STAINLESS STEEL REINFORCEMENT – A SURVEY

NICHTROSTENDE BETONSTÄHLE – EIN ÜBERBLICK

ARMATURES EN ACIER INOXYDABLE – UN APERÇU

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SUMMARY

World-wide numerous stainless steel reinforcing steels are applied for the purpose of preventive corrosion protection of reinforced concrete structures. In this report the performance characteristics, the corrosion behaviour, practical experiences and existing standards are dealt with in a survey. It is shown that reinforced concrete structures, reinforced with suitable stainless steels can be classified as durable.

ZUSAMMENFASSUNG

Weltweit werden eine Reihe von nichtrostenden Betonstählen zum Zwecke eines vorbeugenden Korrosionsschutzes von Stahlbetonkonstruktionen angewendet. In diesem Bericht werden die Gebrauchseigenschaften, das Korrosionsverhalten, baupraktische Erfahrungen sowie bestehende Standards in einem Überblick behandelt. Es wird gezeigt, dass Stahlbetonkonstruktionen, die mit geeigneten nichtrostenden Betonstählen bewehrt sind, aus korrosionstechnischer Sicht als dauerhaft eingestuft werden können.

RESUME

Mondialement, de nombreuses armatures en acier inoxydable sont utilisées comme mesure de prévention contre la corrosion des constructions en béton armé. Ce rapport donne un aperçu sur les caractéristiques de fonctionnement, le comportement face à la corrosion, des expériences pratiques et les normes existantes. Il s'avère que les constructions en béton armé avec des armatures inox appropriées peuvent être classifiées durables du point de vue de la corrosion.

KEYWORDS: Stainless steel, reinforcement, corrosion, properties, specifications

1 INTRODUCTION

In reinforced concrete structures the concrete guarantees chemical and physical corrosion protection of the unalloyed reinforcement.

Loss of durability in reinforced concrete apart from problems caused by poor design and construction only occurs if the passivation oxide layer is rendered unstable (if depassivation occurs) due to carbonation of the concrete reducing the alkalinity of the pore solution in the hardened cement paste around the steel or to the ingress of chlorides to the steel /concrete interface [1-2].

There are several conventional options open to the designer when long life is required or corrosion is anticipated. One attractive technical solution is to apply a stainless steel based reinforcement [3-8].

Although the initial cost of stainless steel is much higher than that of carbon steel, its use can be justified on the basis that the increase in total project cost is small and is easily overtaken by the benefits of lower maintenance and repair costs, particularly where disruption times and costs for such work are taken into consideration.

Corrosion resistant materials for reinforcement may be used in the following applications:

- structures are exposed to attack of corrosion promoting substances,
- the concrete cover and the concrete quality is – by design or otherwise – reduced relative to the necessary values for the surrounding environmental conditions (e.g. in extremely slender elements),
- special structures have to be built, e.g. connections between precast and cast in place elements or heat insulated joints between the structure and external structural elements (e.g. balconies),
- prefabricated wall- and roof-elements where the reinforcement connects the outer and inner walls,
- non-dense or dense lightweight concrete is designed to reach a required thermal insulation as well as low ownweight,
- cases where access to the structure is strongly limited, making future inspection and maintenance costly, such as in underground structures in aggressive soil

- and where future maintenance is possible but may cause extreme indirect costs due to non-availability, such as in bridges in the main traffic arteries of densely populated areas.

There exist recommendations for a convenient use of stainless steel reinforcement [3,5,9,10]. The decision on which type of stainless steels to use depends on:

- the degree of corrosion protection required,
- cost aspects,
- workability and application characteristics (mechanical and physical properties, weldability).

Typical applications where reductions in maintenance costs warrant the use of ferritic-austenitic and austenitic stainless steels include offshore structures, piers at the sea coast, parts of highway structures subject to de-icing salts or splash, multi-storey car parks, plants for the desalination of sea-water, concrete elements in thermal bath and each kind of repair work. A guidance on locations where use of stainless steel reinforcement is recommended in new highway structures is published in [10]. It is possible to substitute all carbon steel reinforcement on a structure with corrosion resistant reinforcement but this would nearly always too expensive to justify. Replacement with stainless steel reinforcement should be limited to those major components where the consequences of future repair are likely to be highly disruptive and costly and the possibility of chloride attack is likely.

Components of highway structures that may meeting these requirements include

- Decks of bridges carrying heavily trafficked roads over busy railway lines with limited possessions for repair,
- exposed piers and columns in centre reserves (but not deeply buried elements),
- deck slabs where access for maintenance is going to be very difficult because of traffic levels.

An alternative approach is to use stainless steel reinforcement selectively in conjunction and also contact with carbon steels. It is not envisaged that stainless steel will replace any really significant part of the massive tonnage of the present carbon steel reinforcement output.

The applications of stainless steels must not be restricted to chromium-nickel-(molybdenum) steels with austenitic and ferritic-austenitic structure. Ferritic chromium-alloyed steels might be the best choice in moderate aggressive environments, e.g. in carbonated normal and lightweight concrete if chloride attack can be excludet, where the higher resistance of the more expensive stainless steels is not necessary.

2 STEEL TYPES [1,11]

The term stainless steel does not refer to a single specific material but rather to a group of corrosion resistant high alloyed steels, which in contrast to unalloyed steels do not show general corrosion and noticeable rust formation in normal environmental conditions (atmosphere, humidity) and in aqueous, nearly neutral to alkaline media. Basic requirement for the before-said reaction is a minium concentration of that steel on particular alloying elements and the existence of an oxidising agent (e.g. oxygen) in the surrounding medium. This causes a passivation of the surface. „Passivitiy" describes a condition that produces a strong inhibition of the reaction of resolving iron after forming a passive layer on the surface. Chromium, in particular, is an element that tends to passivation. A self-forming inert chromium oxide layer on the surface of the material protects against corrosion. In the event of the protective surface layer being damaged, it is self-healing in the presence of oxygen. This property is transmitted on iron resp. steel through alloying: General corrosion decreases in corrosion-promoting media contrary to the content of chromium (see Fig. 1). The content of chromium that causes passivity when exceeded depends on the attacking agent. The content of chromium in water and in the atmosphere should at least be 12 M.-%. Corrosion resistance may be further improved by additions of further alloying elements. Chromium, molybdenum and nitrogen are important elements in relation to pitting corrosion. Nickel especially increases corrosion resistance in acid media.

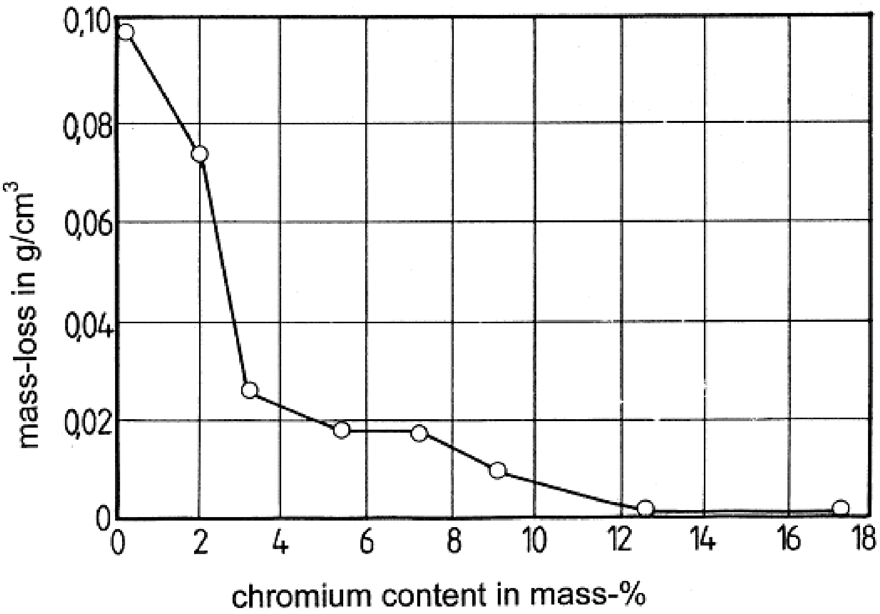

Fig. 1: Corrosion of chronium steels in industrial air (Binder and Brown in [11])

Changing the balance of the alloying elements (chromium, nickel, molybdenum, nitrogen, titanium and others) will influence the structure as well as the other properties such as corrosion behaviour, mechanical and physical properties and weldability. Therefore members of the stainless steel family are usually grouped in groups having the same metallographic structure. Within the area of concrete reinforcement three types of stain-less steels are in question and are available in the adequate product form. These are ferritic, austenitic and ferritic-austenitic (duplex). Interest in the use of these alloys as reinforcing steel for concrete is due to their increased resistance to corrosion particularly in chloride containing media, but particular technological characteristics are aimed at with regard to processing and application, as well. However increasing the alloy level the cost of the material will also increase. Therefore it is important to select steel types at an alloy level which are sufficiently corrosion resistant for the job to be done and with sufficient mechanical properties and weldability.

In common conditions, that prevail in construction engineering (attack of light acid to alkaline aqueous media), **ferritic steels** with about 11 to 30 M.-% of chromium have a sufficient resistivity against general corrosion. With an addition of a sufficient content of chromium and molybdenum up to about 2 M.-%, resistivity against pitting corrosion can be achieved as well. Besides, ferrites have a high resistivity to stress corrosion cracking in an environment containing chlorides. Above all, if you assume comparable contents of chromium, the reaction of ferritic steels towards crevice corrosion is much more adverse than it is e.g. at austenitic steels.

Ferritic steels are ferromagnetic. An adventage of these steels in comparison with austenites is the higher yield stress in the as-rolled condition. Advers is the low fracture-elongation, the more difficult workability and the brittleness at low temperatures. The workhardening during cold forming is low in comparison with austenitic steels. They are not so readily weldable as the other types.

Austenitic steels have between 17 to 25 M.-% of chromium and 8 to 26 M.-% of nickel. These steels are especially used because of their positive corrosion properties and their superior workability in comparison with other stainless steels. In case of a proper content of alloy, they have got a high resistivity to general corrosion, pitting corrosion and crevice corrosion, but are sensitive to stress corrosion cracking in their typical compound with about 10 M.-% nickel. The resistance to pitting corrosion, crevice corrosion and stress corrosion cracking can be improved with an addition of chromium, molybdenum and nickel.

Austenitic steels are not ferromagnetic. They have a higher toughness and a much better weldability but a lower yieldstress in the as-rolled condition than ferritic steels. The tendency to workhardening is very pronounced. For that reason austenites can increase their strength evident by means of cold forming without unacceptable reduction of deformability. The ductility of austenitic stainless steel always exceeds that of conventional bars and they have a very high toughness and good ductility properties at low temperatures. In seismic areas, austenitic steels are often used in reinforced concrete structures, as their strength and ductility intensify the material´s specific deformation energy. This is advantageous for absorbing the impact of a violent earthquake.

Ferritic-austenitic (duplex) steels have a binary structure of ferrite and austenite. The typical range of their chemical analysis is 22 to 28 M.-% of chromium, 4 to 8 M.-% of nickel. Molybdenum can be added in order to improve the corrosion resistivity. These steels combine good properties of ferritic steels (high yield strength) and austenitic steels (good ductility, improved corrosion properties). Owing to their excellent mechanical properties (high yield strength, good ductility) in already the as-rolled condition and the very high resistivity to chloride attack, duplex steels are of interest as material for reinforcement.

Table 1a: Ferritic steel - chemical composition according to [13]

Steel designation		% by mass											Grades
Steel	Steel No.	C	Si	Mn	P	S	N	Cr	Mo	Ni	Ti	Others	
X3CrNb 17	1.4511	≤ 0,05	≤ 1,00	≤ 1,00	≤ 0,040	≤ 0,015	-	16,0 to 18,0	-	-	-	Nb: 12xC to 1,00	InE235
X2CrNi 12	1.4003	≤ 0,03	≤ 1,00	0,50 to 1,50	≤ 0,040	≤ 0,015	≤ 0,03	10,5 to 12,5	-	0,30 to 1,00	-	C+N≈ 0,03	InE500

Table 1b: Austenitic steels - chemical composition according to [13]

Steel designation		% by mass											Grades
Steel Name	Steel No.	C	Si	Mn	P	S	N	Cr	Cu	Mo	Ni	Others	
X5CrNi 18-10	1.4301	≤ 0,07	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,030	≤ 0,11	17,0 to 19,5	-	-	8,0 to 10,5	-	InE235, InE500, InE650
X2CrNiN 18-10	1.4311	≤ 0,030	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,030	0,12 to 0,22	17,0 to 19,5	-	-	8,0 to 11,5	-	InE235, InE500, InE650
X5CrNiMo 17-12-2	1.4401	≤ 0,07	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,030	≤ 0 ,11	16,5 to 18,5	-	2,0 to 2,5	10,0 to 13,0	-	InE235, InE500, InE650
X2CrNiMoN 17-13-3	1.4429	≤ 0,030	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,015	0,12 to 0,22	16,5 to 18,5	-	2,5 to 3,0	11,0 to 14,0 b	-	InE235, InE500, InE650
3CrNiMo 17-13-3	1.4436	≤0,05	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,030	≤ 0,11	16,5 to 18,5	-	2,5 to 3,0	10,5 to 13,0 b	-	InE235, InE500, InE650
X6CrNiMoTi 17-12-2	1.4571	≤0,08	≤ 1,00	≤ 2,0	≤ 0,045	≤ 0,030	-	16,5 to 18,5	-	2,0 to 2,5	10,5 to 13,5 b	Ti:5xC to 0,70	InE235, InE500
X1NiCrMoCu 25-20-5	1.4539	≤ 0,020	≤ 0,70	≤ 2,0	≤ 0,030	≤ 0,010	≤ 0,15	19,0 to 21,0	1,2 to2,0	4,0 to 5,0	24,0 to 26,0	-	InE235, InE500, InE650
X8CrMnCaB 17-8-3	1.4597	≤ 0,10	≤ 2,00	6,5 to 8,5	≤ 0,040	≤ 0,030	0,015 to 0,30	16,0 to 18,0	2,0 to3,5	≤ 1,00	≤ 2,0	0,0005 to 0,0015	

Table 1c: Ferritic-austenitic (duplex) steels - chemical composition according to [13]

Steel designation		% by mass											Grades
Steel Name	Steel No.	C	Si	Mn	P	S	N	Cr	Cu	Mo	Ni	Others	
X2CrNiMoN222 -5-3	1.4462	≤ 0,030	≤ 1,00	≤ 2,00	≤ 0,035	≤ 0,015	0,10 to 0,22	21,0 to 23,0	-	2,50 to 3,50	4,50 to 6,50	-	InE500, InE650, InE800

Table 1 lists the chemical composition of the main stainless steels suitable for the manufacturing of reinforcing stainless steels. This survey was taken from a common European standard [12] which at this time is in preparation. It was added by the ferritic steel type 1.4003 which is used in Germany and other countries. The numbers of the steels are according to European Standard codes as given in EN 10088 [13].

For particular types of corrosion, e.g. pitting corrosion and stress corrosion cracking, the existence of a passive layer is a necessary requirement. Because of that, passive steels are resistant against general corrosion, but are sensitive to local corrosion in presence of specific media (e.g. chloride ions) in case of an insufficient content of alloy. There are four types of corrosion of stainless steels to be observed: general corrosion, intergranular corrosion, pitting corrosion and stress corrosion cracking.

3 PRODUCTION OF STAINLESS STEEL REINFORCEMENT [3,1,16]

For application in concrete structures, ferritic, austenitic and ferritic-austenitic (duplex) steels can be produced as ribbed bars within the normal range of strength and deformability requirements. Up to 14 mm diameter the bars are available in rings permitting the confection of any shape and length of reinforcing bar. Above 14 mm diameter the bars are supplied in straight lengths (length up to 12 m are available in the UK).

One of the initial problems in producing stainless steel reinforcing bars was that the yield strength $Rp_{0.2}$ of ferritic and above all austenitic as-rolled bares were approximately the same as those of mild steel. The general mechanical properties in the annealed condition are such that the yield strength of ferritic and austenitic types are about 300 N/mm^2 respectively 200 N/mm^2 where as the corresponding values for duplex steels are higher (400 - 480 N/mm^2). Therefore no ferritic or austenitic standard steel in the normal as-rolled condition would have sufficient strength.

However, in order to meet the requirement for use as reinforcement in concrete the strength of the steels must be increased. As these steels had a metallurgical structure incapable hardened significantly by heat treatment other methods of increasing strength had to be pursued.

Subsequent treatment, either special heat treatment or cold and warm working, the latter also with a nitrogen addition, will enable high yield reinforcement strength to be reached. These processes are however complicated and increase the high material cost of stainless steel.

Ferritic steels in the as-rolled condition have a higher yield strength than austenitic steels. There is a certain probability that the bars may be further strengthened by cold twisting [14] or drawing and cold rolling [15]. These processes can be facilitated by employing a special alloy composition. In this, the carbon and nitrogen contents are limited to avoid hardening after cooling from the austenite phase. The steel retains sufficient strength and deformation properties after cold deforming from 4 to 14 mm diameter. In addition to strengthening the bars, twisting is also an effective methods of removing millscale, which has been found to aggravate pitting corrosion and was previously removed by pickling and shot blasting.

Acceptable high yield reinforcing bar strengths can be obtained from **austenitic stainless** steels. The lower dimensions from 4 to 14 mm may be strengthened by means of cold working (drawing and rolling) [15-17]. For the austenitic types cold working results in a reduction of the elongation from 40 % to 20 - 25 %, which is beneficial for the function of the rebars in concrete.

The literature [18] sometimes makes reference to the possibility of a somewhat reduced corrosion resistance of cold worked austenitic stainless steel whereas in duplex materials this is not the case. Cold working of austenitic stainless steel may cause a transformation of some of the austenite into martensite. Alloys with a lower content of alloying elements (e. g. 1.4301) are more prone to develop martensite than alloys with a higher content (e. g. 1.4539) (see section 4.2). Martensite is in the position to favour pitting corrosion. However, the amount of cold work of reinforcing steel does not exceed about 35 % which results not in a damaging martensite formation and a reduction of the pitting corrosion resistance [15].

For small dimensions (< 12 mm) also warm working at reduced temperature may be used for increasing the strength of austenitic steels resulting in mechanical properties similar to those obtained by cold working [16,17]. An effective solution for large diameter bars up to 40 mm for ribbed bars and 50 mm for plain bars is the combination of using a modified composition (an addition of 0.15/0.20 M.-% nitrogen) and the warm working process.

Owing to their excellent mechanical properties in the as-rolled condition, duplex stainless steels are of interest as materials for reinforcements. In Germany [15] such wires are cold deformed, in Italy [19] they are as-rolled or cold deformed.

In principle manufacture of stainless steel reinforcement by hot and cold deforming does not distinguish from production of mild steel reinforcement. Another development, which can significantly reduce the cost, involves producing a stainless steel clad reinforcing bar [20]. In this approach, a core of ordinary steel is encapsulated in a stainless steel sheath to resist corrosion. However, the difficulties associated with inserting the core and fusing the metals together added to the cost which thereby offset the savings resulting from the use of a cheaper core. Furthermore, of pinholes were present in the cladding there was a potential problem of 'undercutting' corrosion [17]. At that time improved products are on the market in UK.

4 STRUCTURAL PROPERTIES

Mechanical and physical properties as well as welding behaviour are very important in order to evaluate the ability of any material to withstand the expected loads during the designed service life. These depend on the method of manufacture, material composition respectively microstructure and bar size.

4.1 Mechanical properties

The mechanical properties of stainless steels that are of main concern to the designer are characteristic strength, ultimate tensile strength and elongation. The stress-strain-behaviour of austenitic and duplex grades differs from that of carbon steels in that they do not exhibit a well-defined yield point when test pieces are submitted to tensile load. To characterise the design strength of such materials, proof strengths are used and are determined as the stress $Rp_{0.2}$ of 0.2 %. After [9] a modulus of elasticity for austenitic and ferritic-austenitic stainless steel reinforcement of 200 KN/mm^2 may be used in design, except for the austenitic steel 1.4529, which has a modulus of 195 KN/mm^2. The Tables 2 – 4 show typical properties for different steel grades from UK, Germany and Italy.

Temperature influence

Austenitic stainless steels in the warm deformed condition retain considerably higher strength than carbon steels, ferritic and ferritic-austenitic(duplex) stainless steels at **elevated temperatures** [4,9]. At temperatures up to 500 °C, there is negligible reduction in the 0.2 % proof stress. This suggests that concrete elements reinforced with austenitic stainless steel will behave better in fire than conventionally reinforced elements with the same depth of cover.

The increase in strength of stainless steels from cold working process gradually reduces with increasing temperature. At 500 °C, austenitic stainless steels exhibit a marginal decrease in the 0.2 % proof strength and a significant reduction in the ultimate tensile strength. The strength of heated cold deformed reaches the strength of annealed material at a little over 800 °C.

Table 2: Mechanical properties of stainless reinforcing steels in UK (from [16] and steel maker information)

steel grade	chemical composition	condition	bar size	yield stress	tensile stress	elon-gation
			mm	$N\ mm^{-2}$	$N\ mm^{-2}$	%
1.4401 austenitic	X5CrNiMo 17-12-2	warm worked [1)]	10	865	1000	20
			20	745	880	25
			32	620	775	25
			40	550	685	25
		as rolled [2)]	25	279	579	52
		cold twisted [2)]	20	660	780	28

[1)]minimum values [2)]values of specific specimens

Table 3: Mechanical properties of stainless reinforcing steels in Germany (from [15] and steel maker information

steel grade	chemical composition	condition	bar size	yield stress	tensile stress	elon-gation
			mm	$N\ mm^{-2}$	$N\ mm^{-2}$	%
1.4429 austenitic	X2CrNiMoN 17-13-3	hot rolled [4)]	10	880	990	20
			20	790	900	25
			32	630	790	25
			40	550	790	30
1.4571 austenitic	X6CrMiMoTi 17-12-2	cold rolled [3)]	10[1)]	456	599	39
1.4462 ferr.-aust.	X2CrNiMoN 22-5-3		7[1)]	870	934	13
1.4003 ferritic	X2CrNi 12		8[1)]	518	608	16
		hot rolled [2)]		~350	~490	~25

[1)]6-14 mm is possible [2)]no reinforcing steel
[3)]values of specific specimens [4)]minimum values

Table 4: Mechanical properties of stainless steels in Italy (from [19] and steel maker information)

steel grade	chemical composition	condition	bar size	yield stress[1)]	tensile stress[1)]	elongation[1)]
			mm	N mm^{-2}	N mm^{-2}	%
1.4301	X5CrNi 18-10	cold finished	10	671	831	21.4
1.4307	X2CrNi 18-9	hot rolled	20	761	864	27.9
1.4401	X5CrNiMo 17-12-2		32	754	863	25.9
1.4404	X2CrNiMo 17-12-2		40	717	878	31.1
1.4571	X6CrNiMoTi 17-12-2					
1.4462	X2CrNiMoN 22-5	cold finished	10	950	1059	14.0
1.4362	X2CrNiN 23-4	as rolled	18	485	668	-

[1)]Values of specific specimens

For example, liquefied natural gas is stored at a **low temperature** of -165 °C and liquid oxygen below -190 °C. Any materials forming part of a containment system for such gases must have satisfactory and predictable properties at these temperature to avoid failure. Austenitic stainless steel reinforcement, which retains ductility to temperatures as low as -196 °C, is suitable for use in such applications [4,9], unlike carbon steel, which exhibits a transition from ductile to brittle behaviour well above this temperature. The ultimate tensile strength and the 0.2 % proof stress increase slightly with descending temperature. The elongation decreases. Ferritic-austenitic (duplex) and above all ferritic stainless steels undergo a marked decrease in toughness at sub-zero temperatures. These steels are not recommended for cryogenic applications.

4.2 Physical properties

The important physical properties of stainless steel considered in relation to application in concrete are: density, thermal conductivity, coefficient of thermal expansion and magnetic permeability. In Table 5 typical values of these parameters for different types of stainless steel in the annealed condition are collected.

From the structural point of view, the most important physical property is the coefficient of linear thermal expansion [3]. The coefficients of thermal expansion of ferritic steel and concrete are more or less the same (1.2 and 1.1 x 10^{-5} °C^{-5}respectively). In comparison, the coefficient of thermal expansion of austenitic stainless steel is higher (1.7 x 10^{-5} °C^{-5}). If a concrete structure with austenitic reinforcement is exposed to high temperatures, tensile stresses will be produced in the uncracked concrete as a consequence of the different thermal coefficient of steel and concrete. This may in theory cause some minor defects in the contact zone and expansion cracking, particularly in heavily reinforced sections. However, there is no practical evidence or laboratory results supporting this assumption. Compared to carbon steels, the higher coefficients of thermal expansion for the austenitic steels, and the lower thermal conductivities, may rise to greater welding distortions (section 4.3).

Table 5: Physical properties of stainless steel

	Density g/cm^3	Thermal conductivity W/m · °C	Specific heat J/g · °C	Coefficient of thermal expansion cm/cm · °C	Magnetic
Ferritic steel	7,7	23	0.46	$1{,}2x10^{-5}$	Yes
Austenitic steel	7,8-8,0	12-15	0.44	$1{,}7x10^{-5}$	No
Martensitic steel	7,7	23	0.46	$1{,}2x10^{-5}$	Yes
Duplex steel	7,7	20	0.44	$1{,}3x10^{-5}$	Yes

Ferritic stainless steels are (ferro-)magnetic, as are carbon steels. The magnetic behaviour of the various types of austenitic steel varies, but they have low magnetic permeabilities compared to other ferrous steels and are generally considered to be non-magnetic.

Relative magnetic permeability is defined as the ratio of the magnetic flux density produced in the material to that produced in free space by the same magnetising force; thus the lowest achievable magnetic permeability is 1. For austenitic stainless steels magnetic permeability depends on chemical composition and production process. Concerning the steel grade magnetic permeability decreases in the designation order 1.4301 - 1.4401 - 1.4436 - 1.4429 - 1.4529. However, the values varies with production process, e.g. values for cold-drawn steel bar are greater than for bar that has been warm-worked. Heavy cold working, particularly of the lean alloyed austenitic steel, can also increase magnetic permeability; subsequent annealing would restore the non-magnetic properties. Cold working produces phase transformation from austenite to martensite (section 3). These strain induced martensite phases are magnetic and increases magnetic permeability. In particular the more highly with chromium, manganese, nickel, molybdenum and nitrogen alloyed grades have a increased austenite stability and are effectively non-magnetic after cold deformation (lit. in [21]). So, bars required to have a low permeability (~ 1.005) must be hot-rolled and/or of a specific composition.

4.3 Weldability

All stainless steel can be welded either to themselves or to carbon steel provided that necessary precautions are taken [4,9]. However, welding method and type of weld should be considered. Welding of reinforcement can be made by resistance welding as well as metal arc welding. As most materials used for reinforcement have been strengthened by cold working, reduction of strength at the weld is possible depending of the heat input applied.

Resistance welding is the most widely used welding method in factories. For instance, it is used for prefabrication of mesh reinforcement. Resistance welding having generally the lowest heat input will have the least effect on the properties. On the other hand, it requires well adjusted parameters in order to obtain a mechanical connection which is able to transfer sufficient force. This is done by optimising the electrical parameters along with the press force by welding.

Gas metal arc welding (MIG/MAG) is the most frequently used method for welding carried out on site. It is a very rational method for joining crossing rebars. When arc welding reinforcing bars some loss of tensile and yield strength may result from the welding heat. Consequently it is advisable to adjust the welding parameters resulting in shortest possible welding time and the best possible gas shielding. The latter is in order to minimise oxide formation. Gas mixture used is 96 % argon, 3 % CO_2 and 1 % hydrogen. If the weld products (temper colours) followed by high heat input metal arc welding are not completely removed, corrosion resistance is reduced. Pickling or shot-blasting the weld can often solve this problem, but is not always on construction sites.

The weldability of stainless steel depends on its structure and chemical composition. The weldability of the steel types is best for the austenitic types, similar but more restricted for the duplex materials and very limited for the ferritic ones. Weldability is improved by decreasing the carbon content, increasing the nickel content and by stabilisation. As a rule low carbon grades of stainless steel with max. C = 0.03 % or with titanium or niobum stabilised grades can be welded without fear of any detrimental effect.

In comparison with carbon steel, the higher thermal expansion of austenitic stainless steel coupled with its lower value of thermal conductivity, increases the possibility of distortion occurring during the welding process. However, the higher electrical resistance of stainless steel is an advantage because it results in the generation of more heat for the same current. Together with the low heat conductivity this can be advantageous when resistance welding processes are used.

When welding the duplex stainless steels, it is the cooling rate which controls the microstructure, therefore the heat input should be controlled in conjunction with the material thickness to obtain the correct weld structure.

Because stainless steel concrete reinforcing bars have different chemical compositions it is important to select welding electrodes or wires which result in welds with identical or better composition to those of the bars. That provide weld filler with corrosion resistance properties as nearly identical to the base metal. Proper weld rod selection not only preserves corrosion resistance properties, but is also important in achieving optimum mechanical properties.

When welding stainless steel to carbon steel the electrode or wire has to be higher alloyed than the stainless steel that is to be welded in order to compensate for the diluting effect of the carbon steel. The chemical composition of weld, depending only on the welding electrode or wire used, shall not be too lean in alloying elements as otherwise brittle welds are the result. As a minimum the weld should have the composition of stainless steel type 1.4301. This can be achieved with an electrode or wire that contains at least 23 % chromium and 12 % nickel.

5 CURRENT SPECIFICATIONS

UK

BS 6744 [22] was one of the first standards covering stainless steel reinforcement. This standard specifies stainless hot-rolled and cold-worked steel bars to achieve characteristic strength levels of 500 N/mm^2 or higher. Strength grades are defined in Table 6. The 200 grade steel is only available as plain bar.

In the UK stainless steel is currently produced from the austenitic and ferritic-austenitic materials 1.4301, 1.4436, 1.4429, 1.4462, 1.4501, 1.4529. They are listed from left to right in order of increasing corrosion resistance and, consequently, of increasing initial cost. In most situations standard austenitic grades 1.4301 or 1.4436 will provide an acceptable solution when designing against corrosion. The higher grade austenitic and ferritic-austenitic steels should be considered when the possibility of high levels of chloride build-up in concrete over time is anticipated (e. g. marine structures, traffic structures heavy contaminated with de-icing salts). The mentioned materials are typically available in all three strength grades; however the duplex steel designation 1.4462 is only available in 650 grade.

The range of sizes of bars shall be from 3 mm to 50 mm. Typical mechanical properties are listed in Table 2.

Table 6: Minimum tensile properties

Strength grade	0.2 proof strength $R_{p0.2}$ (N/mm^2)	Stress ration $R_m/R_{p0.2}$ (N/mm^2)	Elongation at fracture A_3 (%)	Total elongation at maximum force A_m (%)	Nominal size (mm)
200	200	1.10	22	5	3-50
500[1)]	500	1.10	14	5	6-50
650	650	1.10	14	5	3-25

[1)]Recommended grade

Germany

In Germany there exist an approval of the Deutsches Institut für Bautechnik in Berlin concerning stainless reinforcing steels [23]. The application of these steels has up to now been limited because of the high price.

Small diameters of 4 to 14 mm are cold rolled plain or ribbed bars and are of the ferritic type 1.4003, the austenitic type 1.4571 and the ferritic-austenitic (duplex) type 1.4462. The wires are weldable and also used for welded wire mesh. Typical mechanical properties are documented in Table 3. The strength grade corresponds to the British strength grade 500, but the elongation at fracture is 10 %. It is recommended to use the grades 1.4571 and 1.4462 if the possibility of high levels of chloride are to be expected.

The steel grade 1.4003 may be used if quick carbonation of concrete cover can not be excluded reliable.

Further in Germany bars of 10 to 40 mm are offered in the hot rolled condition. With the austenitic steel grade of 1.4429 a yield stress of 550 to 880 N/ mm^2 can be reached (Table 3).

USA

In the USA, stainless steel reinforcement is specified in ASTM A955M - 2001 [20], which covers deformed bar in a wide range of alloys and plain stain-

stainless steel clad carbon steel bars from 9,5 to 57,3 mm diameter. In particular austenitic stainless steels with designation numbers 1.4429 and 1.4404 are often used, an typical ferritic-austenitic (duplex) stainless steels are types equivalent to 1.4462. They are generally of one of three minimum yield levels, 300, 420 and 520 N/mm^2, designated as grade 300, 420 and 520, respectively.

Other countries

In Denmark, cold rolled weldable austenitic stainless steel smooth and profiled bars of the types 1.4301 and 1.4401 are in use [24]; dimensions from 4 - 16 mm are available. Resistance welding is the most widely used welding method. For instance, it is used for prefabrication of mesh reinforcement. MIG/MAG welding is the most frequently used method for welding carried out on site. In other Scandinavian countries also steel types 1.4301 and 1.4401 are specified. In particular in Norway and Finland the steel type 1.4436 has been used.

In Italy, mainly austenitic stainless steels 1.4301 and 1.4401 and ferritic-austenitic (duplex) steels of grade 1.4462 and 1.4362 have been used in reinforced concrete structures (Table 4).

In France, the low austenitic carbon steel types 1.4307 and 1.4404 are specified.

Many specifications in the Middle East are based on BS 6744 [22], particularly using 1.4401 steel. Duplex steel 1.4462 has been used in repair contracts in the Middle East. In parts of Far East, such as China, Japan and India, the American codes are generally used.

European standard

At present a common European standard [12] is in preparation. This standard specifies the requirements for the chemical composition, mass per unit length, dimensional, mechanical, technological and shape properties of bars and coils (wire rod and wire) of reinforcing stainless steel, smooth of grade InE235 and smooth, ribbed or indented of grades InE500, InE650 and InE800, with a nominal diameter between 5 mm and 50 mm. The designation of reinforcing stainless steels covered by this standard consists of the indication of the specified proof strength of the product.

The tensile mechanical properties shall be in accordance with the requirements of Table 7. The specified values are a 0.05 fractile for $R_{p0.2}$ and 0.10 fractiles for the ratio $R_m/R_{p0.2}$ and A_{gt}, to which minimum values are associated.

Table 7: Mechanical properties in [12]

Steel grade	0.2 % Proof strength $R_{p0.2}$ (Mpa)		Ratio $R_m/R_{p0.2}$		Total elongation at maximum force A_{gt} (%)	
	Fractile value	Minimum value	Fractile value	Minimum value	Fractile value	Minimum value
InE235	235	220	1,15	1.12	8	7
InE500	500	475	1.10	1.08	5	4
InE650	650	625	1.10	1.08	5	4
InE800	800	775	1.10	1.08	5	4

The Table 1a - c lists the chemical composition of the main stainless steels, suitable for the manufacturing of reinforcing stainless steels. For each of these steels, the grades that are possible to get are indicated in the last column of the tables; getting these grades depends on the diameter of the product, its manufacturing process (hot or cold rolling) and its profile (smooth, indented or ribbed). The steels mentioned may be welded under certain conditions.

For the proposed steels in Table 1 (excepting the steel 1.4003)), the standard gives guidlines for the selection of stainless steels depending on the conditions of use and environment as well as example of application. However, this recommendation for use is not quite straight, too complicated and seems not to be covered by research and practical experience.

6 PRACTICAL EXPERIENCES WITH APPLICATION

Stainless steel reinforcement have been used in concrete structures in UK, USA, Italy, France, Denmark, Norway, Sweden, Finland, Germany, in the Middle and Far East and South Africa. Typical applications of stainless steel reinforcement are structures which are exposed to very aggressive environments.

Only relatively small quantities of stainless steel reinforcement have been used in the past. However, an increasing amount of austenitic or ferritic-austenitic (duplex) steel reinforcement is to be found in bridge engineering, multi-storey car park decks, tunnels and underpasses, retaining walls, marine structures like piers at the sea coast, where influence of seawater or de-icing salt cannot be excluded, and historic buildings and buildings with long service lives [4,5,9,10,25,26]. Further these steels are generally located at construction joints or critical gaps between columns and deck.

Ferritic stainless steels are used as reinforcement in pre-cast elements of normal-weight and light-weight concrete. Another typical application is in pre-fabricated wall elements with inner heat insulation where the reinforcement connects the outer and inner concrete walls [6].

The experiences are positive; core samples taken after some years and long-term monitoring of embedded corrosion probes showed no sign of corrosion of the stainless steel reinforcement [5,9]. However, there exist no extensive long-term experiences with the use of stainless steels as reinforcement in concrete. In [27] a case of long-term application of stainless steel reinforcement (steel grade 1.4301) from Mexican Gulf is reported. Due to the harsh environmental exposure of concrete piers (hot and humid marine environment) it was decided to use stainless steel in selected areas. 60 years after construction no significant corrosion was found for the reinforcement with a cover larger than approx. 20 mm, despite the extremely high chloride contents of up to 1.9 % Cl^- of dry concrete weight. For other piers at the same place reinforced with ordinary carbon steel serious chloride and/or carbonation-induced corrosion problems occurred.

1.4571 (X6CrNiMoT 17-12-2) had been stored and sprayed under conditions of parking decks and walls by the road side exposed to chloride containing water. The concrete was of medium quality; the concrete cover was 2.5 and 5.0 cm and the crack widths 0.05 to 1 mm. The cracks were carbonated artificially.

During the storage the corrosion potential of the steel was measured continuously, to detect the start of corrosion inside concrete cracks. Some beams were opened to reveal the state of the bars.

In the case of unalloyed steel, there existed an essential drop of corrosion potential, when the chloride reached the reinforcement in the concrete cracks and the steel became active after 1 to 3 months. Concerning the corrosion resistant reinforcement, the steel remained passive over the whole testing time of 2.5 years.

After breaking up some beams strong corrosion was found in the concrete cracks if the crack width exceeded 0.1 mm in the case of unalloyed steel. No serious corrosion was detected on the high alloyed steels up to a crack of 1 mm. Stainless steel reinforcement of type 1.4462 and 1.4571 is suitable for the very unfavourable case of highly chloride contaminated cracked concrete.

7 CORROSION BEHAVIOUR

The informations collected in [3] have shown that stainless steel offers excellent resistance to corrosion in concrete structures exposed to aggressive environment.

As opposed to carbon steels which is protected by a passive film only in alkaline environments, the protective film which forms on stainless steel is stable in alkaline to neutral and slightly acid environments. Consequently, stainless steels do not suffer general corrosion and will not corrode even in carbonated concrete.

Stainless steel reinforcement has a much higher corrosion resistance against chloride attack and can withstand much higher chloride contents compared to the normal carbon steel; however also stainless steels can be subjected to localised corrosion if the chloride content in the concrete resulting from seawater or de-icing salts exceeds a certain critical value.

Such threshold values depend on the chemical composition and microstructure of the stainless steels ,surface finishing and the presence of welding scale, the pH-value of the concrete solution and environmental conditions (humidity and temperature). The intensity of the pitting corrosion increases with increasing chloride content. Carbonation of the concrete will lead to a significant reduction in the critical chloride concentration for pitting initiation.

The unalloyed steel commonly leads to widespread corrosion in chloride-contaminated environments with spalling of the concrete cover while for stainless steel only locally concentrated attack may occur. It was noted that a corrosion attack on a not sufficient resistant type of stainless steel develops different than on black steel. On stainless steel the attack does not spread in the same way as on black steel, but grows more like a pinhole attack. This might lead to a quick reduction in the cross section and consequently in the load bearing capacity if corrosion occurs under extreme conditions if the stainless steel is not highly enough alloyed with respect to the environment.

Depending on the actual corrosion attack, ferritic or austenitic steel as well as ferritic-austenitic (duplex) steel can be used. The corrosion resistance increases in the sequence:

unalloyed		
ferritic	e. g.	Cr12 .... Cr17
austenitic	e. g.	CrNi 18-10
ferritic-austenitic	e. g.	CrNiN 23-4
austenitic	e. g.	CrNiMo 17-12-2
ferritic -austenitic	e. g.	CrNiMoN 22-5-3

These steels used as concrete reinforcement will not corrode at all provided they are selected in accordance with the expected conditions.

The corrosion properties appear to be extremely dependent on the state of the steel surface. In particular, all scale and temper colours can aggravate pitting corrosion and therefore the usual welding procedure will lead to a significant reduction in the corrosion resistance; it reduce the level of chloride contamination at which corrosion can take place. This problem can be anticipated by higher alloying the steel or removing millscale and temper colours by pickling or shot blasting. However all studies also indicated that there was no corrosion of welded molybdenum alloyed steel type 1.4571 and 1.4462 steel under practical conditions of strongly chloride-contaminated uncarbonated and carbonated concrete (chloride concentrations up to 5 M.-% and higher).

Fig. 2 summarises the results of the literature in [3] and draws the corrosion degree based on pitting depth and loss of weight. Areas without and weld are separated:

- As expected mild steel bars corrode in carbonated and/or in chloride contaminated concrete. The strongest attack occurs in carbonated plus chloride-contaminated concrete; cracking and spalling of the concrete specimen are common.
- The unwelded low-chromium ferritic steel of type 1.4003 shows a distinctly better behaviour than unalloyed steel when embedded in carbonated or in alkaline concrete containing low chloride levels. The critical chloride content for pitting corrosion is about 1.5 to 2.5 M.-% depending on state of surface, type of cement (pH-value of pore liquid) and concrete quality. However, at higher chloride contents this steel suffers pitting attack, which is concen-

trated at a few points on the surface. The tendency to concrete cracking is distinctly lower than for corroding mild steel. In chloride contaminated concrete the (unwelded) steel may suffer a stronger attack if carbonation had reached the steel surface.

For the welded steel within the weld line, chlorides in the order of ≥ 0.5 M.-% produce locally distinct pitting corrosion. The depth of pitting increases with increasing chloride content and is more pronounced in chloride-containing carbonated concrete. However, for the ferritic chromium steel the pitting at weld lines is deeper than for unalloyed steel, but the overall general corrosion (loss of weight) is significantly smaller.

- All the higher alloyed stainless steels have a very high corrosion resistance in all the environments tested. No corrosion appeared with the austenitic steel CrNiMo 17-12-2 (1.4571) and the ferritic-austenitic (duplex) steel CrNiMoN 22-5-3 (1.4462). These properties are also maintained at the highest chloride levels that appear in practice and when these steel types are welded.

  The ferritic-austenitic (duplex) steels offer even better properties. These materials may provide a suitable solution to the problem of concrete structures requiring rebars with high mechanical strength and good corrosion resistance.

  The corrosion properties of austenitic and ferritic-austenitic Cr-Ni-Mo-steels are better than for Cr-Ni-steels. Some results [28,29] suggest that, within this group of stainless steels, bars without molybdenum are sufficiently resistant and therefore suitable for application in chloride contaminated concrete. Nevertheless, after results of [24], welded bars without molybdenum seems not to be sufficiently resistant and not suitable for application in presence of more than 3 M.-% chloride in concrete (related to the amount of cement).

Concluding one can say that ferritic stainless steel with at least 12 M.-% of chromium might be the best choice in moderately aggressive environments (carbonated concrete or exposed to low chloride levels), where the higher resistance of the more expensive austenitic stainless steels is not necessary. Austenitic stainless steel of type CrNiMo 17-12-2 and ferritic-austenitic (duplex) steel CrNiMoN 22-5-3, even in the welded state, proved to give excellent performance in chloride-containing concrete, even at the highest chloride levels that appear in practice. Austenitic stainless steel of type CrNi 18-10 may be satisfactory in many cases with 'normal' exposure to chlorides and no welding of the reinforcement. Higher alloyed steels than the mentioned types seem not to be necessary unlike the recommendations in [4,10,12].

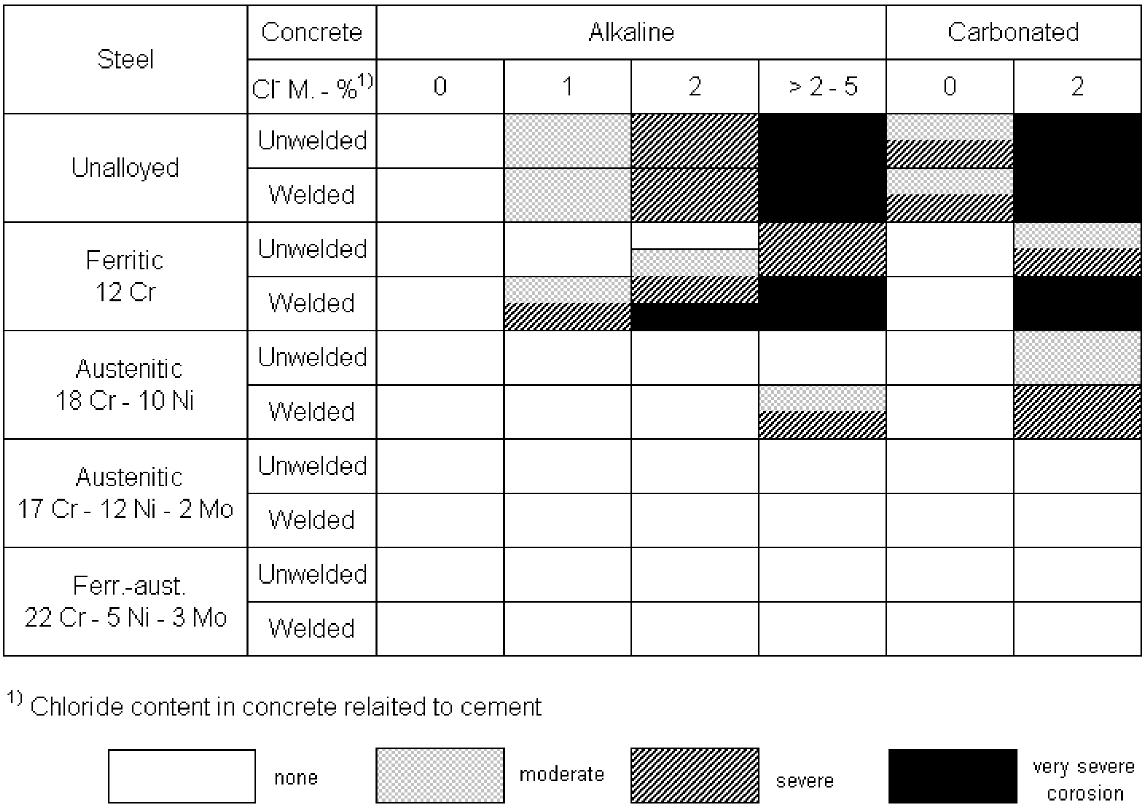

Fig. 2: Corrosion behaviour of steel in concrete (survey)

Stainless steels can be used for complete or partial substitution of carbon steel in new reinforced concrete structures exposed to aggressive environments or when a very long service life is required.

Due to the very high cost of stainless steel reinforcement it is not likely that the entire reinforcement, for example in a large marine structure, would be made of stainless steel. A possible alternative is to use stainless steel only as the outer reinforcement in the splash zone. Stainless steel and unalloyed steel will then probably be in electrical contact and this could lead to a theoretical risk of galvanic corrosion. Furthermore, in the rehabilitation of corroding reinforced concrete structures, stainless steel are often used in structures reinforced with normal carbon steel and galvanic coupling can occur.

As long as both metals are in the passive state, i. e. not corroding, their potentials will be more or less the same when embedded in concrete and galvanic coupling does not produce appreciable effects. Even if there should be minor differences in potential, both black and stainless steels can be polarised significantly without serious risk of corrosion, i. e., their potentials will approach a common value without the passage of significant current.

In situations where the unalloyed carbon reinforcement is corroding and the stainless steel is passive, the galvanic coupling will give rise to accelerated corrosion. However, the coupling of corroding carbon steel with stainless steel is generally without risk and is negligible compared to coupling to passive carbon steel which always surrounds the corroding area [30-32]. Fig. 3 shows that the macrocouple current density (increase in corrosion) was almost one order of magnitude lower when corroding carbon steel in 3 M.-% Cl^- concrete was connected with passive stainless steel, compared to the current density measured during the tests with a passive bar of carbon steel. That means that the increase in corrosion rate of corroding carbon steel embedded in chloride-contaminated or carbonated concrete, due to galvanic coupling with stainless steel, is significantly lower than the increase brought about by coupling with passive carbon steel. Stainless steel has in the absence of welding scale (see below) a higher over-voltage for cathodic reaction of oxygen reduction (the cathodic oxygen reaction is a very slow process) with respect to carbon steel. That means, the increase in corrosion rate on carbon steel embedded in chloride-contaminated concrete due to galvanic coupling with stainless steel is significantly lower than the increase brought about with passive carbon steel. Therefore, coupling with stainless steel seems to be less dangerous than coupling with passive areas on carbon steel that always surround the area where localised corrosion takes place. Thus, assuming the 'correct' use of the stainless steel, i. e. stainless steel is used at all positions where chloride ingress and subsequent corrosion might occur, the two metals can be coupled without problems.

Nevertheless, a worse behaviour was observed in the presence of a welding scales (see Fig. 3). Oxide scale produced at high temperature increases the macrocouple current density generated by stainless steels, to the same order of magnitude or even higher than that produced by coupling with carbon steel.

The fact that stainless steel is a far less effective cathode in concrete than carbon steel, makes stainless steel a useful reinforcement material for application in repair projects. When part of the corroded reinforcement, e. g. close to the concrete cover, is to be replaced, it could be advantageous to use stainless steel instead of carbon steel. In being a poor cathode, the stainless steel should minimise any possible problems that may occur in neighbouring corroding and passive areas after repair.

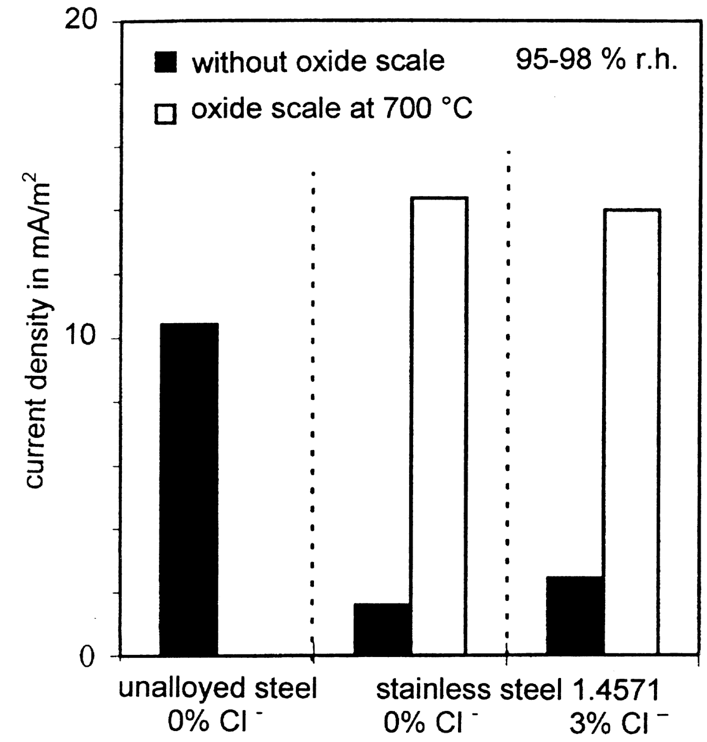

Fig. 3: Macrocouple current density in a corroding bar of carbon steel in 3 % chloride contaminated concrete when it was coupled
- with a passive bar of unalloyed steel in chloride free concrete,
- bars of 1.4571 stainless steel in chloride free concrete,
- bars of 1.4571 stainless steel in 3 % chloride contaminated concrete
Results on stainless steel bars also with the surface covered with oxide scale produced by heating at 700 °C in order to simulate a welding scale [31]

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