STAINLESS STEEL REBAR: THE CHOICE OF SERVICE LIFE

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Abstract

Use of stainless steel rebar for concrete reinforcement is increasing worldwide. When life cycle costs of the structures are taken into account, stainless steel proves to be a viable solution because of its enhanced properties.

Austenitic and duplex stainless steels are used as rebar because they present an excellent combination of corrosion resistance in concrete, high strength and good ductility. This article summarizes those data in comparison with conventional carbon steel reinforcements to point out the specificities and advantages of the stainless steel solution. The influence of the fabrication method (cold or hot rolling) on microstructure, strength and ductility is also discussed.

The resistance to pitting corrosion of various stainless steels has been evaluated in the laboratory by electrochemical tests to select the most suitable one according to the environment in which the concrete structure is located and the risks of aggressive atmospheres and attack to which it will be exposed during its life. The studied grades are: 1.4301, 1.4311, 1.4404, 1.4429, 1.4362 and 1.4462. The tests were carried out at pH between 8 and 12 in chloride-containing solutions to simulate the concrete pore liquid in a seawater environment or in case of penetration by road de-icing salts. A classification of the selected austenitic and duplex grades was obtained.

INTRODUCTION

Corrosion is the most important cause of deterioration and failure in reinforced concrete structures and buildings. Because it possesses good corrosion resistance, stainless steel enables this phenomenon to be overcome. The use of stainless steel reinforcing bars as a partial or total replacement of steel reinforcing bars is a solution for vulnerable structures that are subject to aggressive atmospheres, especially those exposed to chloride attacks (seawater in coastal areas, de-icing salts). The use of stainless steel rebar is seeing continuous and constant growth in a number of countries: their effect on the durability of structures is now proven and recognised [1-3].

Austenitic stainless steels are often recommended since they present an excellent combination of corrosion resistance in concrete, strength and ductility. Duplex grades may have an economical and technical advantage. Their corrosion resistance is similar or better than austenitic grades and they possess higher tensile and yield strengths.

MAIN BENEFITS OF STAINLESS STEEL REBARS

Corrosion resistance

Conventional carbon steel reinforcing bars find their limitations when there is a contamination of the concrete by aggressive agents that corrode the rebar and lead to the failure of the structure. Corrosion will be initiated when the pH value decreases. This phenomenon is caused by carbonatation (long term evolution due to carbon dioxide diffusion into the concrete) and/or penetration of chlorides, in seawater environment or in the presence of road de-icing salts [4].

Traditional methods to prevent carbon steel rebar to corrode include: higher concrete covers, additives to concrete, coated rebar (epoxy or galvanisation), corrosion inhibitors, cathodic protection, etc... [5] Corrosion can also be avoided by using stainless steel as partial or complete substitution to carbon steel rebar. It offers high corrosion resistance and decreases the risk of spalling of the concrete cover caused by the corrosion products expansion. Austenitic and duplex grades are usually recommended for use as rebar [6]. Their corrosion behaviour in concrete is discussed in section 3.

Mechanical properties

Mechanical specifications are usually aligned to those of carbon steel rebar. Table I summarizes the tensile properties required by some European standards. Part of these texts applies exclusively to stainless while others include both carbon and stainless steels.

The tensile properties of stainless steel rebar at room temperature depend on composition and method of fabrication [7]. This topic will be discussed in the next section. In general, stainless steel rebars offer higher strength and ductility (Table II). Therefore weight saving is possible by decreasing the sections of the reinforcements.

Table I. National standard requirements for mechanical properties of stainless steel rebar (R_m: tensile strength, $Rp_{0.2}$: 0.2% proof strength, A_{gt}: total elongation at maximum force, A: elongation at fracture).

	France: NF A35-014	G.B.: BS 6744	Italy: DM 09/01/96	Germany: DIN 488
R_m (MPa)	-	-	> 540	> 550
$Rp_{0.2}$(MPa)	> 500 or > 650	> 500 or > 650	> 430	> 500
$R_m/Rp_{0.2}$	> 1.10	> 1.10	-	-
A_{gt} (%)	> 5	> 5	-	-
A (%)	-	A5d > 14	A5d > 12	A10d > 8

Table II. Comparison of tensile properties of 1.4301 stainless steel and carbon steel rebar, cold rolled, Ø8mm.

	Carbon steel	Stainless steel
R_m (MPa)	600	880
$Rp_{0.2}$(MPa)	560	670
$R_m/Rp_{0.2}$	1.07	1.31
A_{gt} (%)	7.5	21
A_{5d} (%)	12	35

Fatigue

Stainless steel, especially austenitic, offer good fatigue resistance and ductility. The plastic energy dissipation is more than twice as high as carbon steel, which is a strong advantage for construction projects in seismic areas [8].

High temperature

Austenitic stainless steels maintain high mechanical properties at elevated temperatures: yield and tensile strengths decrease gradually with temperature whereas carbon steels show a significant drop above 500°C. Moreover, stainless steel reinforced structures are less sensitive to the spalling of concrete as few oxides form on steel surface at high temperature. Both aspects lead to a better resistance in fire.

Low temperature, cryogenic applications

Austenitic stainless steels does not present a ductile to brittle transition around 0°C as it happens in carbon steels. They are ideal candidates for cryogenic applications, as their toughness remains very high at temperatures as low as -196°C. Duplex stainless steel may not be used below -50°C [9].

Physical properties

Austenitic steels are considered in essence as non-magnetic (paramagnetic) although their magnetic permeability varies with chemical composition and cold working. Austenitic stainless steel rebar may be used whenever magnetic fields have to be controlled or reduced, for instance: medical buildings, radio and TV transmitters, highly computerized sites, airports and bioarchitecture. [10,11]

Austenitic stainless steels also have the advantage of lower thermal conductivity, which finds use in buildings to limit heat bridges for better thermal insulation.

Austenitic and, to a lower extend, duplex stainless steels have higher coefficients of thermal expansion than that of conventional steels (Table III), but this is counterbalanced by the reduced thermal conductivity. However no problem in concrete has been reported in the literature so far.

Table III. Physical properties of stainless and carbon steel rebar.

	Carbon steel	Austenitic stainless	Duplex stainless
Magnetic	yes	no	yes
Mean coefficient of thermal expansion between 20°C and 100°C (10^{-6} K^{-1})	10	16	13
Thermal conductivity at 20°C ($W.m^{-1}.K^{-1}$)	40	15	15

Cost

The main apparent drawback of stainless steel rebar is its cost. The price of stainless steel is about six to ten times higher than carbon steel. But the cost of rebar is only a small percentage of the overall initial cost of a project. Ultimately the differences are minimal because:

- all the steel reinforcements are very rarely replaced by stainless steel reinforcements; only some of the reinforcing bars are replaced;

- the differential only relates to the material cost threshold, since all the other costs (transport, shaping and installation) remain identical.
- the use of stainless steel reduces the quantities of concrete, weights of the reinforcing bars (due to higher mechanical strength).

This cost differential is often largely offset by long-term benefits derived from stainless steel. The savings to be made include: maintenance and inspection costs, operating interruptions due to maintenance and, of course, the extension of service life of the structure.

Life cycle costing techniques have been developed to take into account all costs (direct and indirect) during the desired service life of a construction: initial costs, maintenance, replacement, traffic disruption costs, etc... Numerous studies based on life cycle cost calculations, conducted in North America and in European countries on structures monitored over several years, have demonstrated that the use of stainless steel reinforcing bars represents an advantageous economic solution sought to optimise the overall cost of the structure, in particular by reducing the maintenance costs. Several case studies have been published and demonstrate that the use of stainless steel as rebar is a cost-effective solution mainly because it offers a maintenance free service life. [1,10,12-14].

INFLUENCE OF FABRICATION ON MECHANICAL PROPERTIES AND MICROSTRUCTURE

Manufacturing methods

The two main production routes of stainless steel reinforcing bars are cold rolling and hot rolling, depending on which process is used to shape the ribbed profile (Figure 1). Plain round bars can also be used as reinforcement. In this paper, we only refer to ribbed bars. Size range covers 5 to 50mm. Small diameters may be produced in bars or coils. Cold rolling is limited to smaller diameter because of the force required for plastic deformation.

Comparison of hot- and cold-formed stainless steel rebars

The stainless steel rebar studied in this paragraph were produced by Ugitech.

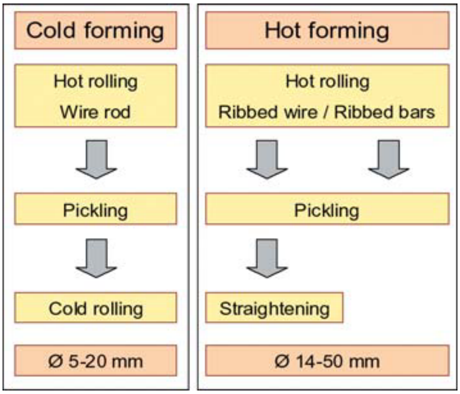

Figure 1. Usual production routes of stainless steel rebar.

Austenitic stainless steels:

Cold-formed austenitic long products (drawn bars or wires, cold-rolled rebar) offer a combination of high strength and good ductility. The high work-hardening rate of austenitic stainless steel grades makes it possible to achieve yield stress level of 500 MPa or higher and elongation at maximum force higher than 15%.

On the contrary, hot rolled austenitic bars usually exhibit a lower yield stress because recrystallization process takes place during hot working. For instance, the yield strength of a 1.4301 round bar in the normal as-rolled condition is about 300 MPa. The solutions to increase strength include using a modified chemical composition (addition of nitrogen) and/or warm working process. 1.4311 (304LN) and 1.4406 or 1.4429 (316LN) may substitute for 1.4301 and 1.4404 when hot-rolling process is chosen. Nitrogen alloying has been widely used to increase strength in austenitic stainless steels [15, 16]. The effect of nitrogen on yield strength in the annealed condition is about +50 to 70 MPa per 0.1%N. As a consequence, a 0.2%N containing austenitic grade will hardly reach 450 MPa in the normal as-rolled condition. To achieve higher strength, hot-rolling conditions have to be controlled, to limit grain size (Hall-Petch effect) or even inhibit recrystallization. Decreasing finishing temperatures is a way to get a partially recrystallized microstructure and guarantee high yield strength [17]. This process is similar to warm working.

Figure 2 shows the differences in tensile test between hot- and cold-rolled austenitic stainless steel rebars. The hardening effect of cold rolling is higher than that of thermo-mechanically controlled hot rolling. Both stainless products maintain high ductility, measured by elongation at maximum force or elongation at fracture.

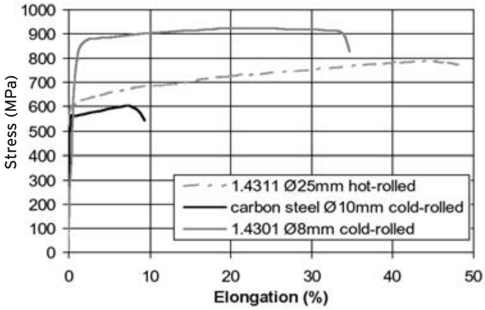

Figure 2. Tensile curves of hot and cold rolled austenitic stainless steel rebar and cold rolled carbon steel rebar.

Microstructures of the corresponding reinforcements are displayed in Figure 3.

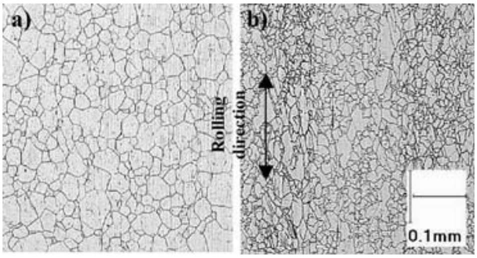

Figure 3. Microstructures of hot and cold rolled austenitic stainless steel rebar (nitric acid etching) a) 1.4301 cold rolled Ø8mm; b) 1.4311 hot rolled Ø25mm.

Duplex stainless steels:

Duplex grades exhibit twice as high yield strengths as austenitic grades in the annealed condition. Levels of 500 MPa and 650 MPa are easily achieved by respectively hot rolled and cold rolled 1.4462 rebar. The strong strain hardening potential of 1.4462 and 1.4362 duplex grades lead to very high strengths. However, ductility remains at least as good as that of carbon steel.

Thermo-mechanically controlled hot rolling can be applied to duplex stainless steels too to achieve higher strengths. The hardness of the austenite phase is increased when rolling temperature decreases.

Thanks to its remarkable mechanical properties, duplex rebar may enable weight savings as the sections of the reinforcements can be decreased for a given load.

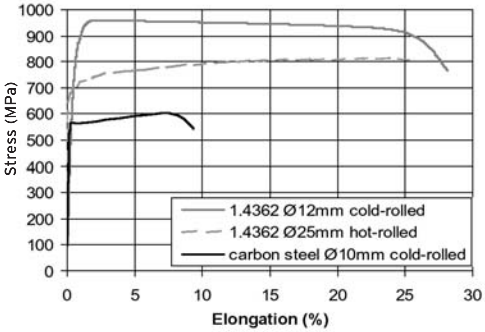

Figure 4. Tensile curves of hot and cold rolled duplex stainless steel rebar and cold rolled carbon steel rebar.

CORROSION RESISTANCE OF STAINLESS STEEL REBAR

Materials

The following austenitic and duplex stainless steel grades have been tested: 1.4301, 1.4311, 1.4597, 1.4404, 1.4429, 1.4362 and 1.4462. Their chemical composition is given in Table IV. The samples were taken from commercial rebar or wire-rod produced by Ugitech. The preparation includes: mechanical polishing (grade 1200), degreasing, rinsing and drying. The tested surface is 3.5cm², oriented in the longitudinal direction of the products.

Table IV. Chemical composition of the investigated stainless steels (wt%).

	1.4301	1.4311	1.4597	1.4404	1.4429	1.4362	1.4462
C	.043	.024	.053	.018	.020	.019	.023
Si	0.4	0.4	0.8	0.5	0.5	0.4	0.5
Mn	0.8	1.5	7.5	1.5	1.7	1.6	1.5
Ni	8.9	8.6	1.9	11.3	11.1	5.5	4.7
Cr	18.1	18.6	16.3	18.2	18.3	22.9	23.2
Mo	0.4	0.4	0.3	2.5	2.7	2.8	0.2
Cu	0.4	0.4	3.0	0.1	0.3	0.2	0.2
N	.040	.140	.205	.046	.132	.150	.081
S_{ppm}	85	13	2	13	6	3	5

A sample of carbon steel was used as a reference.

Experimental procedure

Stainless steels are passive in concrete as pH is alkaline or almost neutral when carbonated. Therefore general corrosion may not occur. Stress corrosion is generally not a problem because the conditions required to induce this type of corrosion do not occur in normal practice [1,3]. Finally, stainless steel rebar is only subjected to pitting corrosion.

In this study the criterion for evaluating corrosion resistance behaviour is the pitting potential. The higher the pitting potential the greater is the corrosion resistance. Accelerated corrosion tests were carried out using a potentiostat to determine potentiodynamic polarization curves. Samples are placed in an electrochemical cell at a controlled temperature of 50°C, in a chloride-containing solution simulating the concrete pore liquid near the rebar surface. The pitting potential is measured versus a saturated calomel electrode (SCE) and a counter electrode. The polarization curve is plotted from the free potential to the potential corresponding to a $100 \mu A/cm^2$ increase in current density, followed by reverse polarisation to the potential corresponding to a current density of $5 \mu A/cm^2$. The scan rate is 10mV/min.

The tests were carried out in three different conditions. These very aggressive media may represent a bridge pillar in seawater or submitted to de-icing salts.

- Condition A: NaOH 0.1M, NaCl 21 g/l, pH=12, non-carbonated concrete at the beginning of its service life;
- Condition B: $NaHCO_3$ 0.025M, Na_2CO_3 0.025M, NaCl 21 g/l, pH=10, carbonated concrete after ~20 years of service life;
- Condition C: saturated $CaCO_3$, $CaCl_2$, NaCl 21 g/l, pH=8, carbonated concrete after ~50 years of service life.

RESULTS AND DISCUSSION

In condition A simulating a non carbonated concrete, all grades show a good corrosion resistance to pitting (figure 5). 1.4597 austenitic grade has a slightly inferior pitting potential due to its lower nickel content. In these conditions, there is no difference between duplex and austenitic grades. Any grade can be chosen as reinforcement.

Obviously, the presence of chlorides cause accelerated corrosion of the carbon steel reference whose passivity is broken. The corresponding pitting potential is about 500mV in all conditions; it is only displayed in Figure 5.

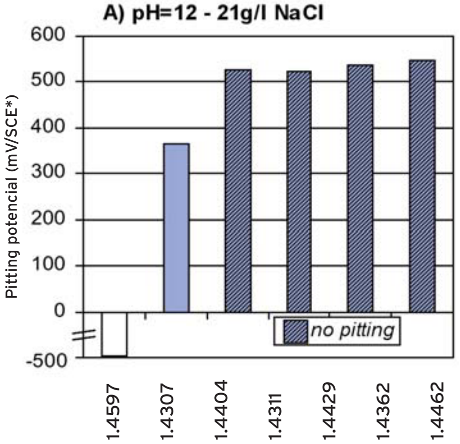

Figure 5. Pitting potential in condition A: NaOH 0.1M, NaCl 21g/l, pH=12, 50°C (non carbonated concrete).

Figure 6 displays the results in condition B where pH is reduced to a value of 10. Duplex grades do not exhibit pitting corrosion in these conditions. A major difference is noted between 1.4301 and 1.4404 austenitic grades and their nitrogen-alloyed counterparts (1.4311 and 1.4429). Nitrogen enhances corrosion resistance, but molybdenum has apparently no effect in this alkaline media. This result differs from the usual observations in acid solutions where Mo significantly improves resistance to pitting [18]. Mo becomes Mo^{3+} that combines with chlorides to inhibit pitting corrosion. A possible explanation of the results reported here is that in alkaline environment Mo dissolves into MoO_4^- that do not interact with chlorides.

In very aggressive corrosion conditions (Figure 7) when pH is significantly reduced by the carbonatation of concrete, it becomes easier to highlight the differences between the investigated grades and obtain a classification. 1.4462 duplex grade has the highest resistance to pitting and will be recommended in the most severe conditions. 1.4362 has a lower pitting potential still higher than that of austenitic grades. Among the latter, high-nitrogen austenitic grades show superior pitting potentials. Figure 7 confirms that in alkaline media, molybdenum does not improve pitting corrosion significantly, as 1.4301 and 1.4404 on the one hand and 1.4311 and 1.4429 on the other hand have close behaviours. This differs from the traditional conditions of use of stainless steels. 1.4362 duplex grade appears as a promising substitute to austenitic grades.

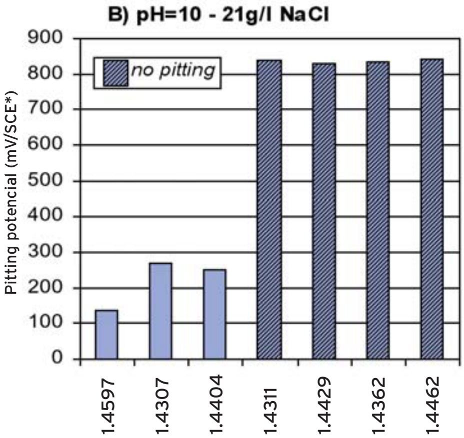

Figure 6. Pitting potential in condition B: $NaHCO_3$ 0.025M, Na_2CO_3 0.025M, NaCl 21g/l, pH=10, 50°C.

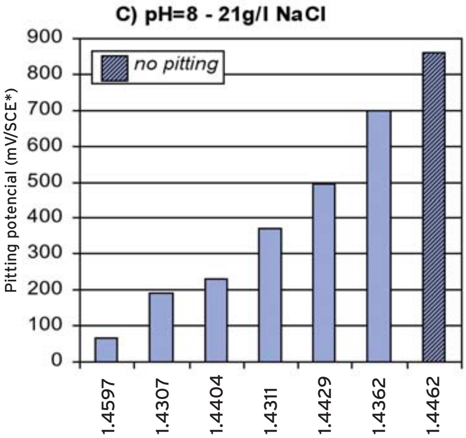

Figure 7. Pitting potential in condition C: saturated $CaCO_3$, $CaCl_2$, NaCl 21g/l, pH=8, 50°C.

Recommendations based on these corrosion test results can be made using the classes of exposure defined in the European Standard EN 206-1. Each class corresponds to environmental actions that potentially risk giving rise to corrosion phenomena in the structure. Table V propose a choice of suitable grades for each class of exposure.

Table V. Recommended grades according to the classes of exposure defined in Eurocode 2.

Class	Definition	Grades
XC	Corrosion induced by carbonatation	1.4597, 1.4301, 1.4404, 1.4311, 1.4429
XD	Corrosion induced by chlorides other than of marine origin	1.4362, 1.4311, 1.4429
XS	Corrosion induced by chlorides present in seawater	1.4462
XF	Frost/defrosting attack, with or without de-icing salt	1.4462

CONCLUSION

Austenitic and duplex stainless steel rebar is a cost-effective solution to overcome corrosion issues in concrete reinforced structures. Their main benefits are:

For austenitic:

- higher yield strength than carbon steel, at room and elevated temperature
- high ductility and plastic energy dissipation (use in seismic areas)
- high toughness even at cryogenic temperature
- non magnetic
- low thermal conductivity

For duplex:

- higher yield strength than austenitic with good ductilty
- very high corrosion resistance to pitting

Fabrication process is the key to achieve high strengths and thus reduce the sections of the rebar (weight saving). Cold forming (rolling, straightening) is a well-known solution, taking advantage of the strain hardening of austenitic and duplex grades. Hot formed rebar can be strengthened as well by thermo-mechanical controlled rolling or warm rolling.

Electrochemical tests in chloride-containing solutions at pH between 8 and 12 simulating the concrete pore liquid in contact with the rebar were carried out. The following classification of the investigated grades was obtained: (in decreasing resistance to pitting order) 1.4462 > 1.4362 > 1.4429~1.4311 > 1.4404~1.4301 > 1.4597. These results show no effect of molybdenum in alkaline media and a positive effect of nitrogen additions to austenitic grades. 1.4362 has a technical and economical advantage versus austenitic grades and may be a substitute. 1.4462 may be chosen in very aggressive atmospheres.

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