]:

$$\% \text{Ferrite} = -20.93 + 4.01\text{Cr}_{\text{eq}} - 5.6\text{Ni}_{\text{eq}} + 0.016T, \quad (3)$$

where

$$\text{Cr}_{\text{eq}} = \% \text{Cr} + 1.73\% \text{Si} + 0.88\% \text{Mo}, \quad (4)$$

$$\text{Ni}_{\text{eq}} = \% \text{Ni} + 24.55\% \text{C} + 21.75\% \text{N} + 0.4\% \text{Cu}, \quad (5)$$

T – the annealing temperature ranging from 1050°C to 1150°C.

According to EN 10088-1 [7], austenite-ferrite stainless steel contains between 40% and 60% of austenite, usually roughly 50%.

The main alloying element of ferritic stainless steel is chromium (Cr) – Fig.5a, for austenitic stainless steel these are chromium (Cr), nickel (Ni) and molybdenum (Mo) – Fig. 5c, as is the case with austenite-ferrite (duplex) stainless steel – Fig. 5b, however, duplex steel has higher content of chromium (Cr) and lower content of nickel (Ni) than austenitic steel.

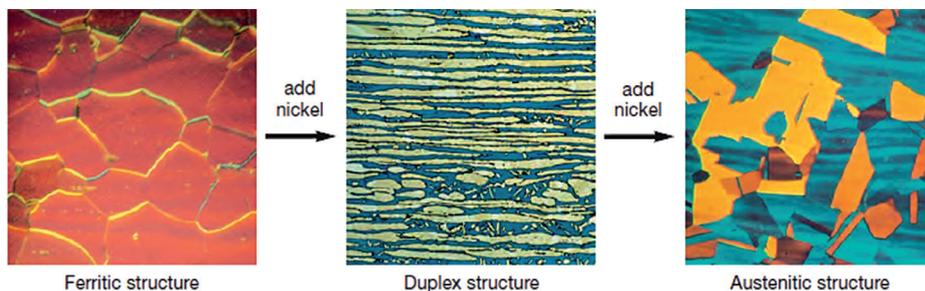


Fig. 5. Changes of stainless steel microstructures due to increasing nickel (Ni) content [12]

Due to having the lowest content of expensive nickel (Ni), ferritic stainless steels are the cheapest of all stainless steel categories. The high content of chromium (Cr) and low content of carbon (C) cause the ferritic microstructure to be stable. In older ferritic steels with a higher content of carbon, some high-temperature austenite formed, this transformed into martensite if quenched [15]. The structural ferritic stainless steels listed in Table 2.1 of EN 1993-1-4 [4] have a chromium (Cr) content in the range of 10.5% to 18.0%. Ferritic stainless steel resistance to corrosion and oxidation is good but steels with a lower (11–12%) content of chromium (Cr), i.e. 1.4003 and 1.4512, are treated as steels with increased resistance to corrosion and

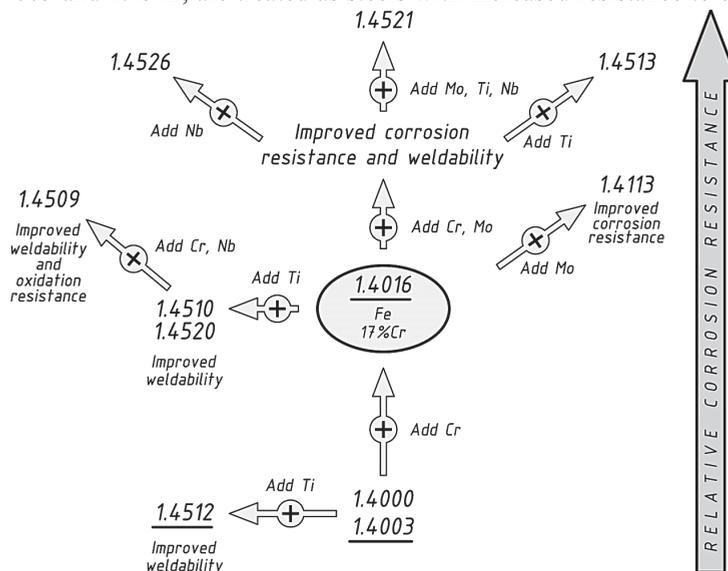


Fig. 6. Influence of alloying components on properties of ferritic stainless steel

should be used only in mildly corrosive environments, because in unfavourable conditions, their corrosion resistance is limited. A particular advantage of ferritic stainless steels is their high resistance to stress corrosion cracking caused by chlorides [19]. The mechanical properties of ferritic steel are moderate. This stainless steel category is characterized by good ductility and high resistance to elevated temperatures, they can only be hardened by cold working. Ferritic stainless steels are often used as light-gauge sheet because their toughness decreases rapidly for heavier sections. Their weldability varies from low to high, depending on the alloy chemical composition. Ferritic steels are magnetic [2, 15, 17, 20].

The most popular grade of ferritic stainless steel is 1.4016 (also in Poland [16]) with a chromium (Cr) content of about 17%. Figure 6 presents the effect of alloying elements on selected properties of ferritic stainless steel [18], structural steel grades listed in Table 2.1 of EN 1993-1-4 [4] are underlined.

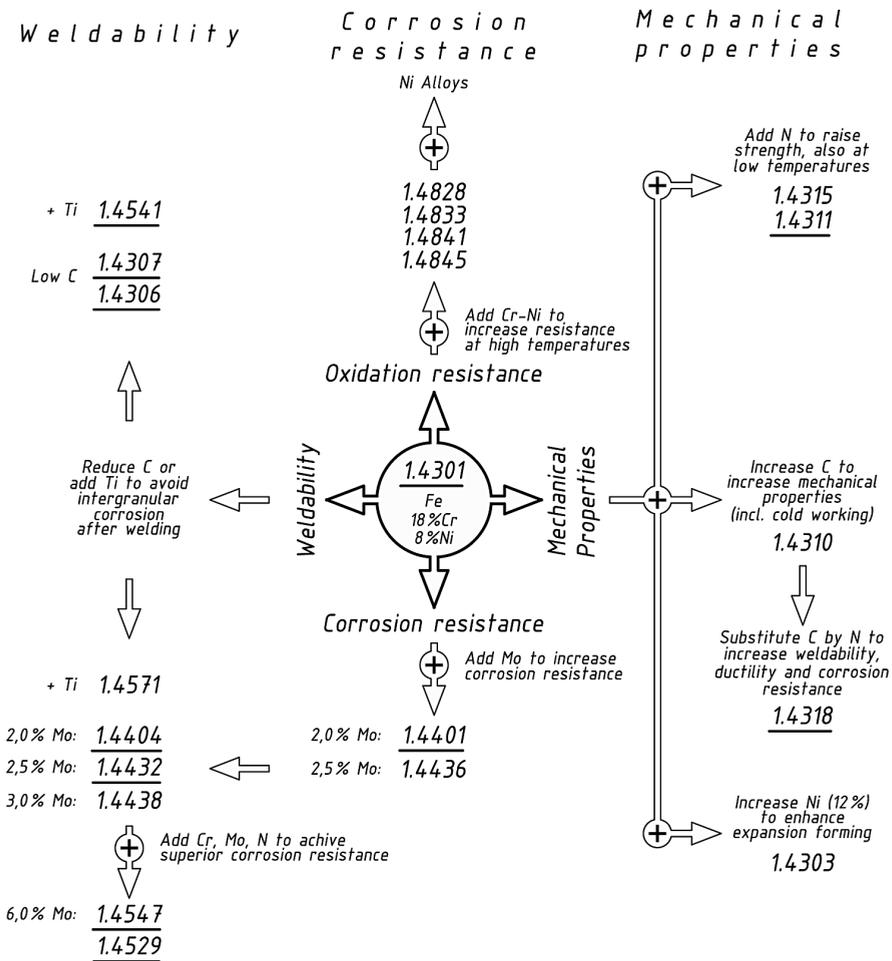


Fig. 7. Influence of alloying components on properties of austenitic stainless steel

Structural austenitic stainless steels, included in Table 2.1 [4], are comprised of at least 16% of chromium (Cr) and 6% of nickel (Ni). Due to their increased chromium (Cr) content, they are more corrosion resistant than ferritic stainless steels, while the high content of nickel (Ni) causes the austenitic microstructure to be stable and makes it resistant to brittleness at low temperatures. Austenitic stainless steels can be used in a wide range of temperatures, from cryogenic to red heat temperatures. They have very good formability and weldability and can be hardened by cold work. In an annealed condition, they are nonmagnetic. Because of their very good mechanical properties, corrosion resistance and weldability, this stainless steel category is the most popular. It should simultaneously be noted that austenitic stainless steels are less resistant to cyclic oxidation than ferritic steels because their greater coefficient of thermal expansion causes possible spalling of the protective oxide coating. Additionally, if austenitic stainless steel corrosion resistance is insufficient for application in a particular environment, stress corrosion cracking can occur [1, 15, 19, 20].

Figure 7 shows how, starting from the most popular grade 1.4301 [16], properties of austenitic stainless steel can be modified by changing the alloy composition [18]. Structural steel grades listed in Table 2.1 of EN 1993-1-4 [4] are underlined.

The microstructure of austenitic-ferritic stainless steels consists of austenite and ferrite, usually in the proportion of one to one. The content of chromium (Cr) in structural austenitic-ferritic stainless steel, listed in Table 2.1 [4], is 21–24%, the content of nickel (Ni) – 3.5% to 6.5% [7]. The mixed microstructure causes duplex steels to combine properties of ferritic and austenitic stainless steels, for example, their resistance to stress corrosion cracking (e.g. due to chlorides) is higher than austenitic but not as high as ferritic steel, they have higher toughness than ferritic but not as high as austenitic steel. The toughness of austenitic-

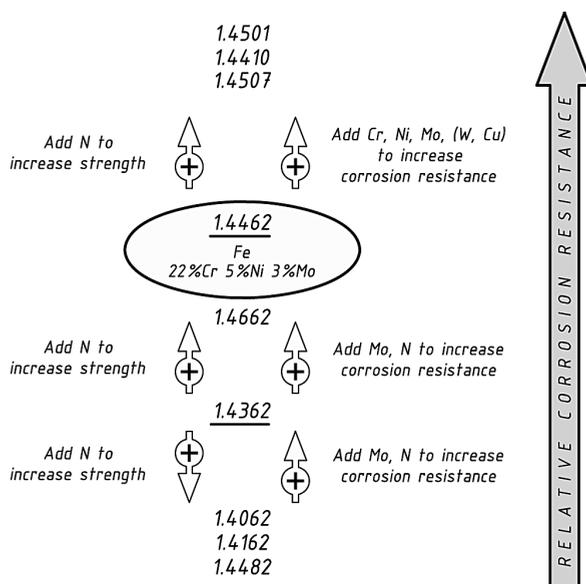


Fig. 8. The influence of alloying components on properties of austenitic-ferritic (duplex) stainless steel

ferritic stainless steel is reduced at temperatures below -50°C and above 300°C , so they should only be used between these temperatures. Duplex steels have a high yield strength, about two times higher than that of comparable austenitic grades, they also have good fatigue parameters, even in corrosive environments. The weldability of austenitic-ferritic stainless steels is good, but there are problems associated with the heat affected zone (HAZ) – loss of corrosion resistance, toughness or post-weld cracking. To avoid these problems, speed and heat input during welding should be diligently controlled. Duplex stainless steels have a lower coefficient of thermal expansion than austenitic stainless steel, so their welding distortions are usually also smaller. Austenitic-ferritic stainless steels can be strengthened by cold working but not by heat treatment. Steels of this category are magnetic. Their lower content of expensive nickel (Ni) makes them more economical than austenitic grades. Furthermore, duplex steels have a higher strength than austenitic steels which results in lower steel consumption. Typical applications of austenitic-ferritic stainless steel are investments where high strength, good corrosion resistance, low susceptibility to stress corrosion cracking or combinations of these requirements are needed [1, 12, 15, 19].

Differences between austenitic-ferritic stainless steel grades, usually showing higher mechanical properties and corrosion resistance than the most popular ferritic and austenitic grades, is shown in Fig. 7 [18], structural steel grades listed in Table 2.1 of EN 1993-1-4 [4] are underlined. According to Euro Inox data [18], the most popular grade of duplex steels is 1.4462.

4. Physical properties of stainless steel

4.1. Density

In contrast to carbon steel, density ρ of stainless steel is not a constant value but changes depending on microstructure and grade, from 7.5 to 8.1 kg/dm^3 [7]. Density of ferritic and austenitic-ferritic stainless steels is a little bit smaller than density of carbon steel (7.7 kg/dm^3 for ferritic grade 1.4016, 7.8 kg/dm^3 for austenitic-ferritic grade 1.4462, in comparison with 7.85 kg/dm^3 for carbon steel). The biggest density have austenitic stainless steels (e.g. 7.9 kg/dm^3 for grade 1.4301 and 8.1 kg/dm^3 for grade 1.4529). In general, within the particular steel category, steel density increases with increasing content of alloying elements, particularly heavy elements (e.g. molybdenum (Mo)) [14].

4.2. Modulus of elasticity

Initial modulus of elasticity E (Young's modulus) of stainless steel is not a constant value but depends on the steel microstructure. Values of Young's modulus taken into account for the design of building structures according to EN 1993-1-4 [4] due to ultimate limit state (ULS) are determined on the basis of EN 10088-1 [7]: 220 kN/mm^2 for ferritic stainless steels, 200 kN/mm^2 for austenitic-ferritic stainless steels and 195 - 200 kN/mm^2 for austenitic stainless steels. These values were determined at temperature of 20°C . The changeability of Young's modulus with temperature for different steel microstructure is shown in Fig. 9 [7].

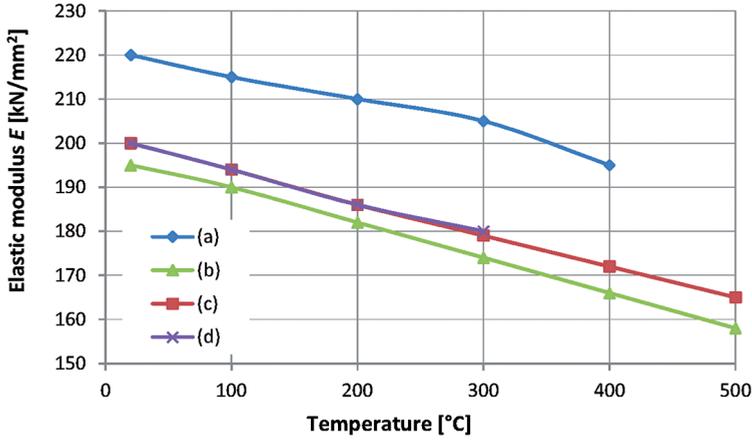


Fig. 9. Elastic modulus E of structural stainless steel: (a) ferritic, (b) austenitic (grades: 1.4539, 1.4547, 1.4529), (c) austenitic (other grades), (d) austenitic-ferritic

The behaviour of stainless steel in the annealed condition can alternatively be described by a nonlinear stress-strain curve according to Annex C of EN 1993-1-4 [4]. Depending on the accuracy required and the maximum strains attained, European Standard [4] specifies three approaches for modelling the material behaviour:

1) stress-strain curve with strain hardening:

$$\varepsilon = \begin{cases} \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{f_y} \right)^n & \text{for } \sigma \leq f_y \\ 0.002 + \frac{f_y}{E} + \frac{\sigma - f_y}{E_y} + \varepsilon_u \left(\frac{\sigma - f_y}{f_u - f_y} \right)^m & \text{for } f_y < \sigma \leq f_u \end{cases}, \quad (6)$$

where:

- n – the coefficient depending on rolling direction, defined as $n = \ln(20)/\ln(f_y/R_{p0.01})$; it may be taken from Table 2 or it may be calculated from measured properties,
 - $R_{p0.01}$ – the 0.01% proof strength,
 - 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 $\varepsilon_u \leq A$ where A is the elongation after fracture defined in [8–11],
 - m – the coefficient that may be determined as $m = 1 + 3.5 f_y/f_u$.
- 2) stress-strain curve calculated as in a) based on experimental data,
- 3) true stress-strain curve calculated from an engineering stress-strain curve as measured as follows:

$$\begin{aligned} \varepsilon_{\text{true}} &= \sigma(1 + \varepsilon) \\ \sigma_{\text{true}} &= \ln(1 + \varepsilon) \end{aligned} \quad (7)$$

Table 2

Values of n according to [4]

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	7	9
1.4401		
1.4404		
1.4432		
1.4435		
1.4539	5	5
1.4571		
1.4462		
1.4362		

Nonlinear stress-strain curves for the section made of exemplary stainless steel grade 1.4016, determined from formula (6) for longitudinal ($n = 6$) and transversal ($n = 14$) rolling direction, are shown in Fig. 10.

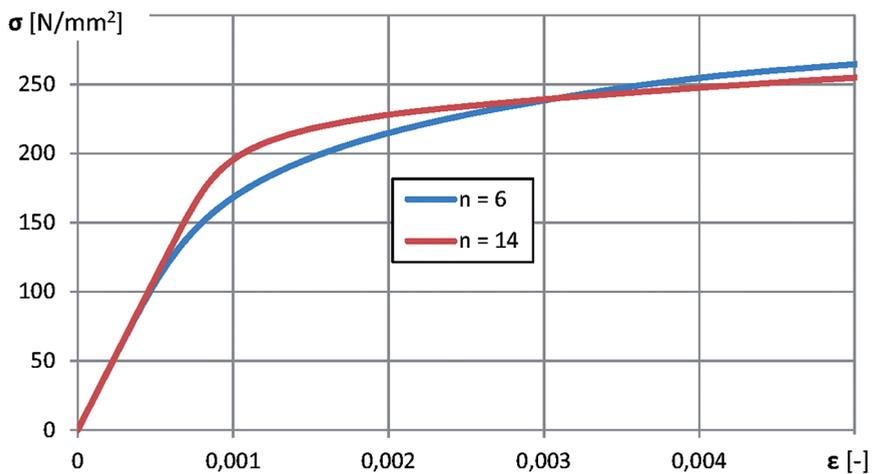


Fig. 10. Influence of the parameter n on the nonlinearity of the stress-strain curve

Calculating deflections of structural element European Standard EN 1993-1-4 [4] requires taking stainless steel nonlinear stress-strain behaviour into account; for annealed material guidelines given in Annex C [4] can be used.

Deflections in an individual member may be determined using the secant modulus of elasticity $E_{s,ser}$ appropriate to the stress level in the member at the serviceability limit state (SLS) and to the rolling direction or, alternatively, using Finite Element Methods (FEM) [5], assuming nonlinear material behaviour according to Annex C [4].

The value of the secant modulus of elasticity $E_{s,ser}$ may be calculated according to EN 1993-1-4, p.4.2(5) [4] as follows:

$$E_{s,ser} = \frac{(E_{s,1} + E_{s,2})}{2}, \quad (8)$$

where:

- $E_{s,1}$ – the secant modulus corresponding to the stress σ_1 in the tension flange,
- $E_{s,2}$ – the secant modulus corresponding to the stress σ_2 in the compression flange.

The values of $E_{s,1}$ and $E_{s,2}$ for the appropriate serviceability design stress $\sigma_{i,Ed,ser}$ ($i = 1$ or 2) and rolling direction, may be estimated using:

$$E_{s,i} = \frac{E}{1 + 0.002 \frac{E}{\sigma_{i,Ed,ser}} \left(\frac{\sigma_{i,Ed,ser}}{f_y} \right)^n}. \quad (9)$$

Parameter n may be taken from Table 2 or determined according to Annex C [4].

To simplify calculations, European Standard EN 1993-1-4 [4] allows us to neglect variations of the secant modulus of elasticity $E_{s,ser}$ along the length of the member and use minimum value of $E_{s,ser}$ corresponding to the maximum values of the stresses $\sigma_{1,Ed,ser}$ and $\sigma_{2,Ed,ser}$ in the member, throughout the member's length.

4.3. Shear modulus

According to EN 1993-1-4 [4], stainless steel shear modulus G is determined depending on Young's modulus value as

$$G = \frac{E}{2(1 + \nu)}, \quad (10)$$

where

- ν – Poisson's ratio, in elastic stage equal to 0.3.

4.4. Coefficient of thermal expansion, thermal conductivity and specific heat

Coefficients of thermal expansion α and thermal conductivity k are the physical properties that take significantly different values depending on the microstructure of stainless steel, they also distinguish stainless steel from carbon steel. Values of the coefficient of thermal expansion α between 20°C and 100°C are as follows [7]: $12 \cdot 10^{-6}/K$ for carbon steel, $10.0 - 10.5 \cdot 10^{-6}/K$ for ferritic stainless steel, $13.0 \cdot 10^{-6}/K$ for austenitic-ferritic stainless

steel and $15.8 - 16.5 \cdot 10^{-6}/\text{K}$ for austenitic stainless steel. The values presented above concern stainless steel grades listed in Table 2.1 EN 1993-1-4 [4]. High thermal expansion of austenitic stainless steels is the reason for large thermal stresses and distortions. The thermal elongation ε_T of austenitic stainless steel included in EN 1993-1-4 [4] may be determined according to Annex C of EN 1993-1-2 [3]:

$$\varepsilon_T = \frac{\Delta l}{l} = (16 + 4.79 \cdot 10^{-3} \theta_a - 1.243 \cdot 10^{-6} \theta_a^2)(\theta_a - 20)10^{-6}, \quad (11)$$

where

- Δl – the temperature induced expansion,
- l – the length at 20°C,
- θ_a – the steel temperature [°C].

According to (11), the thermal elongation Δl of a 6000 mm long exemplary element made of austenitic stainless steel, heated to 800°C is equal to $15 \cdot 10^{-3}$ (see Fig. 11), this means that temperature induced expansion Δl is about 90 mm. Figure 11 illustrates how the thermal elongation Δl of structural austenitic stainless steels, determined according to [3], changes with temperature.

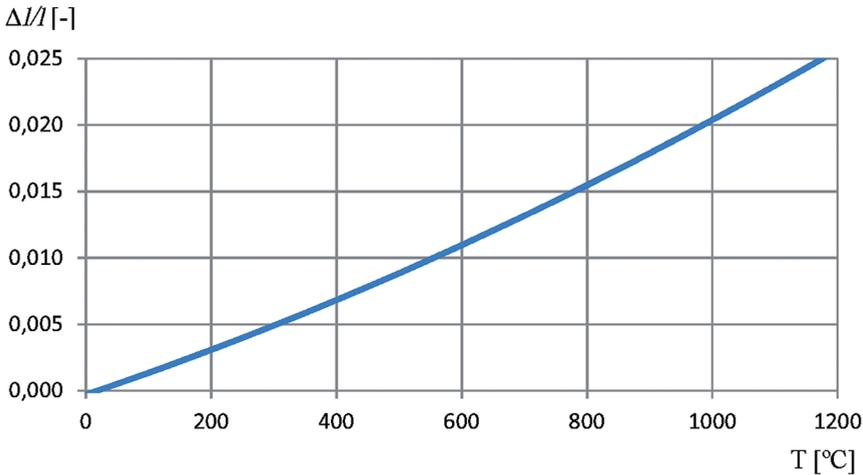


Fig. 11. Thermal elongation $\Delta l/l$ of stainless steel as a function of temperature

Thermal conductivity k of stainless steel is lower than thermal conductivity k of carbon steel, this is related to the high content of chromium in stainless steels. For each stainless steel category, it decreases with increasing the alloying elements content. Austenitic stainless steels have the lowest thermal conductivity k at temperature of 20°C – 12–15 W/m·K, for austenitic-ferritic stainless steels this parameter is equal 15 W/m·K, ferritic stainless steels have the highest thermal conductivity k – 25 W/m·K [7]. The presented values concern stainless steel grades listed in Table 2.1 EN 1993-1-4 [4]. By comparison, carbon steel thermal conductivity k at 20°C is about 53.3 W/m·K. Thermal conductivity k of stainless steel increases with increasing temperature [3] – Fig. 12.

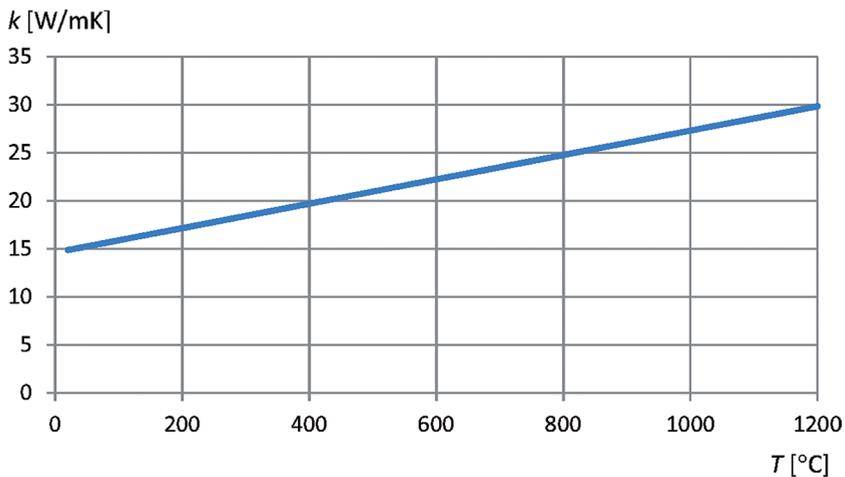


Fig. 12. Thermal conductivity k of stainless steel as a function of temperature

The specific heat c (unitary thermal capacity at 20°C) of ferritic stainless steels varies in range of 430–460 J/kg·K, so it is of a value similar to specific heat c of carbon steels – 440 J/kg·K, most austenitic grades and austenitic-ferritic stainless steels are characterized by greater specific heat $c = 500$ J/kg·K [7]. Stainless steel specific heat c is a monotonically increasing function of temperature; its value may be calculated according to Annex C.3 of EN 1993-1-2 [3] – Fig. 13.

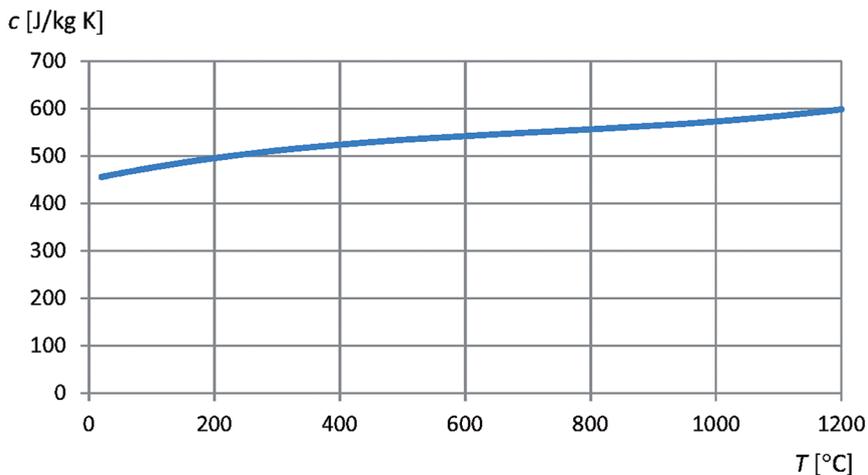


Fig. 13. Specific heat c of stainless steel as a function of temperature

5. Technological properties of stainless steel

5.1. Corrosion resistance

The corrosion resistance of stainless steel is connected with its high chromium (Cr) content (min. 10.5% [7]) which supports the forming of a passive film protecting the steel surface against corrosion. A significant distinguishing feature of the passive film is its ability to immediately self-repair in the presence of air or an oxidising environment without any additional treatments. The passive film formed on the stainless steel surface is stable and makes stainless steel resistant to corrosion in normal atmospheric and mild aqueous environments. The main alloying elements that increase corrosion resistance are, apart from chromium (Cr), molybdenum (Mo), nickel (Ni) and nitrogen (N). Chromium (Cr) enhances the stability of the passive film, and with molybdenum (Mo), increases resistance to chloride penetration. Nickel (Ni) improves the resistance of the passive film in some acid environments. Structural austenitic stainless steel grade 1.4401 has a higher corrosion resistance than grade 1.4301 because it contains molybdenum (Mo) and more nickel (Ni). In order to improve corrosion resistance in a particular environment, some other elements may be added to the alloy, e.g. copper (Cu) which enhances corrosion resistance to sulphuric acid [1, 2, 15]. To keep appropriate corrosion resistance of stainless steel, one should pay attention to the fact that during fabrications, the passive film on stainless steel structural components should not be broken down, for example, by using the same tools for the processing of stainless and carbon steels.

The corrosion of stainless steel can occur when the passive film is damaged and, because of environmental conditions (lack of oxygen, strong acid or alkaline environments), is not allowed to re-form. Stainless steel grades may differ in their corrosion resistance depending on the steel chemical composition and the type of corrosive environment. For that reason, the selection of stainless steel grade for a given application should be preceded by an analysis of the corrosion environment effect on the particular grade. Sometimes, the actual durability of the stainless steel structure is lower than assumed. Possible reasons for this situation are: an incorrect selection of stainless steel grade for corrosive environment; exposure to unexpected conditions (e.g. contamination by chloride ions); incorrect treatment of steel components decreasing its corrosion resistance; incorrect detailing of steel structures increasing the possibility of corrosion (dirt entrapments, notch causing stress concentration, etc.).

Corrosion resistance is also dependent on the type of surface finishing – the smoother the surface, the higher the corrosion resistance. The exception is stainless steel susceptible to stress corrosion cracking because stresses caused by surface mechanical polishing can initiate corrosion cracking in the structure elements situated in the environment containing chloride ions.

European Standard EN 1993-1-4 [4] specifies six types of corrosion that may occur in structural elements made of stainless steel: pitting; crevice corrosion; bimetallic corrosion; stress corrosion cracking; general corrosion and inter-granular attack; weld decay. Only pitting, crevice corrosion and bimetallic corrosion are likely to occur in buildings [4].

Corrosion of stainless steel elements causes many problems. The reduction of structural member cross section leads to the reduction of its capacity. The perforation of tanks and pipes causes leakage of fluids or gases. In food industry, products of corrosion can contaminate the material being handled, etc.

5.2. Heat treatment ability

Stainless steels are often subjected to technological processes of heat treatment such as annealing, hardening and stress relieving. The objective of these treatments is to restore the required properties of material (resistance to corrosion, ductility) and to relieve residual stresses caused by the production process or previous technological treatments. They are also used to produce hard structures of stainless steel able to withstand high stresses or abrasion in service. Heat treatment of stainless steel is performed in specific conditions, depending on the steel category and type of treatment.

The annealing of austenitic stainless steel recrystallizes the work hardened grains but also homogenizes dendritic weld metal structures and relieves remnant stresses from cold working. The obtained austenitic microstructure has no carbides precipitation at grain boundaries which prevents chromium (Cr) impoverishment of grain boundary zones and thus prevents inter-granular corrosion. The temperature of this heat treatment is usually above 1040°C, although, if fine size of grain is important, some grades may be annealed at closely controlled temperatures as low as 1010°C. The annealing of austenitic-ferritic stainless steels is generally very similar to austenitic grades. Ferritic stainless steels, depending on their grade, may be annealed at a temperature in the range of 760°C to 955°C. Heat treatment at higher temperatures of stainless steel in this category may cause the formation of austenite that, during cooling, transforms into martensite, thus making steel brittle [1].

Residual stress relieving of austenitic stainless steels at temperatures below 400°C gives a modest result - only after heat treatment at temperatures in the range of 425°C to 925°C, is a significant reduction of residual stresses achieved. It is assumed that one hour treatment at 870°C relieves about 85% of the residual stresses. It should be noted that stress relieving in this higher temperature range can also precipitate grain boundary carbides, resulting in decreasing corrosion resistance. The full annealing process, i.e. heating to about 1080°C followed by rapid cooling, removes all residual stresses in austenitic grades, but is not a practical treatment for most large or complex fabrications [1].

Stainless steel can also be heat treated in order to surface harden but only to a limited extent. As an example, the surface of austenitic stainless steels can be hardened by nitriding, but it should be noted that the hard and thin surface layer obtained during this process, surrounds the underlying stainless steel core which is relatively soft, this excludes the use of this solution in heavily loaded engineering applications. Additionally nitriding decreases the corrosion resistance of stainless steel [1].

Before heat treatment, the surface of stainless steel must be cleaned in order to remove oil, grease and other carbonaceous residues that would otherwise lead to carburization during heat treating which degrades corrosion resistance.

5.3. Cold forming ability

Characteristic of structural stainless steel is that during cold working, it can be hardened, i.e. made stronger. The hardening rate depends on the stainless steel microstructure and the highest is for austenitic grades. Stainless steel work hardening may be the result of cold rolling or the fabrication process of the structural member, or a combination of both. According to EN 1993-1-4 [4], for the design of stainless steel structures, nominal values of yield strength f_y and ultimate tensile strength f_u may only be adopted for material delivered in the cold worked conditions specified in [8–11]. The recommendations given in [4] may be applied if for steel in the worked harden condition yield strength do not exceed 350 MPa or ultimate tensile strength – 700 MPa. These recommendations may also be used for higher grades when local or global instability is not a deciding factor for the bearing capacity of an element or of a whole structure. In cases when the bearing capacity is determined by local or global stability, and steel yield strength is higher than 350 MPa (or ultimate tensile strength exceeds 700 MPa), stainless steel structures should be designed on the basis of full size tests. Stainless steel work hardening from fabrication may be utilized in the design provided that the effect of work hardening has been verified by full size tests [4].

5.4. Weldability

Welding is the most popular technique of connecting metal elements. The weldability of structural stainless steel may vary from low to high, depending on the steel category and grade. Most austenitic and austenitic-ferritic grades are readily welded. Ferritic grades with a very low carbon (C) content are weldable, while grades with a higher content of carbon (C) are not as easily welded and must often be preheated.

The weld metal and the heated affected zone (HAZ) of austenitic stainless steels has a tendency to crack, especially in fully austenitic microstructures. Stainless steel microstructures containing a small amount of ferrite (5–10%) are less susceptible to cracking. Therefore, when austenitic stainless steel is welded, the selection of filler material composition is very important. The main problem of ferritic stainless steel welding is the low toughness of the heat affected zone (HAZ) due to excessive grain coarsening. The preheating of the stainless steel in this category does not reduce the grain size but will reduce the HAZ cooling rate, maintain the weld metal above the ductile-brittle transition temperature, and may reduce residual stresses. The preheat temperature should be within the range 50–250°C, depending on material composition. Modern austenitic-ferritic stainless steels are readily weldable, but obtaining a proper weld requires the maintenance of process parameters, especially the heat input range. In the case of duplex steel, welding an appropriate selection of filler material is very important because the balance between ferrite and austenite in weld microstructure should be close to that in the parent material microstructure [21].

To weld stainless steel, most welding methods can be used, including welding in an inert gas atmosphere with a consumable (MIG) and non-consumable (TIG) electrode, and welding with a coated electrode and resistance welding. During stainless steel welding, one should remember that this kind of steel has a higher coefficient of thermal expansion and lower thermal conductivity than carbon steel, so relevant actions to limit welding distortions should be undertaken.

6. Conclusions

Stainless steels approved for use in building structures by EN 1993-1-4 [4], may have one of following microstructures: ferritic; austenitic; austenitic-ferritic. The type of microstructure (steel category) strongly affects both the physical and technological properties of stainless steel. These properties are quantitatively and qualitatively diverse in comparison with carbon steel as well as between stainless steel grades. In general, structural stainless steel has a higher work hardening rate, higher ductility and strength, higher cryogenic toughness, higher hardness, much lower thermal conductivity and, of course, higher resistance to corrosion than structural carbon steel. The disadvantage of stainless steel is its high price, about four times higher than the price of carbon steel. On the other hand, its advantages include high strength, durability, low maintenance costs, low thermal conductivity. These advantages can favour the growth of stainless steel applications in building structures.

Diversity of chemical compositions, microstructures and surface finishing means that the selection of an appropriate stainless steel grade for structural application is more complicated than in the case of carbon steel. When selecting a carbon steel grade, the designer only usually takes into consideration the mechanical and technological parameters. In most cases, the choice of anticorrosive protection and the surface visual appearance of the carbon steel structure can be considered as independent of steel grade selection. The corrosion resistance of carbon steel is ensured by appropriate anticorrosive coating matched up to environmental corrosive conditions. This coating can be periodically renovated or, in the case of substantial damage or environment corrosiveness change, can be completely removed and replaced. In contrast to carbon steel, corrosion resistance of stainless steel is inextricably linked with properties of steel grade. For this reason, proper selection of structural stainless steel grade is more important than in the case of carbon steel – it affects not only structure load bearing capacity, but also structure corrosion resistance.

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