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TECHNICAL REPORT

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TR 6.3

STAINLESS STEEL REBARS

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STAINLESS STEEL REBARS

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NOTE:

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented.

PREFACE

The main subjects concerned in this TR were discussed and a general review was made inside the working group WG A6 – Smart & green structural and repair materials. The WG was created in the DURATINET project with the aim to stimulate the creation of a new cluster on smart and green structures and to promote the use of new construction materials environmental friendly and with improved performance and/or durability.

This TR is one of a series of review documents, concerning *smart & green structural and repair materials* theme, which summarizes the current knowledge on the applicability of stainless steel rebars in concrete.

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CONTENTS

Vol. 1 – Stainless steel rebars

Introduction

Reinforcement corrosion is the main cause of premature deterioration of concrete structures. It may cause cracking and spalling of the concrete cover, may lead to structural problems and even to failure of severely deteriorated structures.

Primary corrosion preventive measures include a good design, using both the concrete mix and cover adequate to the environmental corrosivity class, good site practice, and quality control. Nevertheless, it is necessary to provide additional preventive measures when long service life is required, especially for structures in highly corrosive environments. The methods currently used to increase service life include surface treatment of concrete to restrict the ingress of moisture and aggressive substances, coated reinforcements, corrosion inhibitors, and corrosion resistance reinforcements. Among these additional preventive measures to counter reinforcement corrosion, the use of a corrosion resistant reinforcement, like stainless steel, is considered a technical attractive approach to eliminate the cause of corrosion related problems. This solution gives a new insight into design and raises the reliability and durability of structures in highly corrosive environments.

The use of stainless steel reinforcements dates back to the late 1930s [1], i.e., the beginning of the stainless steel technology. A detailed list of examples of early use as well as grades and usage is given in the Concrete Society Technical Report 51 [2].

Since the pioneer studies in Italy [3] demonstrate the superior performance of stainless steels rebars with respect to carbon steel reinforcements, several papers have been devoted to economic aspects involving the whole life cycle of the structure [4]-[6], with the general conclusion that the use of stainless steels is feasible, especially in aggressive environments [7]. However, little attention has been paid to date to fine tuning, i.e. to the selection of stainless steel type as a function of the environment.

The advantages of using stainless steel reinforcement in concrete, such as reduced maintenance, increased durability, and competitive life cycle costs, are reported in recent review articles and books [2],[8]-[11]. Some researchers point out that stainless steel reinforcement may enable a design life of more than 100 years, without significant maintenance, even when applied in highly aggressive environments [2],[11],[12]-[15]. Practical evidence of stainless steel reinforcement durability is provided by a pier in Progreso which has been showing a good performance for more than 65 years in a subtropical environment without repair and significant routine maintenance activities [16].

Stainless steel reinforcing bars for concrete are now available in a wide range of alloys, which are suitable for either new structures or for repair and/or straightening of existing structures. Typical applications of stainless steel reinforced structures, which include transport infrastructures, structures in marine environments and rehabilitated historical structures are spread all over the world [2],[10],[11],[16],[17]-[19].

The often stated disadvantage associated to stainless steel is its initial cost, which can be six to ten times higher for austenitic alloys than that of carbon steel according to steel market prices [20]. Moreover, stainless steel price is governed by commodity prices of alloy elements being in consequence volatile. New less costly alloys [18],[21] with equivalent performance to common austenitic alloys have been developed to minimize this disadvantage.

The fairly higher cost of stainless steel is also offset by its advantages, and generally its use in concrete structures has a positive economic effect on life cycle cost analysis [2],[11],[18], if we take into account a long service life design with benefits associated with lower maintenance and repair. The cost of this corrosion protection method depends on several factors, such as extent of application, grade selection, and properties of bars. Accordingly, if stainless steel is selectively used for replacing carbon steel in most critical areas of the structure, there will only be a marginal increase in total costs.

Guidance for the selection and use of stainless steel reinforcement is given by current standards [22],[23] and other reference documents [2],[8],[18],[19],[24]. The specified grades by most standards are austenitic and duplex [22],[23]. Even though some ferritic alloys have demonstrated to be adequate in moderately aggressive environments, in particular in carbonated concrete or in concrete exposed to low chloride levels [25].

The high corrosion resistance of stainless steel alloys enables a relaxation in design as compared to carbon steel, concerning concrete cover, mix, and quality, surface treatments and crack width. All these possibilities also represent savings in the total cost of the project.

This document reviews the use of stainless steel reinforcement in concrete, including generic information, such as, definition and classification, chemical, physical and mechanical properties, as well as specific facts like the reported corrosion resistance, design and construction practice considerations, specifications, and typical applications.

1 Stainless steel definition and types

According to EN 10088-1:2005 [26], stainless steel is a generic designation given to a wide group of alloys containing at least 10.5% of chromium and a 1.2% maximum of carbon. Other elements may be added to provide different mechanical and physical properties, as well as improved corrosion resistance.

The first steels, named “stainless”, were synthesised by the beginning of the XX century as Fr-Cr alloys that correspond approximately to the present AISI 400 series. The better performance of stainless steels with respect to carbon steels is due to the presence of alloying elements able to generate a thin, compact and adherent passive layer. The major alloying element is chromium, and in fact steel is considered “stainless” when Cr concentration is higher than about 11% because the corrosion rate drops to negligible values (and the corrosion potential moves in the anodic direction), as depicted in Fig. 1. It has been shown that 12.7% in Cr is the minimum concentration able to replace completely the volume of metal dissolved by Cr salts and to fill up the pit with a blocking material [27]. A detail of those precipitates is depicted in Fig. 2.

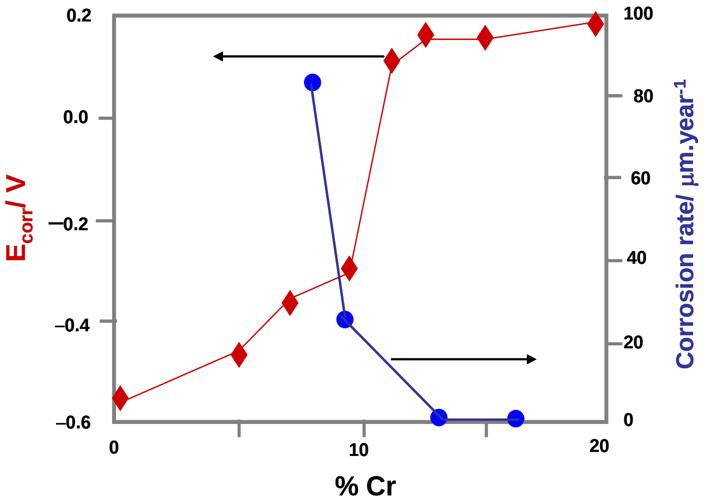

Fig. 1. Corrosion potential for different Fe-Cr alloys in 4% NaCl solution open to the atmosphere. The corresponding corrosion rate in salt spray test chamber is also given [28].

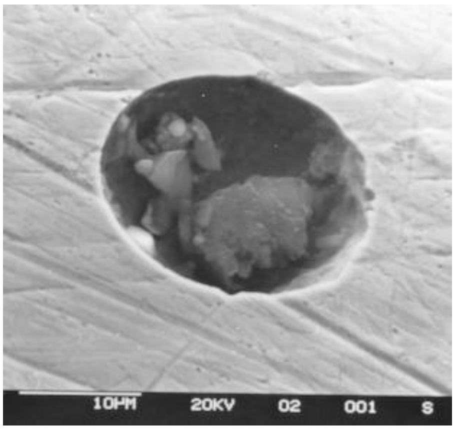

Fig. 2. Detail of the remaining corrosion products that blocked the single pit formed on AISI 304 stainless steel immersed in H_2SO_4 0.5M + 10^{-3}M NaCl solution.

EN 10088-1:2005 [26] classifies stainless steels in accordance with their microstructure, their main properties and significant alloying elements. According to the metallurgical microstructure stainless steels can be grouped in **ferritic**, **austenitic**, austenitic-ferritic (**duplex**), **martensitic**, and **precipitation hardening** alloys. Considering particularly their use properties, stainless steels can be classified into corrosion, heat and creep resisting steels. Corrosion resisting steels have good resistance either to uniform or localized corrosion, provided by a minimum content of 10.5% Cr through the spontaneous formation of a passive film. Heat resisting steels, mainly ferritic and austenitic, have good resistance to oxidation and to effects of hot gases and combustion products at temperatures higher than 550 ºC. Creep resisting steels, mainly martensitic and austenitic, have good resistance to deformation under mechanical long-time stressing at temperatures above 500 ºC. According to EN 10088-1:2005 [26], EN grades of these steels are given steel numbers in the groups indicated in Table 1.

Ferritic stainless steels have a ferritic structure (α-Fe) with a body centred cubic atomic packing (bcc), are magnetic, have a ductile structure but are brittle below a characteristic transition temperature. These steels are annealed at temperatures between 750 and 950 ºC to avoid the formation of austenite, which transforms to martensite on cooling and may cause embrittlement due to grain coarsening. For this reason, and due to sensitivity to intergranular corrosion, ferritic steels have poor weldability. These effects are reduced by stabilization with Ti, Nb or Zr. The ferritic grades used for bars may include a sulphur addition greater than 0.15% to facilitate machining. However, this addition implies a reduction in corrosion resistance.

Table 1. Groups of grade numbers for corrosion, heat, and creep resisting steels (adapted from [26]).

	Grade numbers	Ni	Mo	Special additions
Corrosion resisting	1.40xx	<2.5%	without	without
	1.41xx	<2.5%	with	without
	1.43xx	≥2.5%	without	without
	1.44xx	≥2.5%	with	without
	1.45xx and 1.46xx			with (such as Ti, Nb or Cu)
Heat resisting	1.47xx	<2.5%		
	1.48xx	≥2.5%		
Creep resisting	1.49xx			

Austenitic stainless steels have an austenite (γ-Fe) structure with a face centered cubic packing (fcc) and the possible presence of residual δ-ferrite. The stability of the austenitic structure depends on the amount of alloying elements. In grades with low alloy content (metastable austenitic grades), metastable austenite may transform to martensite, as a result of plastic deformation and/or cooling at low temperature. Ferrite and high chromium and molybdenum contents may promote precipitation of sigma phase, which is brittle. Austenite stability may be increased by austenite forming elements, such as carbon, nickel, manganese, nitrogen, and cupper. Stable austenitic grades are called fully austenitic.

Austenitic steels have good corrosion resistance, good toughness with good ductility in a wide range of temperatures, high safety against brittle fracture, and good weldability. Austenite is not magnetic, and does not harden from heat treatment, but its strength may be increased by cold forming or by solid solution alloying with addition of elements such as nitrogen. These alloys may be susceptible to intergranular corrosion due to precipitation of chromium carbides in a critical temperature range. Nevertheless, this problem can be avoided by reducing carbon to values equal or less than 0.03% or by adding titanium, niobium or zirconium as stabilizers. Similarly to ferritic steels, some austenitic grades have resulfurized variants (S>0.15%) to improve their machinability. Grades with excellent corrosion resistance due to high chromium, molybdenum and nickel contents may be called superaustenitic.

Austenitic-ferritic steels display a two phase structure at room temperature with ferrite content between 30 and 50%. These have higher strength than austenitic steels, good ductility, and have good resistance against stress corrosion cracking. Welds should be cooled rapidly because sigma and other phases that may reduce toughness and corrosion resistance can be formed in the range of 600 to 900 ºC. Superduplex grades, with high chromium, molybdenum and nickel contents, are also grouped.

Martensitc steels have generally a high carbon content, which gives a quadratic body centred α'-matrix transformed from austenite upon cooling. These are magnetic, have low ductility, high hardness and strength. If the structure contains a high amount of ferrite, the steels are designated as martensitic-ferritic or semi-ferritic. Common grades have high carbon contents (0.08-1%), their mechanical strength can be increased by quenching, and their ductility may be improved by tempering. If the steels are made with low carbon content (max 0.06%) and 3 to 6 % Ni, a stable austenite will be promoted after hardening and tempering, the steels being designated as martensitic-austenitic or nickel martensitic. Martensitic-austenitic and supermartensitic steels have good weldability. The low carbon grades have been further developed to supermartensitic steels, which have high strength and good impact strength.

Precipitation hardening steels have increased strength as result of the precipitation of intermetallic compounds, carbide, nitrides, or copper phase from the martensitic structure after heat hardening treatment.

Due to their properties, martensitic and precipitation hardening steels are not considered suitable for reinforcing steels.

Table 2 presents the percentages of carbon and major alloy elements of the corrosion resisting stainless steel groups, adapted from the chemical composition of stainless steels specified in EN 10088-1:2005 [26]. This standard also includes specifications for silicon, phosphorus, sulphur, nitrogen, copper, niobium, titanium, and manganese.

Table 2. Percentage ranges of the major alloy elements in different stainless steel groups (adapted from [26]).

	Ferritic	Austenitic	Duplex	Martensitic and precipitation hardening
C	≤0.08	≤0.15	≤0.03	≤1.20
Cr	10.5-30.0	16.0-28.0	18.0-30.0	11.0-19.0
Ni	≤2.50	≤32.00	3.5-8.0	≤27.0
Mo	≤4.50	≤8.00	0.10-4.50	≤2.80

2 Current Specifications

The first standards of specifications developed for stainless steel bars aimed to concrete reinforcement were BS 6744:2001 [22] and ASTM A955/A955M [23]. Besides these, different standards are in use in other European countries like France, Denmark, Sweden, Norway and Finland, and a European standard is currently being prepared.

BS 6744:2001+A2:2009 [22] specifies bars of austenitic (1.4301, 1.4436, 1.4429, and 1.4529) and austenitic-ferritic grades (1.4162, 1.4362, 1.4462 and 1.4501) with range sizes from 3 mm to 50 mm, of specific sectional areas and mass per meter run. Three strength levels are covered by this standard (200, 500, and 650) corresponding to the tensile properties specified in Table 3.

Table 3. Tensile properties of stainless steel grades specified by BS 6744:2001+A2:2009 [22].

Grade	$R_{p0.2}$ MPa	$R_m/R_{p0.2}$ (min)	A_5 (min) %	A_{gt} (min) %
200 [a]	200	1.10	22	5
500	500	1.10	14	5
650	650	1.10	14	5

[a] Plain only.

The standards of other European countries include the same most commonly used austenitic and duplex alloys (1.4301, 1.4436, 1.4362 and 1.4462), besides other low carbon austenitic alloys and duplex alloys, such as 1.4307 and 1.4404.

The chemical composition requirements of the alloys specified in BS 6744:2001+A2:2009 [22] are given in Table 4. This standard also specifies conditions of supply of ribbed and plain bar, and mechanical and physical properties including bend, fatigue, Charpy impact, and intergranular corrosion tests besides tensile test specifications.

A European standard [29], which is currently in preparation, specifies, according to EN 10088-5:2009 [30], requirements for corrosion-resisting stainless steel used for the reinforcement of concrete structures, and includes specifications for steel performance, mechanical properties and conditions of testing, as well as guidance on steel grade selection. The most recent draft is considering ferritic, austenitic and austenitic-ferritic alloys corresponding to five grades with yield strengths of 450, 500, 550, 600, and 650 Mpa, and an additional grade of 200 MPa, especially for plain bars.

Table 4. Stainless steel chemical composition (cast analysis) in % by mass (adapted from BS 6744:2001+A2:2009 [22]).

Designation Number EN[*] ([†])	**C_{max}**	**Si_{max}**	**Mn_{max}**	**S_{max}**	**$Cr_{min/max}$**	**$Ni_{min/max}$**	**$Mo_{min/max}$**	**P_{max}**	**N**
1.4301[a] (AISI 304N)	0.07	1.0	2.0	0.030	17.0/19.5	8.0/10.5	-	0.045	≤0.11
1.4436[a] (AISI 316)	0.05	1.0	2.0	0.030	16.5/18.5	10.5/13.0	2.5/3.0	0.045	≤0.11
1.4429 (AISI 316LN)	0.03	1.0	2.0	0.015	16.5/18.5	11.0/14.0	2.5/3.0	0.045	0.12/0.22
1.4162 (UNS S32101)	0.04	1.0	4.0/6.0	0.015	21.0/22.0	1.35/1.70	0.10/0.80	0.040	0.20/0.25
1.4362 (UNS S32304)	0.03	1.0	2.0	0.015	22.0/24.0	3.5/5.5	0.10/0.60	0.035	0.05/0.20
1.4462 (UNS 31803)	0.03	1.0	2.0	0.015	21.0/23.0	4.5/6.5	2.5/3.0	0.035	0.10/0.22
1.4501[b] (UNS S32750)	0.03	1.0	1.0	0.015	24.0/26.0	6.0/8.0	3.0/4.0	0.035	0.20/0.30
1.4529[b] (UNS NO8367)	0.02	0.50	1.0	0.010	19.0/21.0	24.0/26.0	6.0/7.0	0.030	0.15/0.25

[a] Nitrogen content may increase to 0.22 % max.

[b] Only required for special applications, according to guidance on Annex B of BS 6744:2001 [22] (also given in Table 7).

ASTM A955/A955M:2004 [23] covers duplex and austenitic alloys including high manganese austenitic alloys. Besides chemical composition, the standard specifies heat treatment, deformation, tensile, bending, hardness, and corrosion resistance requirements. Tensile properties are specified to three strength grades (300, 420, and 520) with yield strength values of 300, 420, and 520 Mpa.

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[*] The European designation system for stainless steels according to EN 10088-1:2005 includes a material number and name. These are respectively represented by the generic forms 1.αβχδ and XεΘΩ(...)θ–ω–(...), with the lower case letters indicating an integer, and Θ, Ω and Ψ chemical symbols. In the material number 1 represents a steel, αβ a group of stainless steels, and χδ the alloy identification. In the material name X symbolizes a high alloy steel, ε is equal to 100 times the carbon content of the alloy, Θ and Ω are the chemical symbols of the main alloy elements, and θ and ω are their respective nominal percentage.

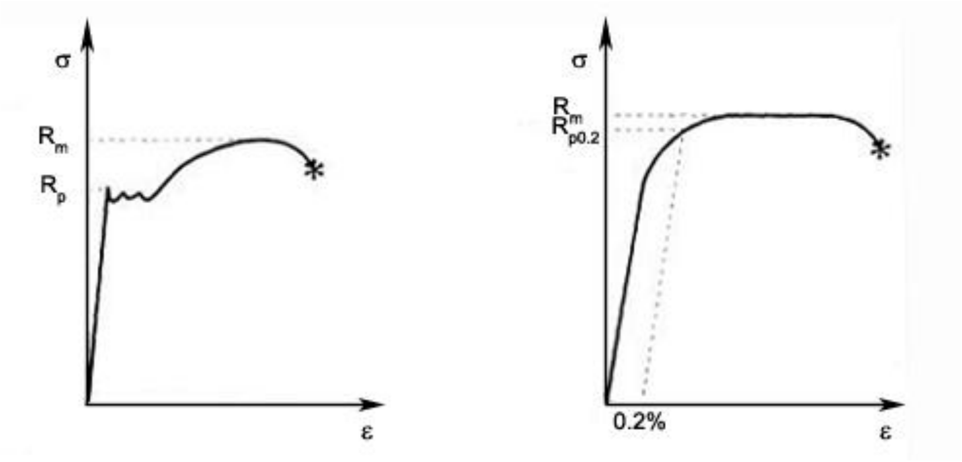
[†] Stainless steel number according to American standard designation system.

3 Stainless Steel Properties

Properties of stainless steels depend on production processes, material composition and microstructure.

3.1 Mechanical Properties

Stainless steels do not show a well defined yield point, the proof strength being determined as the stress at which non-proportional extension equals 0.2% strain (Fig. 3). Characteristic strength is the lower limit proof stress value of an interval at which there is a 90% probability that 95 % of the values correspond or are above this bottom limit. Ultimate tensile strength is the maximum load registered during tensile test, and elongation at fracture is a measure of the ductility of a material. These properties and total elongation at maximum force, determined by the methods described in EN ISO 6892-1:2009 [31], shall comply with the values specified in current standards of stainless steel bars for reinforcement.



(a) *(b)*

Fig. 3. Typical stress-strain curves: (a) carbon steel; (b) stainless steel.

The elastic modulus values of stainless steel alloys are similar to those of carbon steel (200 kN mm^{-2}), although it is recommendable to use the values indicated in EN 10088-1:2005 [26], because it varies slightly with the alloy composition.

Toughness is a measure of the resistance of materials to brittle fracture, conventionally determined by Charpy impact tests, according to EN 10045-1:1990 [32]. Toughness of stainless steel reinforcements shall conform to EN 10088-1:2005 [26].

Unlike carbon steel, which shows a yield stress reduction with high temperatures, especially above 500 ºC, and which exhibits a ductile to brittle behaviour at low temperatures, austenitic stainless steels generally retain their ductility in a wide range of temperatures; showing an increase in strength with decreasing temperature, and only a negligible reduction in proof stress at elevated temperatures. These facts indicate that austenitic alloys are adequate for cryogenic applications, and suggest a better behaviour of austenitic reinforced elements in fire than that of carbon steel elements.

3.2 Physical properties

Reference data on some physical properties for stainless steels are included in EN 10088-1:2005 [26]. Considering stainless steel application in concrete, the main physical properties to be considered are density, thermal conductivity, coefficient of thermal expansion and magnetic permeability. Characteristic ranges of these physical properties, according to guidance data given in EN 10088-1:2005 [26], are summarized in Table 5.

Table 5. Ranges of physical properties of stainless steels (adapted from guidance data in EN 10088-1:2005 [26]).

	Density g cm^{-3}	**Mean coefficient of thermal expansion 20 - 100 ºC** 10^{-6} K^{-1}	**Thermal conductivity at 20 ºC** W / (m K)	**Specific thermal capacity at 20 ºC** J / (kg K)	**Magnetizable**
Ferritic	7.7	10.0-11.7	17-30	430-500	yes
Austenitic	7.7-8.1	10.5-17.0	8.6-17	450-550	no[a]
Duplex	7.7-7.8	11.5-13.0	13-17	470-500	yes
Martensitic and precipitation hardening	7.7-7.9	10.0-16.5	14-30	430-500	yes

[a] Small amounts of ferrite and/or martensite will increase magnetizability.

The coefficients of thermal expansion of ferritic and carbon steels and concrete are similar, while for austenitic and duplex steels are slightly greater. This may cause minor defects and expansion cracking in concrete, although no occurrences have already been documented [2],[25].

Ferritic, duplex, martensitic and precipitation hardening alloys are magnetic, while austenitic alloys are generally considered to be non-magnetic due to their low magnetic permeability values. That property is influenced by the chemical composition and by the manufacturing process, especially by conditions that induce instability of austenite and phase transformations to ferrite and martensite, such as a higher content of ferrite stabilizers and/or less percentage of austenite stabilizers, and cold deformation.

3.3 Weldability

Stainless steel is weldable, although welding design, practice and sequence need to be carefully executed with adequate control to minimize effects on its composition, microstructure, mechanical properties, and corrosion resistance.

Microstructural changes, such as, microsegregation, precipitation of secondary phases, and recrystallization in the heat affected zone (HAZ) may have serious consequences on corrosion resistance. Other possible changes and common defects that must be avoided include volatilization of alloying elements, contamination, scale, slag and spatter, incomplete penetration or fusion, and cracks.

Stainless steel grades with a high carbon content and non-stabilized are susceptible to sensitization with the formation of chromium carbide along grain boundaries and to depletion of chromium in adjacent regions, which may result in intergranular attack. This effect is controlled in low carbon and stabilized grades (addition of Ti, Nb or Zr), and by post-weld heat treatment.

Hot cracking susceptibility is minimized in austenitic weld deposits by solidification as primary ferrite, which is favoured by high chromium to nickel ratios. However, its content must be limited (between 3 to 8 %) to prevent the degradation of the mechanical properties of the material [33].

Pitting corrosion resistance may be improved by the use of filler metals with high corrosion resistance and by special care with surface finishing, which must be uniform and free from contamination, scale, and spatter. Compositional differences must also be avoided to reduce galvanic effects. Stress corrosion cracking susceptibility can be also minimized by post weld treatment that reduces the magnitude of residual stresses.

Cold cracking, which may occur in a microstructure susceptible to hydrogen embrittlement, may be avoided by the use of low hydrogen electrodes, minimization of restraints, preheat, and high penetration. Since the susceptibility to cold cracking of an alloy is related to the solubility of hydrogen, austenite is the least susceptible microstructure.

The weldability of stainless steels is strongly dependent on their chemical composition and microstructure. Austenitic alloys are the most weldable, although additions may have a significant effect on weldability. According to the previously mentioned factors, weldability is improved by decreasing the carbon, by increasing the nickel contents and by stabilization.

The higher coefficient of thermal expansion of austenite than that of ferrite may increase both the distortion and the residual stresses. However, the lower thermal conductivity has the advantage of requiring less heat input for welding.

Ferritic alloys are less weldable than austenitic alloys, and have a poorer toughness in weldable conditions, due to precipitation of intermetallic phases and embrittlement.

The weldability of duplex alloys is better than that of ferritic steels but not as good as that of austenitic stainless steels. The microstructural changes, as austenite/ferrite unbalancing and intermetallic precipitation, are of special concern when welding these alloys.

Resistance and arc welding are used to weld stainless steel reinforcement, arc welding being the most frequently used method in field, despite the reduced effect of resistance welding on stainless steel properties due to its lower heat input.

Welding design, procedures and control include the careful selection of materials, the quality assurance of welds, which must be free from defects and contamination, as well as the avoidance of crevices, residual stresses and sources of hydrogen. All these factors maximize the corrosion resistance of the weld joints and reduce the probability of cracking.

The requirements regarding static loaded structures for materials, as well as for the design, execution, quality, examination and testing of load bearing and non-load bearing stainless reinforcing steel welded joints, are specified in EN ISO 17660:2006 parts 1 and 2 [34],[35].

4 Corrosion Resistance

The high corrosion resistance of stainless steel is due to the formation of a stable passive film, of which the characteristics are determined by the chemical composition, and especially by chromium. Passivation, which may be interpreted by several mechanisms, establishes the corrosion resistance of stainless steel and the influences of different variables on the process, such as environment (temperature, pH, …) and material properties (composition, microstructure, surface condition…) [36].

Pitting and crevice corrosion, which are the main forms of stainless steel corrosion in an alkaline medium, constitute a central research subject.

4.1 Pitting Corrosion

Pitting corrosion is caused by the rupture of the passive film, normally in the presence of aggressive anionic species. The corrosion process once initiated leads to a reduction in oxidant species in the pit, which cause the spatial separation of cathodic and anodic zones. The hydrolysis of cations and the limitation of cathodic reaction in the pit lead to local oxygen depletion and to pH decrease. These restrictions support the autocatalytic propagation of corrosion (Fig. 4).

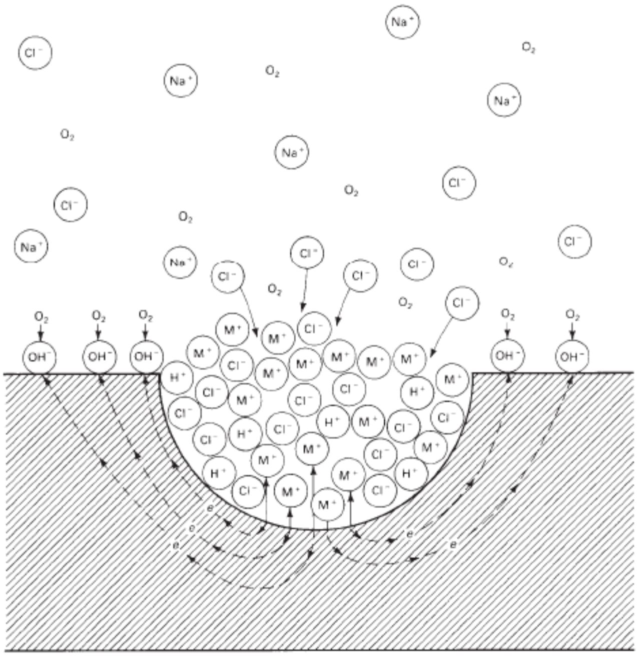


Fig. 4. Autocatalytic process of pitting corrosion induced by chlorides [37].

The pitting resistance equivalent number (PREN) is a common and simple way of ranking the corrosion resistance of stainless steel to pitting corrosion that accounts for the alloy chemical composition as given by one of its most common equations (1). However, there are different factors, related to material properties and environment characteristics, which influence the corrosion resistance of stainless steel besides the chemical composition.

$$\text{PREN} = \%\text{Cr} + 3.3\ \%\text{Mo} + 16\ \%\text{N} \qquad (1)$$

Several variables, such as composition and microstructure of the alloy, surface condition, electrolyte characteristics and environmental parameters have been identified as critical for stainless steel corrosion resistance [2],[3],[8],[11],[14],[25],[36],[38]-[41]. The literature on the subject is briefly reviewed, some of the findings being summarized below and including considerations about the influence of environment and of material variables such as temperature, pH, and welding.

As regards reinforcing bars, it has been shown that the presence of ribs and scratches on the bars has negative effects on the pitting corrosion resistance of stainless steels, especially if oxide films due to welding processes are present [8],[42]. The state of the surface should be included, together with the chemical composition and microstructure, in the corrosion resistance classification of rebars. According to the literature, surface finishing is critical in the stainless steel corrosion performance [28], 0.5 μm being the maximum surface roughness recommended [43].

4.1.1 Critical Chloride Threshold and Pitting Potential

Regardless of the mechanism, both the passive film rupture and the pitting corrosion resistance are characterized by a critical pitting potential and by an induction period, although other parameters, such as critical pitting temperature and chloride threshold, are also commonly used to characterize the pitting corrosion resistance of a passive material.

Several reviewed field and yard exposure tests of concrete specimens sustain the high corrosion resistance of stainless steel rebars comparatively to carbon steel [2],[9],[44],[45]. References are made to the experimental verifications indicating that the critical chloride content for rebars embedded in chloride containing uncarbonated concrete may be as more than ten times higher for stainless steel than for carbon steel.

Despite the proved high corrosion resistance of stainless steel in an alkaline medium, differences in the results reported in the literature may be due to the diversity in test conditions, techniques employed and parameters.

The critical chloride content for low chromium ferritic steel was found to be about 1.5 to 2.5% depending on the surface state, type of cement and concrete quality [39]. Higher critical chloride contents have been reported in solution (pH=12.6) for austenitic grades: higher than 5% and 10% respectively based on potentiostatic [40],[46] and potentiodynamic [36],[41] tests. Pitting potential values higher than 0.3 V_{SCE} , in 10% chloride alkaline solution, have also been reported [36],[40],[41]. Higher corrosion resistance have been documented for austenitic-ferritic stainless steels, both in alkaline solutions and in solutions with lower pH [47],[48].

In mortar and concrete, the critical chloride values are similar to those reported in solution, being higher than 4% and 5%, respectively in mortar and concrete [49],[50], with pitting potentials higher than 0.5 V_{SCE}, inclusively for new austenitic alloys, which means that corrosion is highly improbable in the studied conditions. Based on these results, García-Alonso et al. [49],[50] considered as highly improbable that corrosion will limit service life when stainless steels are used as reinforcements in concrete structures. Bertolini *et al.* [51]-[53] have reported the passive behaviour of austenitic and duplex alloys in concrete with 5% admixed chloride or achieving more than 6% chloride content by weight of cement.

Bertolini *et al.* [11], after having analysed the critical chloride content values either based on exposure tests on concrete or on electrochemical tests in solution and mortar, obtained by different authors, plotted the fields of applicability of stainless steel bars by taking into consideration the worst conditions (Fig. 5). It is however pointed out by the same authors that those values are only indicative, since critical chloride contents depend on the steel potential and thus they can vary with the oxygen access as well as when stray currents or macrocells are present [11],[40]. According to these researchers [11], some stainless steel alloys can be safely used in concrete with chloride contents that are rarely ever reached in the vicinity of the steel surface.

Hurley and Scully [54] have reasoned that 0.2 V_{SCE} is an upper limit potential for stainless steel reinforcement that should never be exceeded in service. As such, the chloride threshold values found at this potential were considered to be conservative. Similar arguments may justify the best behaviour of different stainless steel alloys in test yard and field exposure of reinforced concrete specimens studied just with the application of non destructive electrochemical tests or based on visual inspection. The critical chloride values higher than 8%, reported by Sørensen [46], and higher than 19% obtained by Correia [41] are illustrative of these differences.

The risk of pitting increases not only with increasing chloride ion concentration but also with raising temperature and decreasing pH [6],[8],[11],[14],[39],[51]. Another critical factor is the surface condition, which is associated to changes in passive film properties [36],[55].

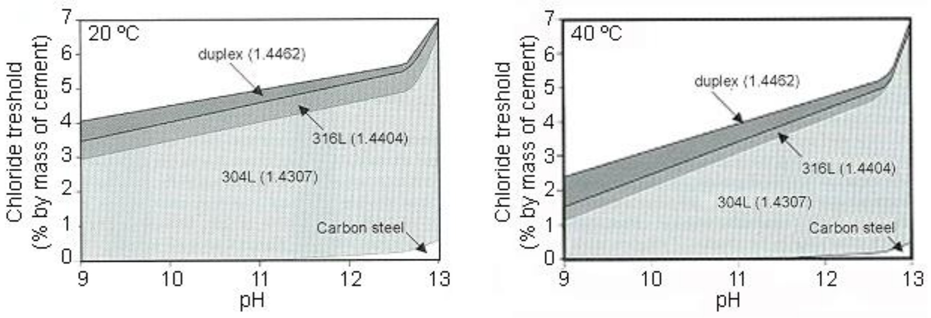


Fig. 5. Fields of applicability of stainless steel pickled bars in chloride bearing environments for 20 ºC and 40ºC (adapted from [11]).

4.1.2 Influence of welding

Since the pitting corrosion resistance is highly influenced by the surface state, welded bars show a poorer performance than unwelded bars. According to the literature, the corrosion resistance of stainless steels is affected by the presence of mill scale and temper colours on their surface [2],[11],[14],[39],[46],[56], though being improved by pickling or blasting [11],[14],[56].

Reductions in both the critical chloride contents and the pitting potentials have been reported [8],[11],[14],[39],[46],[56] for welded bars, comparatively with unwelded stainless steels. Bertolini *et al.* [11] indicate that, despite the high chloride threshold levels exhibited by the stainless steel alloys, in the presence of a welding scale on the surface of the reinforcement, a lower critical chloride of 3.5% (by weight of cement) must be assumed. Correia *et al*. [36],[57] attributed the poorer behaviour of untreated welded specimens to aggravation of the corrosion process by crevice corrosion and galvanic effect, while Sørensen *et al*. [46] indicate both oxidation and insufficient compactation of the concrete around the weld.

Another problem associated with welding, particularly for stainless steel alloys with higher carbon content, is the susceptibility to intergranular corrosion. However, in the literature, there is no reported work specifically for stainless steel reinforcement.

4.2 Crevice Corrosion

Crevice corrosion is normally a consequence of a galvanic cell generated in specific areas with restricted flux (Fig. 6). This corrosion is influenced by different factors inherent to the geometry of crevice, such as mass transport limitation, rate of superficial area and volume of solution in the crevice.

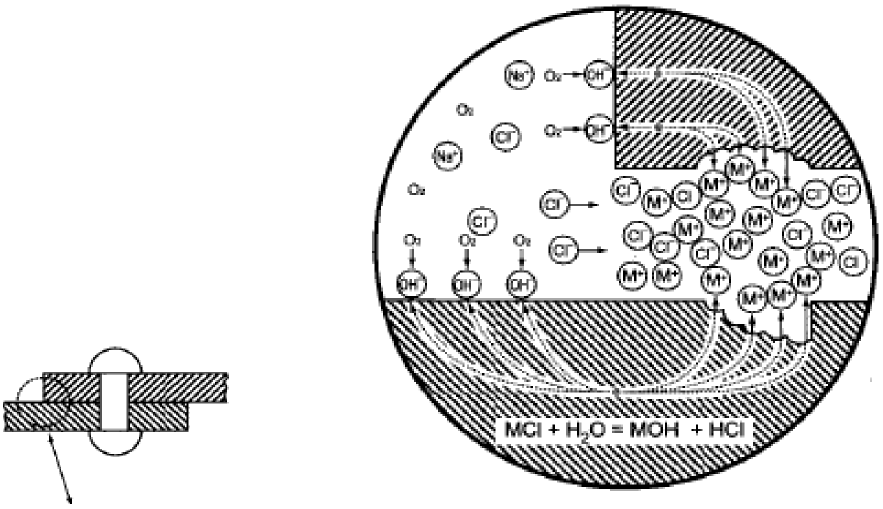


Fig. 6. Schematic drawing of crevice corrosion (adapted from [58]).

The consequences of pH decrease are often investigated in carbonated concrete or in extensively cracked concrete. In this particular case of cracked concrete, the geometry of the system may lead to crevice corrosion.

The critical chloride contents under carbonated or cracked concrete are lower than in highly alkaline concrete [8],[11],[14],[39],[40],[59], especially for steels with low chromium content. The pitting potential is always shifted to negative values in contaminated carbonated concrete comparatively with alkaline concrete having the same amount of chlorides [14],[38].

Nürnberger [38] reported that highly alloyed stainless steels give no sign of corrosion in cracked concrete, up to a crack width of 1 mm, with extreme chloride contents. Salta and Correia *et al.* [36],[60]-[62] reported that some austenitic stainless steel alloys, including recently developed high manganese alloys, resist to corrosion in cracked concrete, with a crack width of 0.8 mm at the concrete surface, under wetting/drying cycles with a 3 weight percent sodium chloride solution. However, the simultaneous action of crevice corrosion and stress disclose the susceptibility to stress corrosion cracking of one of the new high manganese austenitic alloys [36],[62], confirming previous results of slow strain rate tests in solution [63].

4.3 Galvanic Corrosion

The consequences of galvanic coupling of carbon steel and stainless steel have proven to be negligible in most situations found in real structures [6],[11],[14],[40],[64],[65]. When both carbon steel and stainless steel reinforcements are passive, their potential in concrete is similar and the macrocouple current is usually negligible. A significant macrocouple can only arise under very particular conditions, such as for stainless steel with oxide scale [11],[14],[40],[65], or for stainless steel in heavy chloride contaminated conditions and deprived from the access of oxygen with the carbon steel both in aerated condition and in non-chloride contaminated condition [18].

Since generally the passive stainless steel is connected to active carbon steel, in carbonated or chloride contaminated concrete, this coupling is reported to be less dangerous than the coupling between passive and active areas in carbon steel. Stainless steel is considered to be a useful reinforcement material for selective application, because it is a less effective cathode than passive carbon steel [11],[14],[40],[64]-[68].

4.4 Further insight into the galvanic coupling and pitting resistance problems

According to literature [69], the passive layer of iron in alkaline media is a sandwich-like structure, in which magnetite (Fe_3O_4) is sandwiched between an inner layer rich in Fe(II) compounds (FeO, $Fe(OH)_2$) and an outer layer rich in Fe(III) compounds (Fe_2O_3, FeO(OH)). In fact, it can be said that the passive layer is based on the structure of magnetite where the ratio Fe(II)/Fe(III) increases from the electrolyte side towards the metal side [70]. The profile of that concentration gradient depends on the interface potential (or corrosion potential), the film being richer in Fe(II) and more hydrated (richer in hydroxides) when the potential follows the cathodic direction [71]. The increased local hydroxide concentration explains the fact, described in several publications [72],[73] and collected in standards [74], of carbon steel becoming more resistant to chlorides at lower potential values. The reason is that, at the interface level, the local Cl^-/OH^- ratio is lower than the nominal value due to the increased OH^- concentration. However, the development of the passive film is not homogeneous [75] and local sites of lower OH^- concentration can occur, which will be prone to pitting in the presence of chlorides.

The passive layer formed in alkaline media presents always the same structure, no matter the steel (AISI 304, AISI 316 or duplex 2205): an outer part rich in iron and an inner one rich in chromium [55], which are similar to the structure of the native oxide layer depicted in Fig. 7. Thus, from the chemical point of view, there is almost no difference between the two interfaces in alkaline media. Both carbon steel and stainless steel surfaces are rich in Fe(III) species and hence the difference in the electrochemical potential will be very low, which explains the negligible galvanic currents recorded [55]. Additionally, the dielectric character of the chromium oxide, Cr_2O_3, makes the passive films of stainless steels less electronically conducting than the one of carbon steel [55]. The immediate consequence is that oxygen reduction is hindered on stainless steel surfaces, which makes them "*bad*" cathodes. In fact, in the hypothetical case of galvanic coupling between an active rebar and a passive one, the galvanic effect (galvanic current) will be less with a stainless steel cathode than with a carbon steel one.

It is interesting to observe first in Fig. 7 that the thickness of the passive layer is about 50% thinner for the AISI 316 stainless steel, which denotes higher corrosion resistance, i.e. the passive layer builds up with less substrate oxidised. The Ni content in the alloy can be at the origin of that difference because NiO species formed in the first stages of the passive film build up can act as modifiers of the structure of the layer through the process described in equation (2). In fact, that process makes it possible to interpret Ni enrichment observed in Fig. 7, at the metal-oxide interface [55].

$$NiO+3FeO \rightarrow Fe_3O_4+Ni^0 \qquad (2)$$

Those structural changes favour the formation of a more hydrated layer on the AISI 316 than on the AISI 304 stainless steel (compare OH^- profiles in Fig. 7), which, together with the Mo content will result in improved corrosion resistance, this being understood on the basis of a bipolar electrical structure of the passive layer that blocks the access to chlorides [76],[77].

The presence of Mo (in fact adsorbed molybdates) seems to play also an important role in the higher corrosion performance of the 2205 alloy [78]. However, the chemical composition of the alloys seems to be insufficient to explain the experimental data reported in the literature [79] about better performance of the duplex 2205 with respect to the austenitic AISI 316 in concrete pore solution. Further research in this field is necessary to define the limits of applicability of the material.

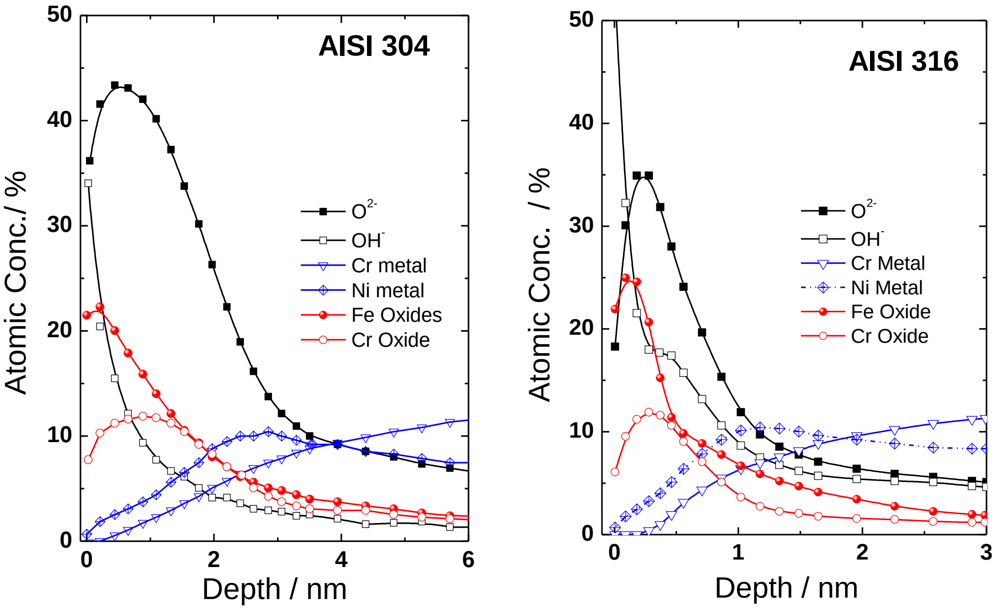


Fig. 7. X-ray photoelectron Spectroscopy, XPS, depth profiles of the passive layers formed on AISI 304 and 316 in the atmosphere.

The development of the passive film on carbon steel in alkaline media is of a topotactic nature [75]. Stainless steels show similar trend. Fig. 8 shows that the development of the passive film is highly dependent on the oxygen availability. When the access of oxygen is limited (Fig. 8 A), the topotactic structure is evident, whereas areas rich in Cr_2O_3 interact with areas rich in Fe_2O_3/Fe_3O_4, which leads to great differences in surface conductivity [80]. Such heterogeneous surface is prone to the formation of local anodic and cathodic sites where pitting corrosion can initiate. Thus, sufficient oxidation power of the environment will be guaranteed for fast and proper development of the passive layer on stainless steels.

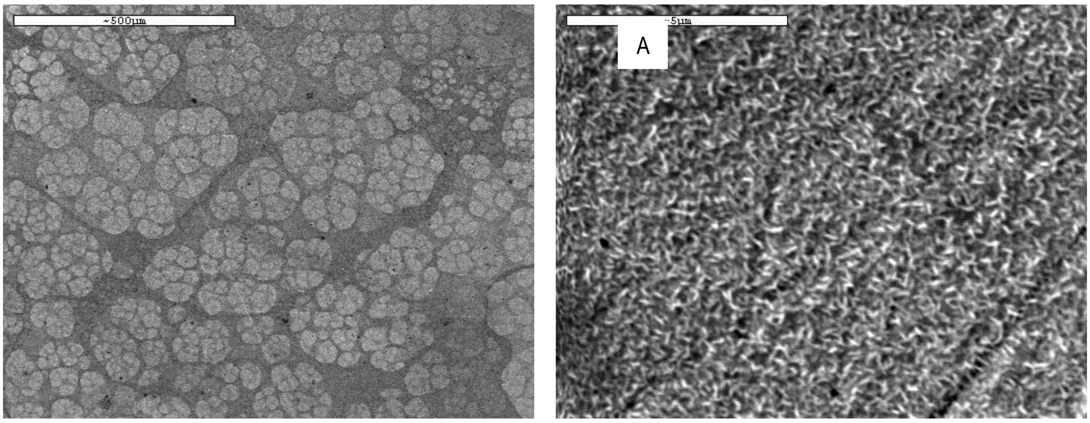


Fig. 8. Passive films grown on AISI 316 stainless steel in 0.1M Na olution. A) Deaerated solution. B) Air saturated solution [80].

4.5 Latest research trends

New alloys have been lately developed to minimize the higher cost of stainless steel reinforcement, comparatively with carbon steel, which is its commonly associated major disadvantage in spite of the benefits established by a total cost analysis.

The new austenitic high manganese alloys have shown a high corrosion resistance [36],[41],[49],[50],[60],[61],[81], although in some circumstances being slightly less than Fe-Cr-Ni conventional alloys. This behaviour is partially justified by changes in the passive film properties induced by the electrochemical destructive test technique [36]. A similar behaviour was found for both new and conventional alloys when analysed by non destructive tests in concrete exposed to NaCl until a maximum of 19% chloride by cement weight [41].

The AISI 204Cu stainless steel is an example of Mn-rich steels where the presence of MnS inclusions represents a potential weakness with respect to pit development. However, pit initiation becomes blocked in the first stages due to cementation of the dissolving copper, which forms nodular precipitates on top of the active sites (see Fig. 9) [82]. The result is an improved corrosion resistance.

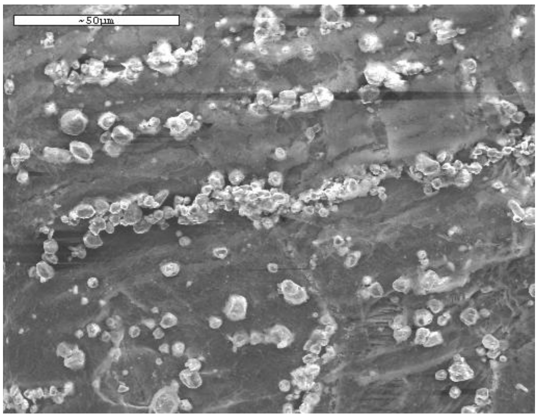


Fig. 9. SEM image showing the nodular Cu deposits formed on an AISI 204Cu immersed in 0.1 M NaOH + 0.5 M NaCl solution and polarised at +0.35 V vs SCE.

One potential problem referring to the integration of AISI 204Cu stainless steel in mixed structures can be the dissimilar interface of the 204Cu (rich in copper), which in electrical contact with carbon steel can give some galvanic activity. This is an aspect that should also be studied in detail.

A critical factor, especially when developing new alloys for use as reinforcement, may be the simultaneous action of stress and environmental conditions that increase the localized corrosion susceptibility. These factors may cause stress corrosion cracking in a vulnerable material, such as the case noticed for one of the innovative high manganese alloys [41],[62],[63].

The knowledge of the corrosion mechanisms and of their relation with passive film characteristics is another important research field because it makes possible to identify the critical factors in the stainless steel performance, which are determinant for its suitable use. Recent research studies on this subject prove its significance by establishing relations between passive film characteristics and corrosion resistance of the alloys accounting the effects of critical factors, such as surface condition, microstructure, chemical composition, and electrolyte properties [36],[55],[77],[80],[81],[83]-[92].

5 Typical Applications

The recognition of economic, social and environmental impact of the repair of damaged structures leads to an increased use of stainless steel reinforcement to eliminate the severe corrosion consequences.

Typical applications of stainless steel reinforcement are structures located in highly corrosive environments including offshore structures, transportation infrastructures exposed to de-icing salts, and structures at or near the sea coast, such as piers, dams, and harbour installations. Stainless steel reinforcement is also indicated for the replacement of carbon steel reinforced elements when these are exposed to aggressive environments and are associated to serious economic and social impacts of future repairs.

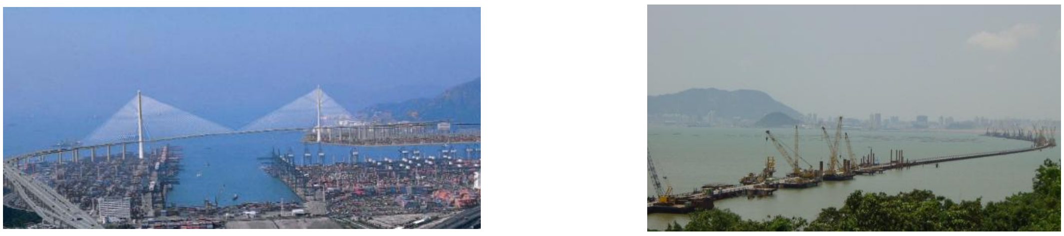
The most ancient and successful well known example of stainless reinforcing steel application is the pier of Progreso de Castro in Yucatán, more than 65 year old (Fig. 10). The inspections performed have proven the good performance of the 1.4301 stainless steel reinforcement. The latter has shown no sign of deterioration, for concrete covers thicker than 20 mm, even with chloride contents of up to 1.9% Cl^- in concrete with relatively high porosity [16]. The remaining service life is estimated to be more than 20 to 30 year old without significant maintenance. By opposition, a neighbouring pier built afterwards with carbon steel is heavily deteriorated (Fig. 10) [16].

Fig. 10. Pier of Progreso de Castro, Yucatán, Mexico. Structure built from 1937 to 1941 with stainless steel reinforcement (adapted from [16]).

In the last few decades, stainless steel reinforcement applications have spread all over the world. These applications include transportation infrastructures exposed to de-icing salts or located in marine environments, structures designed for long-term durability, and renovated historical buildings. Some examples of these structures are listed in Table 6 and illustrated in the following figures (Fig. 11 to Fig. 13).

Table 6. Examples of structures built or rehabilitated with stainless steel reinforcement.

Structure	Date	Material	Elements
Bridge in I-696 highway near Detroit, Michigan, USA	1995	1.4301	Deck
Bridge in 407 highway near Toronto, Ontario, Canada	1996	1.4406	Deck
Seafront structure, Scarborough, UK	Mid 1980's	1.4436 1.4301	Columns and precast beams Further inshore
Guildhall Yard, London; UK	1996	1.4301	Floor spanning and external walls
Underpass, Cradlewell, UK	1995	1.4436	Floor slab
Mullet Creek Bridge on highway 407, Ontario, Canada	1997	1.4436	Demonstration project
Ilfracombe Pavillion, North Devon, UK		1.4436	Parapet ring beam and columns
Schaffhausen Bridge, Switzerland	1995	1.4462 1.4301	Critical elements of the structure
Five bridges on the M4 motorway, UK	1996	1.4301	Selective use on reconstruction
Building of the National Physical Laboratory, Teddington, UK		1.4436	
A48 Highnam Bridge, U.K.	1998	1.4436	Selective use in combination with carbon steel reinforcement
Smith River Bridge, Oregon, USA	1998	1.4406	
Haynes Inlet Slough Bridge, Oregon, USA	2003	1.4462	
French Creek, Chautauqua Co., NY, USA	2003	1.4406	
South Work St. Bridge, Falconer, NY, USA	2004	1.4462	
Bridge on I 29, Sioux Falls, South Dakota, USA	2004	1.4462	
Belt Parkway Bridge, Brooklyn, NY, USA	2004	1.4462	
Thorold Tunnel, Ontario, Canada		1.4406	Rehabilitation of walls
Parking garage, Brighton, UK		1.4406 1.4307	



Stonecutters Bridge, Hong Kong, China
Date: 2010
Material: 1.4301
Elements: part of the towers between the pile cap and deck level

Hong Kong - Shenzen western corridor, China
Date: 2005
Material: 1.4301; 1.4436; 1.4462
Elements: support to the approach bridges

Broadmeadow Bridge, Ireland
Date: 2003
Material: 1.4436
Elements: column reinforcement cages

Sheik Zayed Bridge, Abu Dhabi United Arab Emirates
Date: 2010
Material: 1.4462
Elements: lower part of supports in the outer layer

Gateway Bridge, Brisbane, Australia
Date: 2011
Material: 1.4162 and 1.4462
Elements: Piers and deck

Driscoll Bridge, NJ, USA
Date: 2005
Material: 1.4462
Elements: Expansion and rehabilitation

Woodrow Wilson Bridge, USA
Date: 2008
Material: 1.4406; 1.4462

Fig. 11. Illustrations of transport infrastructures built or rehabilitated with stainless steel reinforcement [*].

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[*] Figure placed together with photos from different sources:
http://www.roadtraffic-technology.com/projects/stonecutters/stonecutters1.html;
http://www.hyd.gov.hk/contractwebsites/swc/SitePhotos/200404/viewphotos.htm;
http://www.stainlessplumbing.net/index.cfm/ci_id/14202/la_id/search.html;
http://www.arminox.com/Default.aspx?ID=341;
http://www.roadstothefuture.com/Woodrow_Wilson_Bridge.html ;
http://www.nj.com/news/index.ssf/2008/07/driscoll_work_is_on_schedule_f.html;
http://www.assda.asn.au/component/rsblog/view/69-stainless-integral-to-bridges-300-year-design-life

Sydney Opera House, Australia
Date: 1990
Material: 1.4436
Elements: forecourt

Colosseo, Rome, Italy
Material: 1.4307
Elements: foundations

Guildhall Yard, London; UK
Date: 1996
Material: 1.4301
Elements: floor spanning and external walls

Fig. 12. Illustrations of contemporaneous and historical buildings rehabilitated with stainless steel reinforcement [*].

Brisbane River Walk, Australia
Date: 2003
Material: 1.4436
Elements: pontoon system

Seawall, Blackpool, England

Sydney Harbour, Australia
Material: 1.4462

Fig. 13. Illustrations of different applications of stainless steel reinforcement [†].

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[*] Figure placed together with photos from different sources:
http://www.blucher.com.au/site/what_we_do/key_projects/sydney_opera_house.jsp
http://www.nickelinstitute.org/en/TechnicalLiterature/Reprint/LongLifeAmbition_14041_.aspx
http://www.reval-stainless-steel.com/restoration___.html

[†] Figure placed together with photos from different sources:
http://www.assda.asn.au/component/rsblog/view/50-brisbane-riverwalk-floating-in-stainless
http://www.arminox.com/Default.aspx?ID=340

6 Design and construction practices

6.1 Guidance on grade selection

Stainless steel reinforcement is generally specified to design structures with a very long service life because being a material more resistant to corrosion will inevitably extend the corrosion initiation period. Considering that corrosion resistance is of primary concern when stainless steel is specified, BS 6744:2001+A2:2009 [22] provides general guidance related with the suitability of different grades for a range of service conditions (Table 7).

Table 7. Guidance on the use of stainless steel reinforcement for different service conditions (adapted from BS 6744:2001+A2:2009 [22]).

Grade EN 10088-1	**Service condition**			
	Structures or components with either a long design life, or that are inaccessible for future maintenance	Structures or components exposed to chloride contamination with no relaxation in durability design	Reinforcement bridging joints, or penetrating the concrete surface and also subject to chloride contamination	Structures subject to chloride contamination where reductions in normal durability requirements are proposed
1.4301	1	1	5	3
1.4162	1	1	5	3
1.4436	2	2	1	1
1.4429	2	2	1	1
1.4362	2	2	1	1
1.4462	2	2	1	1
1.4529	4	4	4	4
1.4501	4	4	4	4

1 – Appropriate choice for corrosion resistance and cost.
2 – Over specification for corrosion resistance for the application.
3 – May be suitable in some instances: specialist advice should be obtained.
4 – Grades suitable for specialist applications which should be specified after consultation with corrosion specialists.
5 – Unsuitable for the application.

The selection of a stainless steel grade for a given application depends mostly on environmental aggressivity, corrosion resistance of the alloy, and design service life. Other determining factors include mechanical and physical requirements, as well as cost aspects.

6.2 Design durability requirements

There are some changes in the design concept of durable structures with stainless steel reinforcement, despite the fact that there are no significant changes in the design specifications comparatively with common carbon steel reinforced structures excepting some changes in the durability requirements.

The high corrosion resistance of stainless steel allows making relaxations in the design durability requirements, which can have additional economic advantages. Concrete cover can be relaxed to 30 mm irrespective of the concrete mix and quality or exposure condition [18],[24]. This enables further optimizations regarding concrete durability and cost. According to EN 1992-1-1:2004 [93], in the cases where stainless steel is used, the minimum cover may be reduced by $\Delta c_{dur,st}$, which may be included in the National Annex of each country. The

Portuguese Annex to 1992-1-1:2004 European standard adopts a 20 mm value for $\Delta c_{dur,st}$ when reinforced austenitic or duplex stainless steel alloys are used.

Stainless steel does not require additional corrosion protection, and the allowable crack width on the concrete surface can be relaxed to 0.3-0.4 mm, if only its consequences on the corrosion process are considered [18],[24].

6.3 Fabrication, transport, storage, and handling

According to BS 6744:2001+A2:2009 [22], the bend tested samples from production batches must show no sign of fracture or irregular bending deformation when submitted to the specified bend tests.

Stainless steel grades can be cut and bend in accordance with BS 8666:2005 [94], by the methods commonly used for carbon steel. Nonetheless, some differences between carbon and stainless steels, as strain hardening and more spring of stainless steel, must be taken into account.

For cut and bend on site, special care is due to avoid contamination of stainless steel with rust staining from carbon steel. Thus, to reduce the risk of impairing the corrosion resistance of stainless steel, it is advisable to use cutting and bending equipment specifically designed for that purpose.

Since corrosion resistance may also be impaired by oxides formed during the cutting process, these should be removed with a pickling paste.

The major concern regarding stainless steel transport, storage and handling is the rust contamination from the contact with carbon steel. The passivity characteristic is self-restored after any likely mechanical damage during handling. However, care is due to avoid formation of crevices that may decrease the corrosion resistance of stainless steel.

6.4 Installation, welding, and coupling

Some documents related with the use of stainless steel reinforcement include guidance on installation and joint techniques [2],[18],[24]. Accordingly, stainless steel reinforcement should be fixed with stainless steel tying wire and should be used with spacers made of plastic, concrete, or mortar, and stainless steel chairs should be used as supports.

Welding of stainless steel reinforcement is possible but generally not recommended on site unless the requirements for a good quality can be fulfilled. Incorrect welding procedures, such as, poor subsequent surface treatment may lead to considerable reduction in corrosion resistance. Instead of welding, the use of stainless steel couplers is normally recommended.

For detecting austenitic grades, which are non-magnetic, special cover meters are already available to locate bars and to measure cover depths. Conventional cover meters can be used to detect duplex grades, though checking and calibrations are necessary due to the poor conductivity of the alloys.

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