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KRZYSZTOF KUCHTA, IZABELA TYLEK*

APPLICATION OF STAINLESS STEELS IN BUILDING STRUCTURES

ZASTOSOWANIE STALI NIERDZEWNYCH W KONSTRUKCJACH BUDOWLANYCH

Abstract

In the paper structural stainless steels consistent with EN 10088 were characterized. Authors described stainless steel categories, production process, basic properties and element joining techniques. Some examples of stainless steel applications in structural building, realized in the last few years in Poland and in the world were presented.

Keywords: stainless steel in building structures

Streszczenie

W artykule scharakteryzowano konstrukcyjne stale nierdzewne zgodne z EN 10088. Opisano ich rodzaje, proces produkcji, podstawowe właściwości oraz technikę łączenia elementów. Podano również przykłady zastosowania stali nierdzewnych w konstrukcjach budowlanych zrealizowanych w ostatnich latach na świecie i w Polsce.

Słowa kluczowe: stale nierdzewne w konstrukcjach budowlanych

* Assist. Prof. Ph. D. Eng. Krzysztof Kuchta, Assist. Prof. Ph. D. Eng. Izabela Tylek, Institute of Building Materials and Structures, Faculty of Civil Engineering, Cracow University of Technology.

1. Introduction

Stainless steel large-scale production began over 100 years ago in France and Germany. In 1912, after four years of researches in Krupp's Concern laboratory in Essen, conducted by professor Benno Strauss and doctor Eduard Maurer, patent for austenitic stainless steel was obtained. This steel is known all over the word as Nirosta (acronym from German language – ***ni****cht****ro****stender* ***Sta****hl*). Development of stainless steel production technology was continued mainly in United States and Great Britain. In spite of long production history and many spectacular applications in building industry, stainless steel began to be perceived as constructional building material about15–20 years ago.

Currently stainless steel is more frequently used not only by architects but also by structural engineers. Apart from its high corrosion resistance, stainless steel has other advantages: high durability, availability of many grades with different mechanical and physical properties, easiness of machining, forming and joining of elements, products diversity (sheets, plates, coils, tubes, bars, profiles, fittings etc.), many types of surface finishing (bright finishes, deco and patterned, fingerprint resistant, polished and brushed, primed and painted etc.), easiness of keeping clean. This is also proper material to work both in low and high temperature. Another reason that stainless steel becomes more popular is ecology. It is estimated that almost 60% of material used for stainless steel production comes from recycling (data from The European Stainless Steel Development Association Euro Inox), addition of expensive chromium and nickel makes profitable to recycle of all waste products. Long life cycle of stainless steel products enables to safe energy as a result of manufacturing process limiting. Very important for environmental protection is the fact that stainless steel elements do not need additional anti-corrosive chemical coatings.

The impulse which strongly stimulated propagation of stainless steel structures was, in last twenty years, appearance of new generation of Standards pertaining to design and execution structures made of stainless steel. Until the European Standards has been introduced in Poland, only metallurgical Standards applicable to stainless steels: PN-71/H-86020 "Stal odporna na korozję (nierdzewna i kwasoodporna). Gatunki", PN-71/H-86022 "Stal żaroodporna. Gatunki", BN-77/0631-11 "Nowe stale odporne na korozję (nierdzewne, kwasoodporne, utwardzalne wydzieleniowo, żaroodporne). Gatunki" were established.

2. Categories and grades of stainless steel

Basic criterion of dividing stainless steel into categories is their microstructure at room temperature, which has a decisive effect on steel physical and mechanical properties. European Standard EN 10088-1 [14] be distinguish following categories of stainless steel: martensitic, ferritic, austenitic, austenitic-ferritic (duplex) and precipitation hardening. Steels from the last category are hardened in a special way which caused formation of precipitates within the microstructure. According to EN 1993-1-4 [8] in building structures only ferritic, austenitic and austenitic-ferritic (duplex) stainless steels can be used. Martensitic steels due to their low toughness and weldability are not permitted.

Selected properties of structural stainless steel categories are compared in Table 1 [3].

Table 1

Comparison of selected stainless steel properties [3]

Micro-structure	Magnetic response[1)]	Work hardening rate	Corrosion resistance[2)]	Harde-nable	Ductility	High temperature resistance	Low temperature resistance
Ferritic	Yes	Medium	Medium	No	Medium	High	Low
Austenitic	Generally: No	Very high	High	By cold work	Very high	Very high	Very high
Austenitic-ferritic (Duplex)	Yes	Medium	Very high	No	Medium	Low	Medium

1) Attraction of the steel to a magnet. Note same austenitic grades can be attracted to a magnet if cold worked, cast or welded.
2) Varies significantly between grades within each group.
3) Measured by toughness or ductility at sub-zero temperatures. Austenitic grades retain ductility to cryogenic temperatures.

European Standards, currently in force, introduce two systems of steel grades designation: by mean of symbolic letters and numbers according to EN 10027-1 [12] and numbering system according to EN 10027-2 [13].

Designation of stainless steel grade according to [12] begins with letter *X* and a number, which are followed by sequence of letters and ended by sequence of numbers separated by a hyphen, for example: X2CrNiN18-10. Letter *X* symbolizes stainless and other alloyed steels, where the mean alloying content of at least one element is above 5%. The first number after X represents 100-times the mean percentage value of the carbon content. The following letters are the symbols for the most important alloying elements, in descending order by content. Numbers separated by a hyphen specify the approximate content of the main alloying elements. If there is no number, it means that content of this element is lower than 1%. As an example: X2CrNiN18-10 it is stainless steel (X) with the mean value of carbon content 0,02% (2/100), containing 18% of chromium (Cr, 18), 10% of nickel (Ni, 10) and less than 1% of nitrogen (N, lack of number).

Steel grades marked according to second of European designation systems [13] have fixed number of digits which refers only to one steel grade. 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. In Table 2.1 EN 1993-1-4 [8] were classified four groups of structural stainless steel:

1) 1.40*yy* – grades with less than 2.5% nickel, without molybdenum, without special additions,
2) 1.43*yy* – grades with more than 2.5% nickel, without molybdenum, without special additions,
3) 1.44*yy* – grades with more than 2.5% nickel, with molybdenum, without special additions,
4) 1.45*yy* – grades with special additions, such as titanium, niobium or copper.

Chemical composition (cast analysis) of stainless steel grades included in Table 2.1 EN 1993-1-4 [8] is compared in Tables 2 to 4.

Table 2

Chemical composition of ferritic stainless steels [14]

Steel grade	% by mass								
	C max.	Si max.	Mn max.	P max	S max.	N max	Cr	Ni	Ti
1.4003	0.030	1.00	1.50	0.040	0.015	0.030	10.50–12.50	0.30–1.00	6x(C+N) to 0,65
1.4512	0.030	1.00	1.00	0.040	0.015		10.50–12.50		
1.4016	0.080	1.00	1.00	0.040	0.015[1)]		16.00–18.00		

[1)] For bars, rods, sections and the relevant semi-finished products, a maximum content of 0.030% S applies.
For any product to be machined, a controlled sulfur content of 0.015% to 0.030% is recommended and permitted.

Table 3

Chemical composition of austenitic stainless steels [14]

Steel grade	% by mass									
	C max.	Si max.	Mn max.	P max	S max.	N	Cr	Cu	Mo	Ni	Ti
1.4318	0.030	1.00	2.00	0.045	0.015	0.10-0.20	16.50–18.50			6.00–8.00	
1.4307	0.030	1.00	2.00	0.045	0.015[1)]	≤ 0.11	17.50–19.50			8.00–10.00	
1.4306	0.030	1.00	2.00	0.045	0.015[1)]	≤ 0.11	18.00–20.00			10.00–12.002)	
1.4311	0.030	1.00	2.00	0.045	0.015[1)]	0.12-0.22	17.00–19.50			8.50–11.50	
1.4301	0.070	1.00	2.00	0.045	0.015[1)]	≤ 0.11	17.00–19.50			8.00–10.50	
1.4541	0.080	1.00	2.00	0.045	0.015[1)]		17.00–19.00			9.00–12.00[2)]	5xC to 0.70
1.4404	0.030	1.00	2.00	0.045	0.015[1)]	≤ 0.11	16.50–18.50		2.00–2.50	10.00–13.002)	
1.4406	0.030	1.00	2.00	0.045	0.015[1)]	0.12-0.22	16.50–18.50		2.00–2.50	10.00–12.00[2)]	
1.4401	0.070	1.00	2.00	0.045	0.015[1)]	≤ 0.11	16.50–18.50		2.00–2.50	10.00–13.00	
1.4571	0.080	1.00	2.00	0.045	0.015[1)]		16.50–18.50		2.00–2.50	10.50–13.50[2)]	5xC to 0.70
1.4432	0.030	1.00	2.00	0.045	0.015[1)]	≤ 0.11	16.50–18.50		2.50–3.00	10.50–13.00	

Steel grade	% by mass										
	C max.	Si max.	Mn max.	P max	S max.	N	Cr	Cu	Mo	Ni	Ti
1.4435	0.030	1.00	2.00	0.045	0.015[1)]	≤ 0.11	17.00–19.00		2.50–3.00	12.50–15.00	
1.4439	0.030	1.00	2.00	0.045	0.015	0.12-0.22	16.50–18.50		4.00–5.00	12.50–14.50	
1.4539	0.020	0.70	2.00	0.030	0.010	≤ 0.15	19.00–21.00	1.20–2.00	4.00–5.00	24.00–26.00	
1.4547*)	0.020	0.70	1.00	0.030	0.010	0.18-0.25	19.50–20.50	0.50–1.00	6.00–7.00	17.50–18.50	
1.4529	0.020	0.50	1.00	0.030	0.010	0.15-0.25	19.00–21.00	0.50–1.50	6.00–7.00	24.00–26.00	

[1)] For bars, rods, sections and the relevant semi-finished products, a maximum content of 0.030% S applies.
For any product to be machined, a controlled sulfur content of 0.015% to 0.030% is recommended and permitted.

[2)] Where for special reasons, e.g. hot workability for the fabrication of seamless tubes where it is necessary to minimize the delta ferrite content, or with the aim of low permeability, the maximum Ni content may be increased by the following amounts:
0.50% (m/m): 1.4571;
1.00% (m/m): 1.4306, 1.4406, 1.4541;
1.50% (m/m): 1.4404.

[*)] Patented steel grade (see: EN 10027–2 [13])

Table 4

Chemical composition of austenitic-ferritic stainless steels [14]

Steel grade	% by mass									
	C max.	Si max.	Mn max.	P max	S max.	N	Cr	Cu	Mo	Ni
1.4362[*)]	0.030	1.00	2.00	0.035	0.015	0.05–0.20	22.00–24.00	0.10–0.60	0.10–0.60	3.50–5.50
1.4462	0.030	1.00	2.00	0.035	0.015	0.10–0.20	21.00–23.00		2.50–3.50	4.50–6.50

[*)] Patented steel grade (see: EN 10027-2 [13])

Elements not quoted in Tables 2 to 4 may not be intentionally added to the steel without the agreement of the purchaser except for finishing the cast. All appropriate precautions are to be taken to avoid the addition of such elements from scrap and other materials used in production which would impair mechanical properties and the suitability of the steel [14].

3. Basic physical and mechanical properties of stainless steel

Diversity of chemical composition and structures of stainless steels is the reason of significant quantitative and qualitative differences of physical and mechanical properties in comparison to other metal alloys used for fabrication of building load-bearing structures. In Table 5 some basic parameters of metal alloys used in building structural elements are compared.

Table 5

Comparison of basic metal alloys for building structures

Metal alloy	ρ [kg/m^3]	f_y [MPa]	E [GPa]	α_T [10^{-6}/K]	λ [W/m K]	C [J/kg K]	$A_5/A_{50}/A_{80}$ 2) [%]	KV [J]
Ferritic stainless steel according to EN 10088 [14–18] 1)	7.70	210–280	220	10,0–10.5	25.0	430–460	18.0–25.0	-
Austenitic stainless steel according to EN 10088 [14–18] 1)	7.90–8.10	175–350	195–200	15.8–16.5	12.0–15.0	450–500	30.0–45.0	90.0–100
Austenitic-ferritic stainless steel according to EN 10088 [14–18] 1)	7.80	400–480	200	13.0	15.0	500	20.0–25.0	90.0–100
Structural carbon steel according to EN 10025-2 [11]	7.85	215–440	210	12.0	53.3	440	16.0–26.0	55.0–63.0
Structural aluminium	2.70	35.0–280	70.0	23.0	142–191	911	1–16	-

1) Applies to steel grades listed in Table 2.1. EN 1993-1-4 [8].
2) Alternatively: A_5 or A_{50} or A_{80}.

where

ρ – specific gravity,
f_y – characteristic value of yield strength,
E – longitudinal modulus of elasticity at 20ºC,
α_T – average coefficient of thermal expansion at temperature between 20ºC and 100ºC,
λ – thermal conductivity at 20ºC,
C – unitary thermal capacity at 20ºC,
$A_5/A_{50}/A_{80}$ – ultimate elongation,
KV – impact energy at 20ºC.

It can be seen that range of yield strength for austenitic stainless steels corresponds to the most popular structural carbon steels S235 and S355. Stainless steels with austenitic-ferritic structure (duplex steels) are characterized by the highest value of yield strength (480 MPa).

Differences between mechanical and physical properties of carbon and stainless steels, important for structural safety, were taken into account when preparing the European Standard EN 1993-1-4 [8], which gives supplementary provisions for the design of buildings and civil engineering works that extend and modify the application of EN 1993-1-1 [6], EN 1993-1-3 [7], EN 1993-1-5 [9] and EN 1993-1-8 [10] to austenitic, austenitic-ferritic and ferritic stainless steels.

According to EN 1993-1-4 [8] in structure global analysis and to determine the resistances of members and cross-sections it may be assumed that longitudinal modulus of elasticity (Young's modulus) E is equal to 200 GPa for the austenitic and austenitic-ferritic (duplex) grades specified in Table 2.1 [8] excluding grades 1.4539, 1.4529 and 1.4547, for which Young's modulus is 195 GPa. Ferritic stainless steels are characterized by modulus of elasticity E = 220 GPa. Shear modulus (Kirchhoff's modulus) is determined, depending on Young's modulus value, based on a formula $G = E/[2(1 + \nu)]$, where ν – Poisson's ratio in elastic range equal to 0.3.

Deflections of individual member may be calculated using the secant modulus appropriate to the stress in the member at the serviceability limit state. Its value should be determined according to 4.2(5) of EN 1993-1-4 [8].

4. Durability and corrosion of stainless steels

Criteria of building structures durability are defined by the requirements that structure shall satisfy according to designer and investor's intentions. European Standard EN 1993-1-4 [8] distinguish two basic types of stainless steel application in structural buildings:

- **cosmetic applications** in which the prime consideration in the choice of material is to maintain the appearance during the life of the structure. In this case it is also necessary to distinguish between indoor and outdoor applications because elements located under shelter have to be cleaned more often than outdoor element that have possibility of natural cleaning by weather agents;
- **structural applications** in which the mechanical properties of stainless steel are essential. In this case most natural atmospheres have no detrimental effects on stainless steels.

Stainless steels can corrode. In particularly corrosively aggressive environment, e.g. hydrochloric acid, stainless steel will corrode not very slower than structural carbon steel. Corrosion, as is the case of ordinary steel, is then the main factor determining durability of stainless steel structures. Expected durability of stainless steel structures is determined by selection of materials, the design process and the fabrication procedures and by the environmental conditions.

Selection of appropriate stainless steel grade for design structure should be preceded by analysis of steel corrosion resistance, its mechanical and physical properties and ability of structure maintenance.

The first step of this analysis is to establish general corrosion characteristic of environment including influence of corrosively active elements and substances which may permanently or periodically come into contact with stainless steels. Important parameters of the analysis can be surface condition, steel temperature and the anticipated service stress. Necessary may occur quantity evaluation of the effects of cyclic heating and cooling of the structure.

Influence of final decision of steel grade selection has also ease of fabrication, availability of product forms, surface finish and expected costs. Proper selection of stainless steel grade ensure long-term use of structure without any problems and also increase its economical effectiveness.

Assessing the suitability of grades is best approached by referring to experience of stainless steels in similar applications and environments. For atmospheric environments, Table A.1 of EN 1993-1-4 [8] (shown below as Table 6) gives guidance for selecting suitable grades from a corrosion point of view.

Table 6

Suggested grades of stainless steel for atmospheric applications [8]

Steel grade according to EN 10088 [14–18]	Type of environment and corrosion category											
	Rural			Urban			Industrial			Marine		
	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
1.4003 1.4016	Y[1]	X	X	Y[1]	X	X	X	X	X	X	X	X
1.4301 1.4311 1.4541 1.4318	Y	Y	Y	Y	Y	(Y)	(Y)	(Y)	X	Y	(Y)	X
1.4362 1.4401 1.4404 1.4406 1.4571	O	O	O	O	Y	Y	Y	Y	(Y)	Y	Y	(Y)
1.4439 1.4462 1.4529 1.4539	O	O	O	O	O	O	O	O	Y	O	O	Y

Corrosion conditions (aggressiveness of environment):
Low: Least corrosive conditions for that type of environment, e.g. low humidity or low temperatures.
Mid: Fairly typical for that type of environment.
High: Corrosion likely to be higher than typical for that type of environment, e.g. increased by persistent high humidity, high ambient temperatures or particularly aggressive air pollutants.

Symbols (assessment of steel usability):
O Potential over-specification from a corrosion point of view.
Y Probably the best choice for corrosion resistance and cost.
Y[1] Indoor applications only. The use of ferritic stainless steels for cosmetic applications should be avoided.
X Likely to suffer excessive corrosion.
(Y) Worth considering provided that suitable precautions are taken (i.e. specify a relatively smooth surface and then carry out regular washing).

It should be noticed that corrosion resistance depends on its alloying components what implies that different grades with the same microstructure may behave differently in the same environment.

Stainless steels show significantly higher durability resulting from higher corrosion resistance than carbon steels. Durability of paint coatings protecting elements from carbon steel from corrosion is defined in EN ISO 12944-1 [24] as expected life of protective paint system to the first major maintenance, in case of "high" durability it should be more than 15 years. In low and medium corrosively aggressive environments, after standard 50 years of use, structures made of properly selected stainless steel grade may need only maintenance for aesthetic reasons.

Stainless steel corrosive resistance is caused by presence of thin (about 5×10^{-6} mm) film formed on steel surface that prevents steel from reacting with an atmosphere. Behaviour of this so called "passive film" depends on steel composition, its surface treatment and the corrosive nature of environment. Unlike carbon steel which for passivation require additional treatments (e.g. oxidizing), passivation of stainless steel surface takes place spontaneously if alloy content of chromium exceeds 12–18%. Corrosion of stainless steels may occur if passive film is broken down and can't self-repair.

Stainless steel corrosion resistance contrary to expectations may be caused by [8]:

– incorrect assessment of the environment or exposure to unexpected conditions (e.g. contamination by chloride ions),
– introduction of a state not envisaged in the initial assessment, by the way in which the stainless steel has been worked or treated (e.g. using the same tools for stainless and carbon steels).

Very important in preventing corrosion is also appropriate structure detailing (e.g. avoiding moisture and dirt entrapment).

European Standard EN 1993-1-4 [8] describes six types of corrosion, but only three of them are likely to occur in buildings:

– **pitting** – localized form of corrosion that can occurs as a result of exposure to specific environments, especially those containing chloride ions. Pitting occurs because chloride ions penetrate the passive film in weak spots. In most structural applications intensity of superficial pitting is low and acceptable because the reduction in the section of the component will be negligible. More restrictive requirements are taken for ducts, piping and containment structures. Products of corrosion may also spoil architectural effects;
– **crevice** – localized form of corrosion, initiated by the differentials in oxygen levels between the creviced and exposed regions. This type of corrosion usually is not a problem, except in solutions where permanent threat of chlorides can occur. The severity of crevice corrosion is very dependent on the geometry of the crevice; the narrower and deeper the crevice, the more severe the corrosion. Crevices typically occur between nuts and washers or around the thread of a screw or the shank of a bolt. They can also occur in welds that fail to penetrate and under deposits on the steel surface;
– **bimetallic** – occurring when dissimilar metals are in electrical contact in any electrolyte (rainwater, condensation etc.). The less noble metal (the anode) corrodes faster than would have occurred if the metals were not in contact. Bimetallic corrosion may be prevented by excluding water from the detail (for example by painting or taping over the assembled joint) or, preferably, by electrically isolating the metals from each other (for example by painting the contact surfaces of the dissimilar metals).

Besides of material loss, effect of corrosion can occur as discolouration and staining (often due to carbon steel contamination) but they can be removed by mechanical and chemical cleaning methods.

Products made of stainless steel are usually subjected to surface finishing operations such as: pickling, skin passing, grinding, brushing, mechanical or electrochemical polishing, colouring etc. These finishing processes, apart from aesthetic effect, also increase uniform corrosion resistance (the smoother surface the higher corrosion resistance). The exception is stainless steel susceptible to stress corrosion cracking. Stresses caused by mechanical polishing of the surface can initiate corrosion cracking in structure elements situated in environment containing chloride ions.

5. Fabrication of stainless steels

Stainless steels can be fabricated in the same conventional way as carbon steels but due to high strength of material and very high hardening rate in stainless steel production process heavier machines which can generate larger forces are required. In first step of stainless steel production scrap and ferroalloys are melting and then refining to adjust the carbon content and remove impurities. Most often stock is melting in an electric-arc furnace and followed by refining by argon oxygen decarburization. Molten stainless steel is casting continuously or into ingots. During the final stages of producing basic mill forms (sheets, strips, plates and bars) the material is subjected to hot reduction with or without subsequent cold rolling operations, annealing, and cleaning. Further steps are required to produce other mill forms, such as wire and tube [3].

Most of stainless steels are subjected to heat treatment. In some of those cases removal of contamination is required, for example: scale formed on stainless steel surface during annealing must be removed e.g. by pickling.

Important characteristic of stainless steel element is surface finishing, especially in the case when, besides of mechanical properties, visual values are also significant. Some types of surface finish form during the production process, the others are result of additional treatments, e.g. polishing, brushing, colouring. Choosing type of surface finish it should be noted that it has influence on element corrosion resistance, e.g. rough surface will decrease effective corrosion resistance in comparison with smooth surface finishing.

It was attempted to define the most common types of surface finish (e.g. EN 10088-2 [15]) but due to fact, that some producers reserve the right to their solutions, full standardization is rather unlikely.

6. Joints in stainless steel structural elements

Stainless steel elements can be join by bolt-and-nuts or by welding. Both bolt-and-nuts and welding materials, besides of appropriate ultimate strength should enable to make joint with corrosion resistance not less than corrosion resistance of connected material. Glue joints are also in use but gluing process is not covered by EN 1993-1-4 [8].

Stainless steel bolts and nuts should conform with EN ISO 3506-1,2,3 [19–21], but grade A1, because of significant sulphur content and connected with it reduction of corrosion resistance, should not be used for bolts. Washers should be of stainless steel and should conform with EN ISO 7089 [22] or EN ISO 7090 [23]. Additionally, according to [8] high strength bolts made of stainless steel should not be used as preloaded bolts designed for a specific slip resistance, unless their acceptability in a particular application can be demonstrated from test results.

In case of welding materials, additionally to EN 1993-1-8 [10], welding electrodes should be capable of producing a weld with a corrosion resistance that is adequate for the service environment, provided that the correct welding procedure is used. The welding electrodes may be assumed to be adequate if the corrosion resistance of the deposited metal and weld metal is not less than that of the material to be welded [8].

The weldability of stainless steel grades depends on their chemical composition and may be different for various grades with the same microstructure [32]:

– ferritic stainless steels can be welded, but they show lower ductility in weld region. All ferrictic stainless steels have tendency to increase in size of grains in heat-affected zone and therefore should be welded with possibly small heat input;
– austenitic stainless steel grades are readily welded but due to high thermal coefficient of expansion they are susceptible to formation of welding residual stresses and strains. Moreover, low thermal conductivity causes higher heat concentration in welding zone but the heat can be easily carrying away by using of cooling copper backing bar;
– austenitic-ferritic (duplex) steels are also well weldable, although not so well as austenitic. It is recommended to use filler with increased content of nickel.

In Table 7 weldability of selected stainless steel grades was compared.

Table 7

Weldability of selected structural stainless steel grades

Stainless steel grade	Microstructure	Weldability
1.4016	Ferritic	Hard to weld, welding not recommended
1.4301	Austenitic	Weldable
1.4306		
1.4307		
1.4401		
1.4404		
1.4435		
1.4439		
1.4529		
1.4539		
1.4541		
1.4571		
1.4362	Austenitic-ferritic (duplex)	Weldable
1.4462		

To weld stainless steel practically all methods can be used, European Standard EN 1993-1-4 [8] recommends professional advice on the selection of welding procedure for joining stainless steels. Proper selection of welding method allows not only to produce a weld with appropriate mechanical properties but also with required visual appearance and corrosion resistance.

Errors occurring during welding are often the results of improper element preparation before welding, e.g. leaving excessive gaps leads to considerable welding strains, contamination of welded element surfaces results degradation of weld mechanical properties and visual appearance. Stainless steels are characterized by large welding shrinkage that why weld area should be minimized.

Post-weld treatment of welded joint includes mechanical and/or chemical processing [5]. The need for surface finishing applies primarily to arc welds, all surface contaminants and irregularities should be removed in order to not act as sites of corrosive attack. In some cases, e.g. where aesthetic or industrial process purity issues are important, it may be necessary to remove surplus of the weld and to polish the weld zone to look like parent material.

Mechanical finishing treatment may be one of the following: hammering, brushing, grinding, polishing and buffing. Irrespective if weld joint was mechanically finished or not, it should always be remembered of weld chemical treatment including acid pickling followed by passivation and washing both after pickling and passivation. Pickling and passivation protecting weld and its surroundings against corrosion due to surface contaminants.

7. Applications of stainless steels

In Europe stainless steel is used mainly in: food and drink industry, household appliances manufacturing, architecture and civil engineering, chemical and pharmaceutical industries, medical equipment manufacturing, pulp and paper manufacturing, water and sewage treatment, transport, energy production and environmental protection.

Stainless steel in civil engineering and architecture is mostly used for balustrades, building wall and roof claddings, elements of building façade, doors and windows, floors, stairs, escalators and lifts and also fastening systems. Wilde field of stainless steel application constitute: installations in e.g. food, chemical and petrochemical industries, chimneys, pipelines, tanks, water seals or steel parts of harbour piers. In Table 8 some examples of typical application of structural stainless steel selected grades of were given.

Among structural applications of stainless steel (especially duplex grades) bridges load bearing elements and reinforcement bars should be mentioned.

One of the first and also the most famous architectural applications of stainless steel is Chrysler Building in New York, which almost whole spire was made of 700 tones of stainless steel produced by American steel mills on Krupp's license.

Tendency to increase structural applications of stainless steel in civil engineering can be observed recently. This material is chosen for its visual appearance, high corrosion resistance, good mechanical properties and high durability.

Examples of structures build in recent few years, where main elements or entire structure were made of stainless steel [4, 25, 26, 29, 30], are shown in Table 9. In this specification

Table 8

Examples of typical applications of selected stainless steel grades

Grade	Application example
1.4003	Tanks, chimneys, conveyors, footbridges, stairs, balustrades, light lattice girders.
1.4016	Tanks in chemical and food industries, pipelines, fasteners, chimney liners
1.4301	Tanks for acids, liquid oxygen, nitrogen and hydrogen, storage tanks in brewing industry, pipelines, springs, nuts, bolts and screws.
1.4306	In highly oxidizing environments such as nitric acid, e.g. storage tanks for tomato purée.
1.4307	Tanks for acids, pipelines, springs, nuts, bolts and screws.
1.4401	Tanks and pipelines in chemical, pulp and paper, pharmaceutical industries, balustrades, architectural applications.
1.4404	Tanks, pipelines, chimneys in chemical, petrochemical, brewing industries, balustrades, architectural applications.
1.4529	Elements having contact with sea water.
1.4539	Tanks and pipelines in chemical, paper and pulp industries, parts exposed to condensates of combustion gases, buildings fasteners in aggressive environments.
1.4541	Pressure vessels, pipelines in chemical and food industries.
1.4571	Elements that need high corrosion resistance, pipelines, tanks, balustrades, architectural applications.
1.4462	Tanks and pipelines in chemical, pulp and paper industries, elements in environments with high content of chlorides and in marine environment.

grade 1.4162 was also taken into account. It is austenitic-ferritic (duplex) grade with lower (1,5%) than typical stainless steels nickel content (see Table 2–4). This grade is not specified in Table 2.1 EN 1993-1-4 [8] but due to low nickel content and its high price, may be economical alternative to other austenitic stainless steel grades.

Table 9

Examples of structural uses of stainless steel outside Poland [4, 25, 26, 29, 30]

Year	Name	Location	Dimensions [m]	Stainless steel	
				Components	Grades
2001	Millenium Bridge (Footbridge)	York, UK	Length: 150 Span: 80.0	Arch	1.4462
2002	Apate Bridge (Footbridge) – Fig. 3	Stockholm, Sweden	Length: 5.0	Main girder	1.4462
2003	Gas-fired combined heat and power station	Isle of Grain in Kent, UK	Diameter: 0.91	Pipes	1.4306
2003	Padre Arrupe Bridge (Footbridge) – Fig. 3	Bilbao, Spain	Length: 142 Span: 80.0	Box girder with carbon steel internal structure	1.4362
2004	Likholefossen Bridge (Footbridge)	Likholefossen, Norway	Length: 24.0	All except concrete columns	1.4162

Table 9 con.

Year	Name	Location	Dimensions [m]	Stainless steel	
				Components	Grades
2004	17 palm-oil storage tanks	Rotterdam, the Netherlands	Diameter/ Height: 17.0/7.00–9.00	Main structure	LDX2101*) (1.4162)
2005	Cala Galdana (Road Bridge)	Menorca	Length: 55.0 Span: 45.0	Main structure	1.4462
2005	Arco di Malizia (Road Viaduct) – Fig. 1	Siena, Italy	Length: 51.5	Arch	1.4362
2005	Storage tank for pure acetic acid – Fig. 4	Tarragona, Spain	Height: 25.0 Diameter: 22.0	Main structure	1.4362
2005	Storage tank for marble slurry	Elnesvågen, Norway	Height: 22.8 Diameter: 15.25	Main structure	LDX2101*) (1.4162)
2006	Piove di Sacco Bridge (Road bridge) – Fig. 1	Padua, Italy	Length: 120	Arches, deck and casing	1.4362
2006	Celtic Gateway Bridge (Footbridge)	Holyhead, Wales, UK	Length: 160 Span: 70.0	Load bearing arche	1.4362
2006	Storage tank for honey and edible oils	Barcelona, Spain	Height: 25.0 Diameter: 19.0	Main structure	LDX2101*) (1.4162)
2007	40 silos for intermediate storage of atomized clay	Castellón, Spain	–	Main structure	LDX2101*) (1.4162)
2007	Al Hidd desalination plant	Bahrain	–	Plates and tube	1.4362 1.4462
2008	Storage tank for biodiesel and edible oils – Fig. 4	Amsterdam, the Netherlands	Height: 20.0 Diameter: 11.0	Main structure	1.4362 LDX2101*) (1.4162)
2009	The Helix Bridge (Footbridge)	Marina Bay, Singapore	Length: 280 Span:65.0	Main structure	1.4462
2009	Towers of Stonecutters Bridge (Road Bridge) - Fig. 2	Hong Kong, China	Length: 1596 Span: 1018 Towers height: 300	Outer skin of the towers (the upper 118 m of the towers are composite sections with an outer stainless steel skin and a concrete core rein-forced with stainless steel rebars)	1.4462
2009	KARRATHA Gas Treatment Plant	Australia	Diameter: 0.30	Pipes	1.4301

Table 9 con.

Year	Name	Location	Dimensions [m]	Stainless steel	
				Components	Grades
2009	41 palm-oil storage tanks	Rotterdam, the Netherlands	Diameter/ Height: 17.0/16.5; 17.0/13.0; 10.0/4.00; 17.0/9.50; 17.0/7.00	Main structure	LDX2101*) (1.4162)
2012	Jetty Boil-Off Gas Project (JBOG)	Quatar	Diameter: 0.76–1.57	Pipes	1.4306
2012	The Porsche Pavillon – Fig. 5	Wolfsburg, Germany	Overhanging part: 25.0 x 30.0	Monocoque: structural elements cover panels	1.4301 1.4571
2013	Wheatstone LNG Project (liquefied natural gas and domestic gas development)	Ashburton North, Australia	Diameter: 0.60–1.83	Pipes	1.4306
*) Registered trademark of Outokumpu					

Fig. 1. Structural use of stainless steel in road viaducts and bridges: Arco di Malizia, Siena, Italy (left) and Piove di Sacco Bridge, Pardua, Italy (right) [1]

In structures listed in Table 9 wide range of product forms have been used, including: plates, large diameter tubes, circular, square and rectangular hollow sections, fabricated straight and tapered box sections made from plates. Steel consumption in selected structures was as follows: 110 tones in Piove di Sacco Bridge, 160 tones in Cala Galdana Bridge, in Celtic Gateway Bridge: 220 tones, The Helix Bridge: 400 tones structural pipes and 200 tones other structural parts, Stonecutters Brigde: 1800 tones plates and 200 tones pipes [4]. Very original Porsche Pavillon is the largest construction of this kind, stainless steel consumption in this internally stiffened, doubly curved shell structure was 425 tones [31]. To fabricate 17 storage tanks for palm oil (Rotterdam) 760 tones of stainless steel was needed [29]. 3000 tones of stainless steel rebars was used in main pylon of Stonecutters Bridge (Hong Kong).

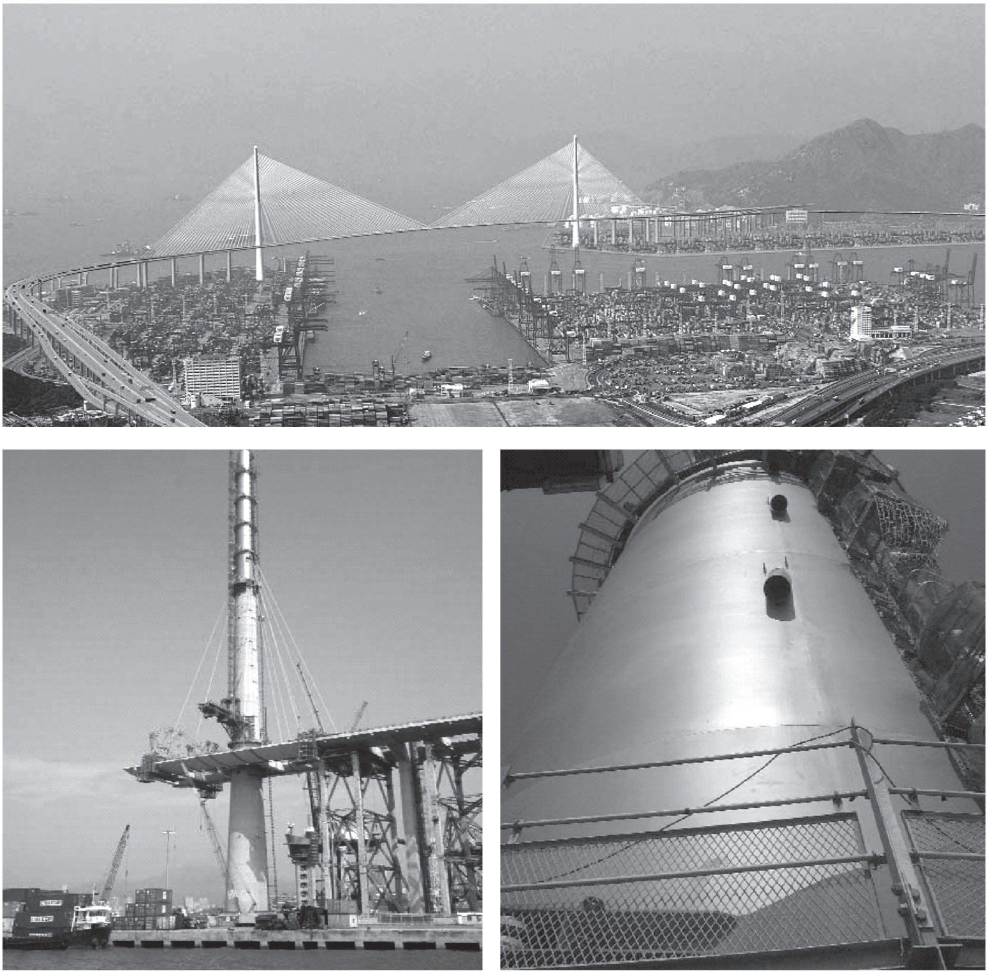

Fig. 2. Structural use of stainless steel in road bridges: towers of Stonecutters Bridge, Hong Kong, China [1]

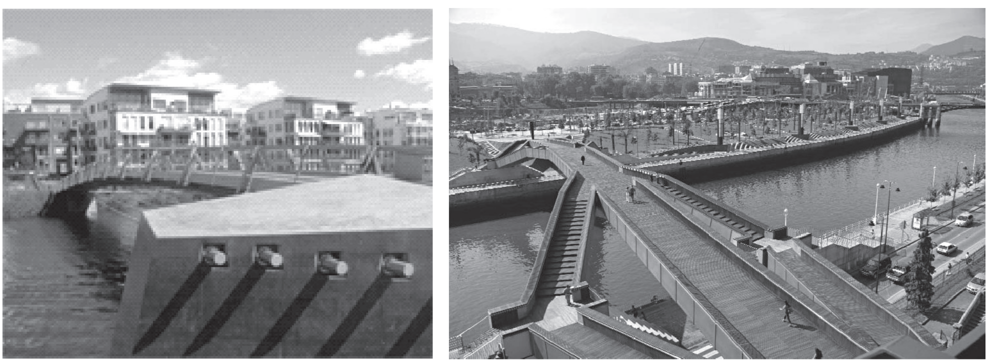

Fig. 3. Structural use of stainless steel in footbridges: Apate Bridge, Stockholm, Sweden (left) (source: www.paintsquare.com) and Padre Arrupe Bridge, Bilbao, Spain (right) [1]

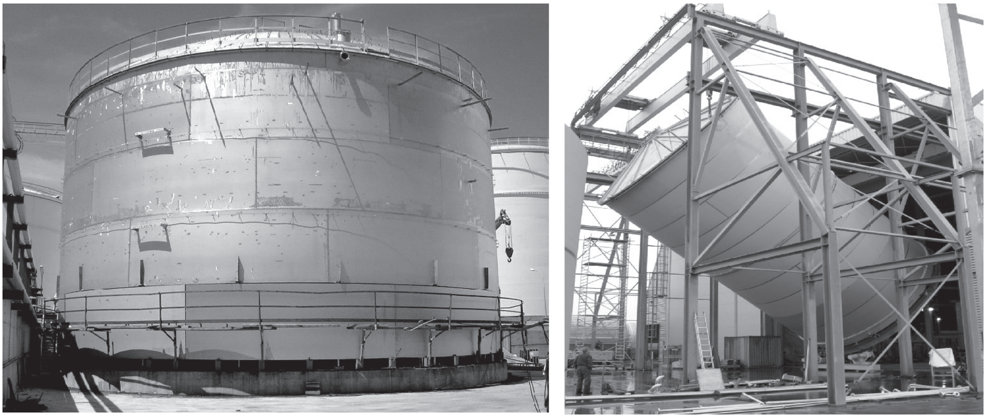

Fig. 4. Structural use of stainless steel in storage tanks: for pure acetic acid, Tarragona, Spain (left) and for biodiesel and edible oils (under construction), Amsterdam, the Netherlands (right) [30]

Fig. 5. The Porsche Pavillon, Wolfsburg, Germany [31]

Fig. 6. Stainless steel façade of ArcelorMittal – Stainless Service Poland Sp. z o. o. building in Siemianowice Śląskie, Poland [2]

Fig. 7. Example of structural use of stainless steel in Poland – tanks (305 m^3) for concentrated fruit juice, Spomasz Zamość S.A., Poland, A. Biczak – author of photography (left) and tanks (490 m^3) in sewage-treatment plant in Targowisko, municipality Kłaj, Poland, P. Żwirek – author of photography (right)

Fig. 8. Example of structural use of stainless steel in Poland – pipelines and tanks for terephthalic acid production line (under construction), ANWIL S.A., Włocławek, Poland (source: www.euroweld.pl)

In Poland stainless steel is still used mainly in architectural applications (Fig. 6). Structural use of stainless steel is still not very common. Stainless steel is utilized mostly in cases where exchange of the structural element will be very expensive due to production process continuity breaking (e.g. pipelines, tanks, chimneys). Selected examples of structural use of stainless steel in Poland are shown in Fig. 7–8.

For many investors low costs of structure erection is still main criterion of building material selection. High price of stainless steel causes that even in case of small structural elements like balustrades, when their number in structure is large, it is worth for investor commissioning design calculations with material and topological optimization of elements.

Fig. 9. Apartment complex "Wiślane Tarasy", Cracow, Poland (contractor: INTER-BUD, structural stainless steel elements design: K. Kuchta, P. Marzec, I. Tylek)

Typical examples of those types of stainless steel applications is apartment complex "Wiślane Tarasy" in Cracow (Fig. 9). In this apartment complex all external steel elements: balustrades, entrance roofs, benches, trash baskets, etc. are made of stainless steel. Original example of stainless steel realization, located in the same apartment complex, where aesthetic aspects were very important was 2800 mm high fountain with internal low-pressure vessel.

It should be expected that in Poland, just like in other countries, more and more often stainless steel will be selected for structures mainly because of its mechanical properties not only visual appearance.

8. Some statistics about stainless steels

Stainless steel as universal material uniting high corrosion resistance, good mechanical properties, high durability and ease of manufacture becomes more popular in building structures. Fig. 10 illustrates how stainless steel consumption changes in Poland for the last 10 years. Maximum and minimum increase of stainless steel consumption in relation to previous year was recorded in 2004 (+40%) and 2012 (+4%), respectively. In 2009, due to global financial crisis, stainless steel consumption in Poland decreased about 7% but as can be seen in Fig. 10 trend line for stainless steel consumption in Poland in the last ten years is ascending.

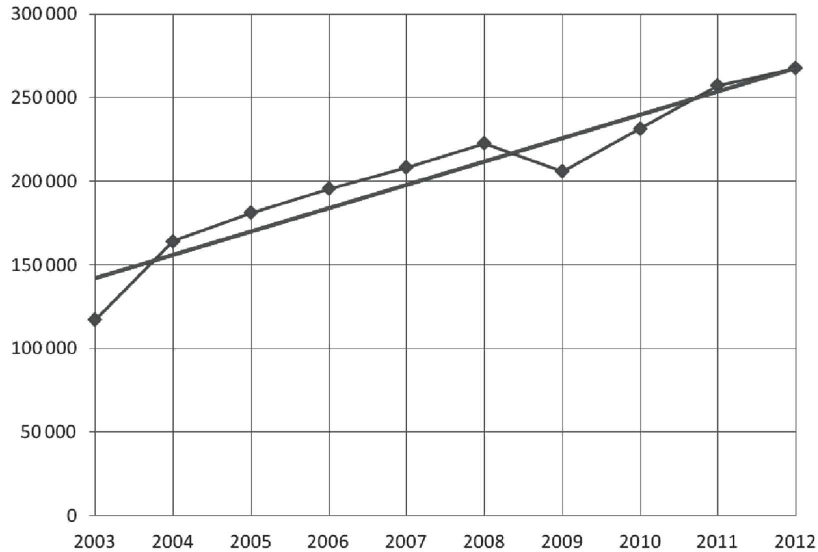

Fig. 10. Stainless steel consumption [t] in Poland in 2003–2012 [28]

The largest stainless steel distributor in Poland, Nova Trading S.A., achieved the mean annual growth of stainless steel sales for last 5 years at the level of 8%. In respect to stainless steel structural grades specified in Table 2.1 EN 1993–1–4 [8], the most popular among buyers was stainless steels: austenitic grade 1.4301 and ferrictic grade 1.4016.

In Poland the dominant was sale on stainless steel sheets and plates (hot– and cold rolled). Statistical data [28] indicates that 74% of 267 000 tones of sold stainless steel were sheets and plates, while consumption of tubes was equal about 17%, bars and profiles – about 2% and 4%, respectively.

One of the most important obstacle in common use of stainless steel structural elements is high price of stainless steel, currently about 4 times higher than price of carbon steel (compare Fig. 11 and Fig. 12).

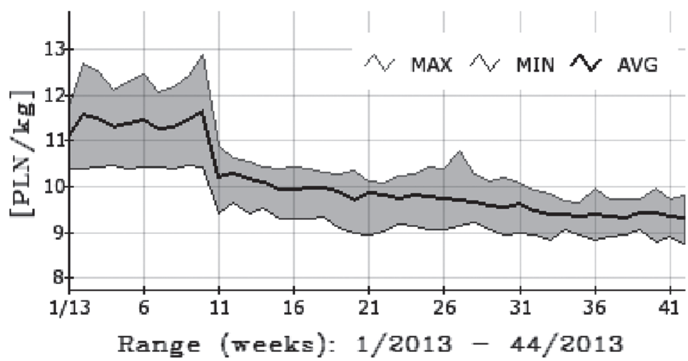

Fig. 11. Prices of 2 mm thick cold-rolled plate made of stainless steel grade 1.4301 with surface finish 2B [PLN/kg] according to The Stainless Steel Association – Stowarzyszenie Stal Nierdzewna (SSN) (source: www.stalenierdzewne.pl)

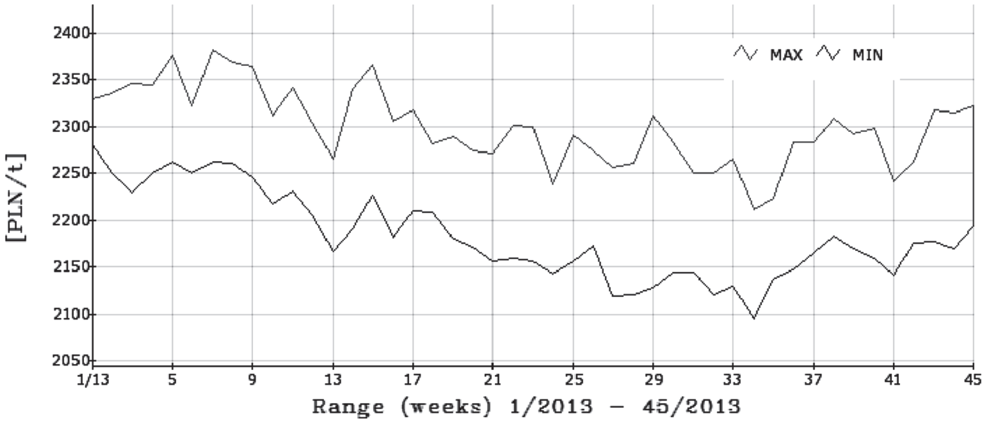

Fig. 12. Prices of 4 mm thick hot-rolled plate made of carbon steel grade S235JR2 (St3S) [PLN/t] according to The Polish Association of Steel Stockholders – Polska Unia Dystrybutorow Stali (PUDS) [www.puds.pl]

Stainless steel mill price is comprised of two parts:

– **the base production cost** that is set by the steel producer,
– **the Alloy Adjustment Factor** (AAF) that relates to the current price of alloy components.

Prices of stainless steel grade 1.4301 with division into base price and alloy surcharge on the German market in 2001–2010 are shown in Fig. 13.

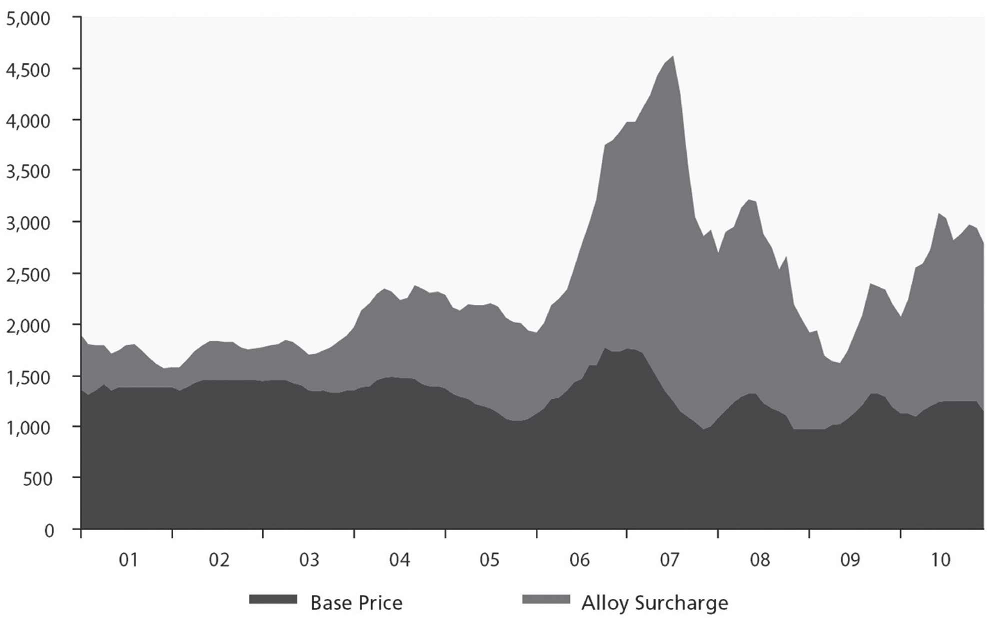

Fig. 13. Prices [x10^3 €/t] of stainless steel grade 1.4301 divided into base price and alloy surcharge on the German market in 2001–2010 [27]

The price of the stainless steel product is mostly determined by the price of alloying components (particularly nickel) that is not directly controlled by the producer or distributor. The costs of molybdenum purchase also influence AAF although not as much as the nickel price. Variation of nickel price for last 12 months and 5 years are shown in Fig. 14. It should be noted that during last 5 years change of nickel price reached more than 250%.

Fig. 14. Variation of nickel price [$/LB] on London Metal Exchange (LME) (source: www.metalprices.com)

Nickel price adversely affect development of stainless steel applications in structural buildings, firstly by causing high costs of stainless steel production, secondly by causing lack of stability of stainless steel price due to frequent changes of nickel price causes, what may lead to difficulties of execution an investment project that in building industry is often planned for several years.

The most influenced by nickel price are austenitic and austenitic-ferritic (duplex) stainless steels because they have the highest content of this alloying component from all structural stainless steels listed in Table 2.1 EN 1993-1-4 [8]. However duplex steels have even 1.5 times higher yield strength than other stainless steels what can results in lower material consumption, so global costs of investment will be less sensitive to nickel price fluctuations. Currently European Standard EN 1993-1-4 [8] specifies in Table 2.1 mechanical properties for only two grades of duplex structural stainless steels: 1.4362 and 1.4462.

9. Conclusions

Stainless steel due to its good mechanical properties and usable values becomes more and more often used for building industry, including load bearing elements and pipelines.
Without any doubt one of the factors that slows down development of stainless steel in structural buildings is high and unstable price of the material. Stainless steels high price may be compensated by reduction of material consumption by using steels with yield strength higher than for carbon steels, e.g. duplex stainless steels.

Increase of structural use of stainless steel is connected with growing consciousness about advantages of stainless steel use, e.g. no necessity of anti-corrosion coatings application and renewing, high durability of material, long life cycle of a structure which decrease real costs of investment. Apart from that, producers introduce new grades of stainless steel with high yield strength and low content of expensive nickel what creates conditions conducive to designing structural elements from stainless steels.

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