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European Federation of Corrosion Publications

Series Introduction

The EFC, incorporated in Belgium, was founded in 1955 with the purpose of promoting European co-operation in the fields of research into corrosion and corrosion prevention.

Membership is based upon participation by corrosion societies and committees in technical Working Parties. Member societies appoint delegates to Working Parties, whose membership is expanded by personal corresponding membership.

The activities of the Working Parties cover corrosion topics associated with inhibition, education, reinforcement in concrete, microbial effects, hot gases and combustion products, environment sensitive fracture, marine environments, surface science, physico-chemical methods of measurement, the nuclear industry, computer based information systems, corrosion in the oil and gas industry, and coatings. Working Parties on other topics are established as required.

The Working Parties function in various ways, e.g. by preparing reports, organising symposia, conducting intensive courses and producing instructional material, including films. The activities of the Working Parties are co-ordinated, through a Science and Technology Advisory Committee, by the Scientific Secretary.

The administration of the EFC is handled by three Secretariats: DECHEMA e. V. in Germany, the Société de Chimie Industrielle in France, and The Institute of Materials in the United Kingdom. These three Secretariats meet at the Board of Administrators of the EFC. There is an annual General Assembly at which delegates from all member societies meet to determine and approve EFC policy. News of EFC activities, forthcoming conferences, courses etc. is published in a range of accredited corrosion and certain other journals throughout Europe. More detailed descriptions of activities are given in a Newsletter prepared by the Scientific Secretary.

The output of the EFC takes various forms. Papers on particular topics, for example, reviews or results of experimental work, may be published in scientific and technical journals in one or more countries in Europe. Conference proceedings are often published by the organisation responsible for the conference.

In 1987 the, then, Institute of Metals was appointed as the official EFC publisher. Although the arrangement is non-exclusive and other routes for publication are still available, it is expected that the Working Parties of the EFC will use The Institute of Materials for publication of reports, proceedings etc. wherever possible.

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Preface

The use of stainless steels as a means of preventing corrosion problems in reinforced concrete structures that are exposed to aggressive environments has been a topic of research in several countries over many years. This review was prepared by a Task Group, chaired by Prof. Dr. U. Nürnberg, as a contribution to the activity of the EFC Working Party on Corrosion of Reinforcement in Concrete. It serves to highlight the differences in performance of a number of the more common grades of stainless steel in concretes that are subject to varying degrees of contamination by chloride salts and carbonation. Relative costs and possible areas of application are also considered.

The members of the Task Group which prepared the review were as follows:

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U. Nürnberg (Germany) – Convenor of the Task Force  
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It is hoped that the document will be of value to civil/structural engineers and materials specifiers working in the construction industry.

C.L. Page  
Chairman  
Working Party on Corrosion of Reinforcement in Concrete  
European Federation of Corrosion
Stainless Steel in Concrete

1. Introduction

In reinforced concrete structures the concrete guarantees chemical and physical corrosion protection of the unalloyed reinforcement. Thus, the alkaline electrolyte of the pores passivates the steel and the concrete – as a more or less dense (fine porous) material – keeps corrosion-promoting substances away from the reinforcement, that is, if a sufficient depth of concrete cover is provided. In general, steel in concrete is adequately protected against corrosion.

However, despite these protective mechanisms, corrosion of reinforcement can occur. This can result either from the carbonation of the concrete or from the effect of chloride ions if oxygen and moisture are also available. Chloride ions may penetrate into hardened concrete of structures exposed to marine environments or to de-icing salts.

As a result of the corrosion reaction rust forms and occupies a volume greater than that of the original metal. This process can cause cracking and spalling of the concrete leading to further corrosion and a loss of bond between the concrete and the steel. A dangerous situation can then arise where a structural member loses cross-sectional area since there will then be increasing stress on the remaining section which could possibly lead to structural failure.

If corrosion problems persist additional corrosion protection methods such as galvanising, epoxy coatings, inhibitors or cathodic protection must be used. Nevertheless, there are limits to the application of these [1] and more comprehensive solutions need to be developed.

In the world of repair and restoration of structures stainless steel appears to be the metal often used. Typical applications are usually where a sufficient cover cannot be obtained. An increasing amount of this material is also to be found in bridge engineering [2, 3] and stainless steel is generally located at construction joints or critical gaps between columns and decks. Another typical application is in prefabricated wall elements where the reinforcement connects the outer and inner walls. In cases of very corrosive environments stainless steel may also be used in new constructions. Nevertheless, 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 use of higher quality steels, such as austenitic stainless steels, will increase the reliability of multi-storey car
Stainless Steel in Concrete

park decks and outer stairs which are likely to be contaminated with de-icing salts, concrete elements in thermal baths, piers at the sea-coast and plants for the desalination of sea water. Stainless steel is also suitable for the reinforcement in lightweight pre-cast elements.

2. General Statements

2.1 Types of Stainless Steel*

The term stainless steel does not refer to a single specific material but rather to a group of corrosion resistant steels containing a minimum of 12% chromium. Various alloying additions (nickel, molybdenum, titanium and others) may be added to provide, depending on composition, different mechanical and corrosion properties, weldability and other properties in service.

A minimum of about 12% chromium produces a self-forming passive film of a mixed iron-chromium oxide on the metal surface. An increased chromium content increases corrosion resistance and this may be further improved by additions of nickel, molybdenum, titanium, nitrogen, etc. Nitrogen, chromium and molybdenum are important elements in relation to pitting corrosion (see section 2.2). Nickel especially increases corrosion resistance in acid media.

Added elements, if present at a sufficiently high level, change the structure of the metal, the corrosion behaviour and other performance characteristics which are structure dependent. Stainless steels that are suitable for reinforcement can be divided into three groups according to their metallurgical structure, namely ferritic, ferritic-austenitic and austenitic. In general, it is convenient to regard the ferritic steels as low carbon plain chromium steels containing less than 17% chromium. The austenitic steels are low carbon steels containing chromium as well as nickel, the basic type having 18% chromium and 8% nickel. The typical composition of ferritic-austenitic steels (duplex steels) is 22–28% chromium and 4–8% nickel.

The decision on which of these types of stainless steels to use depends on:

the degree of corrosion protection required

cost aspects

workability and application characteristics (mechanical properties, weldability).

*Comparison of designations of stainless steels in different countries is given in the annex.
2.2 Types of Corrosion of Stainless Steel

There are four types of corrosion of stainless steels: general corrosion, intergranular corrosion, pitting and crevice corrosion, and stress corrosion. The performance of the different stainless steels is now considered in relation to these corrosion types.

General corrosion takes place only if the medium is sufficiently acid. Therefore, a passivated steel cannot corrode in a medium such as concrete. The passive film is also sufficiently stable if the concrete is carbonated.

Intergranular corrosion can only occur as the result of certain structural changes which may arise due to the welding process. All stainless steels are now specially alloyed to avoid this problem.

Stress corrosion can occur when an appropriate combination of factors, such as specific environments e.g. chloride ions, temperature, stress level and pH value are present. The most common austenitic stainless steel type 18Cr-8Ni is sensitive because the nickel content is above the critical value for maximum resistance. However, for reinforcement applications this mode of failure is not considered to be a problem as in normal service stressing conditions will be below a critical level.

Pitting corrosion is the most common form of corrosion of stainless steels in concrete. Because of the critical role of chloride ions, pitting is a particular problem in concrete with high chloride ion concentrations.

The risk of pitting increases with increasing chloride ion concentration, temperature and H⁺ ion concentration (or decreasing OH⁻ ion concentration) and depends on steel composition as well as surface condition. Thus, pitting corrosion is possible on stainless steel bars depending on the type of steel, the state of the surface, the concrete properties (pH value, chloride content) and the potential of the steel. The susceptibility to pitting corrosion increases with the decrease of the so-called 'pitting resistance equivalent (PRE) number' (1 × %Cr + 3.3 × %Mo) i.e., in the order Cr-Ni-Mo steel, Cr-Ni steel, Cr steel. Examples of commercially available standard grades, which can be used in concrete, and their pitting resistance equivalent are shown below (the numbers are according to European Standard codes as given in EN 10088):

<table>
<thead>
<tr>
<th>Grade</th>
<th>Composition</th>
<th>Property</th>
<th>PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4003</td>
<td>X2CrNi12</td>
<td>ferritic</td>
<td>11</td>
</tr>
<tr>
<td>1.4016 (=430)</td>
<td>X6Cr17</td>
<td>ferritic</td>
<td>17</td>
</tr>
<tr>
<td>1.4301 (=304)</td>
<td>X5CrNi 18–10</td>
<td>austenitic</td>
<td>18</td>
</tr>
<tr>
<td>1.4541</td>
<td>X6CrNiTi 18–10</td>
<td>austenitic</td>
<td>18</td>
</tr>
<tr>
<td>1.4401 (=316)</td>
<td>X5CrNiMo 17–12–2</td>
<td>austenitic</td>
<td>24</td>
</tr>
<tr>
<td>1.4571</td>
<td>X6CrNiMoTi 17–12–2</td>
<td>austenitic</td>
<td>24</td>
</tr>
<tr>
<td>1.4462</td>
<td>X2CrNiMoN 22–5–3</td>
<td>ferr.-austen.</td>
<td>32</td>
</tr>
</tbody>
</table>

Welded bars show a distinctly poorer performance than unwelded bars.
and the adverse action of chlorides is more pronounced in carbonated than in alkaline concrete. In the case of welds, scale and temper colours reduce passivity and can aggravate pitting if not removed. In a lot of cases this problem can be solved by pickling or shot blasting the weld. Pickling is, however, not a practical solution in industrial fabrication involving on-site welding of stainless steel.

2.3 Cost Aspects

The higher the alloy content, the higher the cost. To make the best use of available materials it is important to select a steel which is adequate for the application at the lowest cost. With regard to alloy additions, nickel and molybdenum are particularly expensive and those grades having high contents of those elements would be more costly than the leaner alloy compositions. In an earlier UK publication [2] the following relative costs of typical grades of stainless steel in comparison with mild steel are quoted (only in relation to alloy content):

<table>
<thead>
<tr>
<th>Alloyed</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>unalloyed</td>
<td>1</td>
</tr>
<tr>
<td>Cr17</td>
<td>4.3</td>
</tr>
<tr>
<td>CrNi18–10</td>
<td>5.5</td>
</tr>
<tr>
<td>CrNiMo17–12–2</td>
<td>7.7</td>
</tr>
</tbody>
</table>

In Germany the price (April-June 1995) of coiled reinforcing wire was:

<table>
<thead>
<tr>
<th>Alloyed</th>
<th>Price (DM/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unalloyed</td>
<td>0.7</td>
</tr>
<tr>
<td>CrNi12 (ferritic)</td>
<td>4.9</td>
</tr>
<tr>
<td>CrNiMoN22–5–3 (ferritic-austenitic)</td>
<td>8.2–9.0</td>
</tr>
<tr>
<td>CrNiMo17–12–2 (austenitic)</td>
<td>8.3–9.1</td>
</tr>
</tbody>
</table>

It is true that stainless steel is several times more expensive than unalloyed reinforcement, but the additional costs of a structure are only about 5 to 15%.

Because of the lower alloy content, a ferritic chromium steel is cheaper than the austenitic Cr–Ni (–Mo) grades currently being used as stainless steel reinforcement in many countries. For many years nobody contemplated using the leaner ferritic grades of chromium steel for reinforcing bars, probably because of adverse reports of their durability that had been published in 1978 [5] and in 1989 [6]. In recent years in South Africa [7] and Germany [8] ferritic steels with 12 and 11% chromium respectively have been introduced.
2.4 Production and Performance Characteristics of Stainless Steel Reinforcement

For application in concrete structures, austenitic and ferritic-austenitic steels can be produced as ribbed bars within the normal range of strength and deformability requirements. Such bars can be welded as part of normal construction practice.

One of the initial problems in producing stainless steel reinforcing bars was that the yield strengths of 'as rolled' bars were approximately the same as those for mild steel. Therefore no ferritic or austenitic standard steel in the normal as rolled condition would have sufficient strength.

As these steels had a metallurgical structure incapable of being 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 will enable high yield reinforcement strengths to be reached. These processes are however complicated and increase the high material cost of stainless steel.

Acceptable high yield reinforcing bar strengths can be obtained from austenitic stainless steels. In the UK a number of steel grades (302, 304, 316) exist which fulfil the basic property requirements for British Standard reinforcing steels. Whilst there are other means of increasing the strengths of austenitic stainless steel such as cold working (drawing, twisting), a more attractive method is warm working [2, 9]. Warm working is extremely successful in increasing strength levels of small bars (< 12 mm). An effective solution for large diameter bars up to 32 mm is the combination of using a modified composition (an addition of 0.15/0.20% nitrogen) and the warm working process. In addition to strengthening the bars, twisting is also an effective method of removing millscale, which has been found to aggravate pitting corrosion and was previously removed by pickling and shot blasting.

British Standard (BS 6744, 1986, Specification for austenitic stainless steel bars for the reinforcement of concrete) specifies austenitic stainless hot rolled or cold worked deformed steel bars. The grades are 250 and 460 (specified characteristic yield stress in N mm\(^{-2}\)) and the diameter 6–40 mm. The steel types are 304 and 316, which correspond to 1.4301 (X5CrNi 18–10) and 1.4401 (X5CrNiMo 17–12–2). Table 1 shows typical properties for steel grade 316.

In Denmark, cold rolled weldable austenitic stainless steel ribbed bars of the types 304 and 316 are in use [10]; 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. The welds are normally embedded in concrete without any subsequent treatment such as pickling or grinding.
In Italy, mainly austenitic stainless steels 304 and 316 have been used in reinforced concrete structures (Table 2). For the national market, the properties of stainless steel are in accord with the law in force (D.M. 9-1-96, n° 1086/71).

At present in Germany, bars of 10 to 40 mm are offered in the hot rolled condition. With the type 16.5–18.5%Cr, 10.0–13.0%Ni, 2–3%Mo with ~0.2%N a yield stress of 550–880 N mm⁻² can be reached (Table 2). Small diameters of 6 to 14 mm are cold deformed and are of the austenitic type 1.4571; the wires are weldable and also used for welded wire mesh. Typical mechanical properties of a 7 mm wire are documented in Table 3.
The application of these steel types in Germany has up to now been limited because of the high price (the ratio austenitic steel/unalloyed steel is about 9:1, see section 2.3).

Another development, which could significantly reduce the cost, involved producing a stainless steel clad reinforcing bar [9]. In this approach, a core of high tensile ordinary steel to provide strength was 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, if pinholes were present in the cladding there was a potential problem of ‘undercutting’ corrosion.

Ferritic steels in the as-rolled condition have a higher yield strength than austenitic steels. There is a high probability that the bars may be further strengthened by cold twisting [7] or cold rolling [8] (Table 2). 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 after cold deforming.

Owing to their excellent mechanical properties in the as-rolled condition, duplex stainless steels are of interest as materials for reinforcements. In Germany [8] such wires are cold deformed (Table 3), in Italy [11] they are as-rolled and cold deformed (Table 2).

Table 3 Mechanical properties of stainless reinforcing steels in Germany (from [8] and steel maker information)

<table>
<thead>
<tr>
<th>steel grade</th>
<th>chemical composition</th>
<th>condition</th>
<th>bar size</th>
<th>yield stress</th>
<th>tensile stress</th>
<th>elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4429 austenitic</td>
<td>X2CrNiMoN 17–13–3</td>
<td>hot rolled †</td>
<td>10</td>
<td>880</td>
<td>990</td>
<td>20</td>
</tr>
<tr>
<td>1.4571 austenitic</td>
<td>X6CrMoTi 17–12–2</td>
<td>cold rolled **</td>
<td>10*</td>
<td>456</td>
<td>599</td>
<td>39</td>
</tr>
<tr>
<td>1.4462 ferr.-aust.</td>
<td>X2CrNiMoN 22–5–3</td>
<td></td>
<td>7*</td>
<td>870</td>
<td>934</td>
<td>13</td>
</tr>
<tr>
<td>1.4003 ferritic</td>
<td>X2CrNi 12</td>
<td>hot rolled†</td>
<td>~350</td>
<td>~490</td>
<td>~25</td>
<td></td>
</tr>
</tbody>
</table>

* 6–14 mm is possible  † no reinforcing steel  ** values of specific specimens  ‡ minimum values
Welding
Stainless steel reinforcement is generally weldable. However, welding method and type of weld should be considered.

Reinforcing bars which have been strengthened by cold working may have some problems after welding. Welding would cause some loss of strength, since the work-hardening, which has given the steel its higher strength, will be removed by the heat.

Greater problems which may result include adverse effects on corrosion behaviour: thus, scale and temper colours can reduce passivity and aggravate pitting corrosion if not removed by pickling or shot blasting.

Coefficient of thermal expansion
The coefficients of thermal expansion of ferritic steel and concrete are more or less the same (1.2 and $1.0 \times 10^{-5} \, ^\circ\text{C}^{-1}$ respectively). In comparison, the coefficient of thermal expansion of austenitic stainless steel is higher ($1.8 \times 10^{-5} \, ^\circ\text{C}^{-1}$).

If a concrete structure with austenitic reinforcement is exposed to high temperatures (for instance in connection with a fire), 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.

3. Reported Corrosion Resistance of Stainless Reinforcement

To evaluate the corrosion performance of stainless reinforcing steels in concrete exposed to an aggressive environment the following tests have been conducted:

- electrochemical tests involving metal/solution electrolyte or metal/concrete electrolyte systems;
- accelerated laboratory tests carried out on reinforced concrete specimens (the usual methods adopted are partial immersion of specimens in salt solutions or by intermittent exposure to a salt spray);
- long term site exposure tests of reinforced concrete specimens.

Investigation 1 [5,6]

In a ten-year study in the UK a variety of stainless steels, such as the ferritic types 405 (X6CrAl13), 430 (X6Cr17) and the austenitic types 304 (X5CrNi 18–10), 315 (–), 316 (X5CrNiMo 17–12–2), were compared
Stainless Steel in Concrete

together with unalloyed, weathering and galvanised steel using site exposure and laboratory testing. The surface condition of the stainless steels was 'descaled'.

The steels were used as reinforcement for small prisms fabricated with various qualities of concrete cast to different thickness:

<table>
<thead>
<tr>
<th>Aggregate/cement ratio</th>
<th>high permeability</th>
<th>low permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/cement ratio</td>
<td>0.75</td>
<td>0.60</td>
</tr>
<tr>
<td>Cement content (kgm⁻³)</td>
<td>220</td>
<td>290</td>
</tr>
<tr>
<td>28d cube strength (Nmm⁻²)</td>
<td>29</td>
<td>42</td>
</tr>
</tbody>
</table>

The concrete cover was 10 and 20 mm.

A wide range of chlorides (between 0 and 3.2 mass%) were added to the concrete and the specimens, after curing, were exposed to natural environments.

The durability of the reinforcement was estimated by measurement of the development of concrete cracking, weight loss and extent of pitting.

The results indicated that weathering and galvanised steels are unsuitable for use as corrosion resistant reinforcement in heavily chloride-contaminated concrete.

It appears that the additional corrosion resistance of ferritic stainless steels is of advantage in comparison with unalloyed steel when embedded in concretes containing low chloride levels.

However, at high chloride levels these steels suffered severe pitting attack which was concentrated at a few points on the surface: in the poor concrete this occurred above 1–2 mass% Cl⁻ and in the higher quality concrete above 2–3% Cl⁻.

If the concrete cover was reduced then the corrosion intensity increased. The strongest effects occurred at isolated points, where carbonation had reached the steel surface.

All the austenitic stainless steels showed very high corrosion resistance in all the environments tested. No serious corrosion was encountered on any of the bars.

Figures 1–3 show the weight loss of unalloyed and high alloyed ferritic and austenitic steels with respect to chloride content.

Investigation 2 [13]

In these tests mats of 12 mm diameter bars of unalloyed steel and stainless steel type 304 (X5CrNi18–10) were cast into concrete slabs, using a 0.50
Stainless Steel in Concrete

Fig. 1 Weight loss of shot-blasted high-yield steel with respect to chloride content of concrete

Fig. 2 Weight loss of type 430 ferritic steel with respect to chloride content of concrete

Fig. 3 Weight loss of type 316 austenitic steel with respect to chloride content of concrete
water-cement ratio, 260 kg cement per m$^3$ of concrete and covers of 25 to 50 mm. To increase the rate of chloride penetration into the concrete a 15% sodium chloride solution was used for ponding the specimens. The slabs were ponded for 4 days at 16 to 27 °C, rinsed and dried for 3 days at 38°. This process was repeated for 48 weeks.

The ends of the upper and lower mats of the steel bars were electrically connected so that the flow of macrocell corrosion current between the anodic top mat bars to the cathodic bottom mat could be measured.

The conventional black bar generated an average maximum corrosion current density of about 10 mA m$^{-2}$ with respect to the steel surface area, and became severely corroded. Cracking of the slabs was common. The slabs containing stainless steel exhibited no measurable macrocell corrosion current. After the 48 weeks of testing, the bars were found to be free of any corrosion.

The total soluble chloride at the level of the bars with the 25 mm cover after testing was 2.1 mass% related to weight of cement.

Investigation 3 [12]

A four and a half year accelerated corrosion test was undertaken to assess the behaviour of low chromium steel X3Cr12. Plain descaled chromium steel bars and mild steel bars were encapsulated in chloride free concrete prisms and exposed to a simulated severe marine climate. The concrete cover was 12 or 25 mm; the concrete was of medium or poor quality.

After the exposure, examination of the prisms containing mild steel showed spalling of the concrete. A comparison of the bars showed severe pitting of the mild steel and negligible corrosion of the X3Cr12. It was stated that ferritic stainless steel with 12% of chromium might be the best choice in moderately aggressive environments where the higher resistance of the more expensive austenitic stainless steels is not necessary.

The authors try to give an explanation with regard to the non corresponding results of corrosion of ferritic steels of investigations 1 and 2. They suggest that the initial presence of chlorides in the concrete mix in investigation 1 may have hindered the formation of a passivation film on the ferritic steels (these conditions are more extreme than any likely service conditions).

Investigation 4 [14]

The corrosion resistance of austenitic stainless steel type 316 (X5CrNiMo 17-12-2), partly embedded in concrete and exposed to seawater (immersion and tidal zone), has been determined from tests of up to about 12.5
years duration. Unalloyed steel specimens were also tested for comparison.

In this investigation the emphasis was put on crevice corrosion. It was feared that the concrete/stainless steel interface would provide a narrow crevice, particularly favouring corrosive attack. Corrosion of stainless steel embedded in concrete after the exposure time was very localised but negligible and corrosion resistance was significantly better than that of unalloyed steel in the chloride environment. It was considered that the alkalinity of the concrete exerted a beneficial effect on chloride corrosion resistance of high alloyed steel.

The crevice corrosion, that was expected to occur quite rapidly on stainless steel partly embedded in concrete, occurred only exceptionally, thus the most susceptible point was the stainless steel/seawater/concrete junction.

Investigation 5 [10]

Electrochemical investigations (potentiodynamic and potentiostatic polarisation) have been carried out on industrially produced ribbed bars of black steel and stainless steel type 304 (X5CrNi 18–10) and 316 (X5CrNiMo 17–12–2) with and without welds (resistance and MIG/MAG-welding) in mortar samples. The stainless steels were cold-rolled. No attempts were made to remove any deposits from the steel surface that might have been applied during production or welding. All bars were, however, degreased prior to embedment.

The effect of mixed-in chloride (0–8 mass% Cl⁻ by weight of cement) as well as ingress of chloride was investigated.

The corrosion attack on stainless steel was more localised than on black steel. The critical chloride concentration for rebars embedded in chloride-containing mortar was more than ten times higher for stainless than for black steel. However, the corrosion properties of the Cr–Ni–Mo-steel were marginally better than for Cr–Ni-steel.

Welding reduced the critical chloride concentration to 1/3–2/3 of that of the unwelded stainless steels due to the combined effect of oxidation and insufficient compaction of the concrete around the weld. Deposits of each kind act as a starting point for corrosion attack.

Figure 4 gives the results of the potentiostatic polarisation to 0 mV SCE for the 18Cr–10Ni austenitic and black steels. This potential was assumed to be a realistic value that might be obtained for a steel in the passive state. The externally applied current necessary to bring the potential to this value would therefore reflect the natural condition of the steel with respect to a good passivated state. Larger currents would be required in the case of steels in an active corroding condition – as seen, for example,
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for an unalloyed steel or alloyed steels in presence of high chloride concentrations.

These results suggest that austenitic stainless steel bars without molybdenum are sufficiently resistant and therefore suitable for application in chloride environments.

Further reinforced mortar samples with mixed-in chlorides (up to 8% by weight of cement) without and with stainless steel rebars were stored outdoors for 5 months. After exposure the stainless steel samples were nearly all without any sign of corrosion.

Investigation 6 [15]

Stainless clad reinforcing steels of type 304 (X5CrNi 18–10) and unalloyed, galvanized and epoxy-coated steels have been evaluated in a 7-year exposure site programme for corrosion resistance performance in chloride-bearing concretes. The two variables studied were reinforcing material and chloride content of concrete. Bars were cast in prismatic speci-

Fig. 4 Corrosion current density of steel type 304 versus content of mixed-in chloride at 0 mV
mens of 0.45 water-cement ratio good-quality concrete containing three levels of chloride: 0.6, 1.2 and 4.8 mass% by weight of cement. The specimens were exposed to the environment of Eastern Saudi Arabia.

The results show that unalloyed steel bars had suffered severe rust-related damage for all three chloride levels with significant loss of section and rib degradation for 1.2 and 4.8% chloride-bearing concretes. The use of galvanised steel in concretes with high levels of chloride merely delays concrete failure. Epoxy-coated bars performed exceedingly well as corrosion-resistant steel in 0.6 and 1.2% chloride concretes, as no corrosion and concrete cracking were observed. However for the 4.8% chloride concrete, significant corrosion was observed on the substrate steel under the coating. This caused a systematic break-down of the coating and cracking of concrete. These results indicate that epoxy barrier coatings may have a finite tolerance limit for chlorides.

Among corrosion-resisting steels, the best durability performance was exhibited by the stainless-clad reinforcing bars. After 7 years of embedment in 4.8% chloride concrete, no sign of corrosion was observed on any of the bars tested.

Investigation 7 [11, 16, 17]
Electrochemical tests (monitoring the free corrosion potential, measuring the corrosion rate using the linear polarisation method and potentiostatic tests) have been carried out to study the corrosion behaviour of traditional austenitic stainless steel types 304 (X5CrNi 18–10) and 316 X5CrNiMo 17–12–2), and the duplex stainless steel X2CrNiN 23–4 in chloride-contaminated concrete with up to 3% of chlorides (referred to the weight of cement). The tests were conducted on reinforced concrete slabs exposed in the open air. The concrete (w/c = 0.5 and 400 kg m⁻³ OPC) was of good quality. The stainless steel was as-rolled; the specimen surface condition is not known.

All steel types were in the passive state for the whole range of chloride content considered and there was no substantial difference in their corrosion behaviour. The results of potentiostatic tests confirm the passive state even at +400 mV potentials (with respect to an activated titanium reference electrode).

Investigation 8 [8]
To characterise the corrosion behaviour of steel bars, electrochemical tests to determine the pitting corrosion potential were carried out together with comparative field tests on reinforced elements under typical corrosion conditions.
Determination of the pitting corrosion potential

Table 4 shows a list of the cold deformed stainless steels investigated with austenitic, ferritic-austenitic or ferritic structures together with the unalloyed steel used for comparison. These materials were tested in the welded and unwelded conditions. In general, the weld was not treated which means that the tests were performed with fixed weld seams and a thin oxide layer on the surface of the steel bar within the area of the weld. In special cases the weld seam was removed by a corrosive paste.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>material</th>
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<th>effective sum*</th>
</tr>
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<td></td>
<td>DIN-standard number</td>
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<td>1.4439</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>X2CrNiMoN 22–5–3</td>
<td>1.4462</td>
<td>F–A</td>
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<td>F</td>
</tr>
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<td>X20Cr 13</td>
<td>1.4021</td>
<td>F</td>
</tr>
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<td>6</td>
<td>X2CrNi 12</td>
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<td>F</td>
</tr>
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<td>7</td>
<td>X10CrAl 7</td>
<td>1.4713</td>
<td>F</td>
</tr>
<tr>
<td>8</td>
<td>(unalloyed)</td>
<td>1.0466</td>
<td>F</td>
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</table>

* effective sum: \(1 \times \% \text{ Cr} + 3.3 \times \% \text{ Mo}\)
+ for specimens with plain surfaces

The electrochemical potentiostatic investigations on mortar electrodes were performed firstly on welded specimens with a ground plain surface. The values for the surface roughness, which mainly influences the corrosion behaviour, were \(R_{\text{max}} < 20 \mu\text{m}\). On four typical steels (no. 2, 3, 6 and 8 in table 4) tests were also carried out on cold rolled unwelded and welded ribbed reinforcing bars (compare the details in Table 3).

Different concentrations of 1.3 and 5% chloride (related to the cement-content) were added. One half of the alkaline mortar electrodes (without and with chloride) were artificially carbonated.

The results of the potentiostatic tests on the welded plain bars are presented in Figs 5 and 6. The following important conclusions can be drawn:

- The pitting corrosion potential decreased with decreasing effective sum of the steel types. Three main groups could be identified:
the austenitic and ferritic-austenitic types 1.4439 (mat. 1), 1.4462 (mat. 2) and 1.4571 (mat. 3);
- the ferritic types 1.4016, 1.4021 and 1.4003 (mat. 4 to 6) with chromium content ≥ 11 mass%;
- the ferritic types 1.4713 and 1.0466 (mat. 7 and 8) with chromium content ≤ 7 mass%.

The resistance to pitting corrosion decreased gradually in these three steel groups.

Materials 1 to 6 always showed pitting corrosion and the welding area was also corroded. For the materials 7 and 8 no difference was observed between the corrosion within or outside the welded zone and the corrosion ranged from wide pitting to general corrosion.

- In the carbonated concrete, free of chlorides, the welded austenitic, ferritic-austenitic and the welded ferritic steel with ≥ 11 mass% chromium were passive and showed a distinctly better corrosion behaviour than the active materials with ≤ 7 mass% chromium.
- The pitting corrosion potential decreased with increasing chloride content of the concrete. This reduction was more pronounced between 0 and 1 mass% chloride than between 1 and 5 mass%.
The pitting corrosion potential in carbonated concrete with chlorides was always shifted to negative values compared to alkaline concrete with chlorides.

Figure 7 shows the typical type of corrosion of welded, ribbed reinforcing bars based on attack in concrete with chlorides. Single pits were always present and usually started at scores that were present close to the inclined ribs. For comparison, unalloyed materials under comparable corrosion conditions showed a more general attack with wide pits.

Figure 8 shows the results of ribbed steel types 1.4571 (austenitic), 1.4003 (ferritic) and the unalloyed steel. Based on test results the following conclusions can be drawn – in addition to those from welded specimens with plain surface (see above):

- In the welded state ribbed reinforcing bars show a more unfavourable behaviour than plain bars. This is more pronounced for the ferritic steel 1.4003 than for the austenitic steel 1.4571 and more distinct in alkaline than in carbonated concrete.
- Unwelded ribbed stainless steel reinforcing bars in concrete with chlorides show a more positive pitting corrosion potential, $E_L$, than
welded bars. For unalloyed material no difference between welded and unwelded bars was observed.

After the field tests (see below) corrosion can only be expected, if the pitting corrosion potential is more negative than $-100 \text{ mV}_{\text{SCF}}$; in this case the necessary condition $E_L < E_{\text{corr}}$ is fulfilled. According to this definition and the results presented in Fig. 8, for the following materials and conditions, corrosion cannot be excluded or can be extremely likely:

- unalloyed steel (unwelded and welded) in carbonated and/or chloride contaminated concrete;
- ferritic, unwelded steel 1.4003 in chloride-contaminated carbonated concrete;
- ferritic, welded steel 1.4003 in chloride-contaminated, alkaline and chloride-contaminated carbonated concrete;

On the contrary no corrosion may occur:

- for austenitic steel 1.4571 (unwelded and welded) under all possible
Fig. 8 Pitting potential $E_L$ of deformed steel specimens in mortar-electrodes depending on the steel type, the presence of welds, carbonation and chloride content; potentiostatic test ($t = 24$ h), oxygen evolution potential $E = +600$ mV$_{SCE}$
corrosive conditions (carbonated, chloride-contaminated alkaline, chloride-contaminated carbonated);
- for ferritic unwelded steel in chloride-contaminated alkaline concrete.

Further investigations showed, that the treatment of welded areas of specimens with a pickling paste results in an improvement of corrosion behaviour. For the welded material 1.4003 in alkaline concrete with 3% chloride the corrosion potential increased from $-200$ to $+600 \text{ mV}_{\text{SCE}}$.

**Field tests with reinforced concrete elements**

Concrete elements with cold deformed ribbed bars were exposed in open air for up to 2.5 years. The welded materials consisted of unalloyed and stainless steels 1.4003, 1.4462 and 1.4571. There was no treatment of the weld. The concrete types used were a medium normal weight concrete and two qualities of lightweight concrete (autoclaved gas concrete and permeable concrete). The reinforcing bars had a cover of 1.5 and 2.5 cm. In one part of the specimens 1.0 and 2.5 mass% chloride related to weight of cement was mixed in the fresh concrete. Some elements were additionally carbonated. One part of the lightweight concrete specimens were treated similarly to the conditions of structures in the splash zone of highways where deicing salts are used.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Steel} & \text{Concrete} & \text{Normal-weight-concrete} & \text{Carbonated} \\
& & \text{Alkaline} & \text{Carbon.} \\
\hline
\text{Unalloyed} & \text{Unwelded} & 0 & 0.12 \\
& \text{Welded} & 0.3 & 0 \\
\hline
\text{Ferritic 12Cr} & \text{Unwelded} & \text{Unwelded} & \text{Welded} \\
& \text{Welded} & \text{Welded} & \text{Welded} \\
\hline
\text{Austenitic 17Cr-12Ni-2Mo} & \text{Unwelded} & \text{Unwelded} & \text{Welded} \\
& \text{Welded} & \text{Welded} & \text{Welded} \\
\hline
\end{array}
\]

1) Chloride content in concrete

- None
- Moderate
- Severe
- Very severe corrosion

**Fig. 9 Corrosion behaviour of steel in concrete (survey)**

Figure 9 summarises the results of ferritic, austenitic and unalloyed steel by means of corrosion degrees based on pitting depth and loss of weight. Areas without and with weld are separated:
Stainless Steel in Concrete

- As expected unalloyed steel corroded in carbonated and/or in chloride contaminated concrete. The strongest attack occurred in carbonated plus chloride-contaminated concrete.

- The unwelded ferritic chromium steel 1.4003 showed a distinctly better behaviour than unalloyed steel. In carbonated concrete (normal and lightweight concrete) and in chloride-contaminated, alkaline normalweight concrete no attack took place. Nevertheless, in chloride-contaminated, carbonated concrete as for the unwelded steel a reduced pitting corrosion could occur.

For the welded steel within the weld line chlorides produced locally distinct pitting corrosion (Fig. 7). The depth of pitting increased with increasing chloride content and was more pronounced in chloride-containing carbonated concrete. However, for the ferritic chromium steel the pitting at weld lines was deeper than for unalloyed steel, but the overall general corrosion (loss of weight) was significantly smaller.

- No corrosion appeared with the austenitic steel 1.4571 and the ferritic-austenitic steel 1.4462 whether in the unwelded or welded states. This was so for all conditions within the concrete, carbonated and chloride-infiltrated.

Investigation 9 [18]

Concrete prisms containing black steel and low chromium X3Cr12 stainless steel were exposed to a simulated marine environment throughout a period of 4.5 years. After this time of exposure the corrosion damage on the stainless steel was minimal (see investigation 3 [12]).

Tests were also conducted on low chromium stainless steel X3Cr12 and austenitic stainless steel types 304 (X5CrNi 18–10), 316 (X5CrNiMo 17–12–2), high strength carbon steel, galvanised steel and epoxy-coated steel. Reinforced concrete prisms were exposed to the simulated marine environment. Other prisms were exposed to a natural coastal climate, where high temperatures, the proximity to the sea and high humidity result in a severe corrosive environment.

After 1 year of testing in the simulated marine climate, all carbon steel prisms had cracked and stained. Most of the galvanised specimens had also cracked. In contrast none of the three stainless steels or epoxy-coated rebar prisms showed evidence of cracking although localised corrosion was observed on the XCr12 stainless steel bars.

None of the prisms stored near the sea exhibited any cracking. However during inspection of bars removed it was observed that the black bars exhibited some corrosion damage.
The localised corrosion behaviour of polished austenitic steel 304 (X5CrNi 18–10), 304L (X2CrNi 18–10), 316 (X5CrNiMo 17–12–2) and 316L (X2CrNiMo 17–13–2), martensitic steel 410 (X10Cr13), duplex stainless steel X2CrNiN 23–4, superaustenitic steel X1CrNiMoN 20–18–6, and also carbon steel for comparison purposes, has been studied in several solutions simulating the liquid present in the pores of both alkaline and carbonated concrete in presence of chloride ions. The work was aimed at evaluating the suitability of these steel types as rebars in reinforced concrete structures exposed to very aggressive environments and under temperatures typical of temperate climates, tropical climates, tunnels and tanks.

Electrochemical tests for evaluating the critical chloride content at a potential of +200 mV vs SCE were performed in solutions with pH values in the range 7.6–13.9, chloride concentration ranging from 0 to 10% and temperature of 20 and 40°C. The adverse effect of pH on the critical chloride content is discussed as a function of stainless steel composition and temperature.

Potentiostatic tests in saturated Ca(OH)₂ solution (pH 12.6) of 20°C at +200 mV_SCE showed that corrosion initiated on carbon steel, when a chloride concentration of 0.1–0.6% was reached. The critical chloride content for low-chromium stainless steel 410 (X10Cr13) was 2%. Concentrations higher than 5% were reached for austenitic stainless steels, and no localised corrosion attacks were observed on ferritic-austenitic duplex steel (X2CrNiN 23–4), austenitic stainless steel type 304 (X5CrNi 18–10), 316L (X2CrNiMo 17–13–2) and superaustenitic steel (X1CrNiMoN 20–18–6) up to 10% chloride concentration (Fig. 10).

A beneficial effect of alkalinity on chloride-induced corrosion was observed both on carbon steel and stainless steels. At room temperature, the critical chloride content for carbon steel increased from 0.1–0.6% at pH 12.6 to 6% in the solution at 13.9 pH. All stainless steels had critical chloride contents exceeding 10% Cl⁻ in the solution with 13.9 pH.

Tests in solutions simulating the carbonated concrete pore liquid showed that stainless steels, although still passive, have a lower resistance to chloride-induced corrosion. The critical chloride concentration decreased, especially for steels with low chromium content. For example 0.5% Cl⁻ concentration was enough to promote localised attack on stainless steel 410 (X10Cr13) at 7.6 pH.

The increase of temperature from 20 to 40°C resulted in a decrease of localised corrosion resistance except for superaustenitic stainless steel, which did not suffer any localised attack at 7.5 – 13.9 pH. For example, in the solution of 12.6 pH a reduction of critical chloride content to 4.5% for
stainless steels and 3.5% for duplex stainless steel was found during tests at 40°C.

The results of the tests in solutions simulating the concrete pore solution show:

- Stainless steels of the type X10Cr13 can be used in carbonated concrete, provided a relatively low chloride content (not exceeding roughly 0.5%) is expected. In alkaline environments, this steel might be useful for chloride contents up to 2%.

- For higher chloride concentration (up to 5%) austenitic stainless steels are necessary at pH values typical of alkaline or carbonated concrete. As far as alloy composition is concerned austenitic stainless steel 304 (X5CrNi 18-10) and 316 (X5CrNiMo 17-12-2) and ferritic-austenitic duplex steel X2CrNiN 23-4 showed a similar resistance to chloride induced pitting corrosion in alkaline and carbonated media. At 40°C the austenitic steel showed a better behaviour than the duplex ferritic-austenitic steel. The superaustenitic steel X1CrNiMoN 20-18-6 is justified only under very extreme conditions, i.e., unusually high chloride concentrations and temperatures and carbonated concrete.
Severe cyclic wetting and drying tests were conducted on various types of stainless steel bars, and on a single type of stainless steel clad bar. The performance of the bars was monitored by visual inspection and electrochemical polarisation resistance measurements to determine corrosion rates at selected intervals. All bars were 16 mm diameter. Stainless steel types 304 (X5CrNi 18–10), 304N (X2CrNiN 18–10), 316 (X5CrNiMo 17–12–2), 317L (X2CrNiMo 18–16–4), Nitronic 33 (–), XM–19 (–) and solid titanium rods were tested.

The testing consisted of 1.25 hours of immersion in the salt solution, followed by 4.75 hours of air drying. Two test solutions were chosen to represent conditions found in practice. A 3% NaCl solution was used to simulate outside salt contamination that could occur prior to the bars being placed into concrete. The second solution was a 13.3 pH solution with NaCl used to simulate bars embedded in salt-contaminated concrete.

The results from linear polarisation measurements are shown in table 5. Table 6 shows the ratio of the corrosion rate of each corrosion-resistant material to that of black steel.

The 28-day corrosion rate of the black steel in the high pH environment solution was only 8 percent of the corrosion rate in the pH 7 solution. In the pH 7 salt solution, the corrosion rate of the stainless steels was approximately 1000 times less than that of black steel, and in the high pH salt solution approximately 100 times less than that of black steel.

<table>
<thead>
<tr>
<th>solution type</th>
<th>3 percent NaCl pH 7</th>
<th>0.3 N KOH + 0.05 N NaOH + 3 percent NaCl pH 13.3</th>
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<td>Nitronic 33</td>
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<td>XM–19</td>
<td>0.16</td>
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Table 6 Corrosion rate reduction of stainless steel and titanium as compared to black bar

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<tr>
<th>bar type</th>
<th>solution type</th>
<th>3 percent NaCl pH 7</th>
<th>0.3 N KOH + 0.05 N NaOH + 3 percent NaCl pH 13.3</th>
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No large variations were observed between the corrosion rates for the various grades of stainless steels tested. Corrosion rates were very low, corresponding to the passive state in the high and low pH salt solutions. Thus, it may be reasonable to choose any of these particular materials based upon their physical characteristics, rather than their generally accepted corrosion performance.

4. Conclusions

As a consequence of the investigations performed, stainless steel is recommended for special applications of reinforced concrete structures. Depending on the actual corrosion attack, ferritic steel or austenitic steel as well as ferritic-austenitic steel can be used.

The corrosion resistance increases in the sequence:

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

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 occurs. Contrary to the
case with unalloyed steel, significant corrosion was observed on alloyed steel only near the weld seam.

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 procedures will lead to a significant reduction in the corrosion resistance.

Stainless steels are resistant in carbonated concrete but may suffer pitting corrosion in chloride-containing concrete. 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.

Austenitic stainless steel of type CrNiMo 17-12-2, even in the welded state, proved to give excellent performance in carbonated or 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.

Of comparable resistance are the ferritic-austenitic (duplex) steels. These materials may provide a suitable solution to the problem of concrete structures requiring rebars with high mechanical strength and good corrosion resistance.

A ferritic grade will suffice in less aggressive environments. The welded application of these materials, which have a favourable cost-efficiency relation, seems to be reasonable if attack by chloride-containing aqueous solutions can be excluded.

The use of stainless reinforcing bars based on the above recommendations can exclude steel corrosion in concrete structures for long periods of service.

5. Open Questions

5.1 Effect of Temperature

The effect of temperature on the thermal expansion of stainless steel reinforced concrete has not been determined in these investigations. It might be significant and this should be borne in mind if structures in warm areas are to be considered, or, in the case of fire.

5.2 Galvanic Corrosion

Because of the very high cost of stainless steel reinforcement it is not likely that the entire reinforcement in, for example, a large marine structure, would be made of stainless steel. A possible alternative would be to use stainless steel as the outer reinforcement in the splash zone. Stainless steel
Stainless Steel in Concrete

and unalloyed steel will then probably be in electrical contact and this could lead to a theoretical risk of galvanic corrosion.

As long as both metals are in the passive state their potentials will be more or less the same when embedded in concrete. 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.

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.

In situations where the unalloyed reinforcement is corroding and the stainless steel is passive, the galvanic coupling will give rise to accelerated corrosion. However, it should be noted that the rate of the cathodic reaction, i.e., of oxygen reduction, might be more inhibited on stainless steel than on unalloyed steel [10].

5.3 Stress Corrosion Cracking

As the tendency to stress corrosion normally increases with increasing chloride content and temperature and decreasing pH value, this form of attack is unlikely to be a problem. Stress corrosion cracking is more likely to occur in welded austenitic structures when these are present in carbonated concrete with extreme amounts of chloride at high temperatures. Nevertheless, stress corrosion cracking was not observed in any of the research described in the present report.

The most well known examples of failure related to cracking are concerned with reinforcement which is protruding from concrete.

References

4. D.B. McDonald, M.R. Shermann, D.W. Pfeifer and Y.P. Virmany:
Stainless steel reinforcing as corrosion protection, Concrete Intern., 1995, 65–70.


18. J. Hewitt and M. Tullmin: ‘Corrosion and stress corrosion cracking

Comparison of designations of stainless steels of producer's countries discussed in the report

<table>
<thead>
<tr>
<th>Steel Quality</th>
<th>Germany</th>
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* Comparable to X2Cr11
This guideline document is specifically concerned with the materials requirements for carbon and low alloy steels typically used in H₂S-containing oil and gas field service.

It is comprehensive in considering all possible types of cracking which may result from exposure of such steels to H₂S-containing producing environments. Thus, besides sulphide stress cracking, step-wise cracking, stress-orientated hydrogen induced cracking and soft zone cracking are also considered.

It gives a systematic approach to the definition of sour service in relation to sulphide stress cracking based on pH as well as partial pressure of H₂S.

Guidelines are given on the materials requirements (strength, hardness, stress relief requirements, microstructure, composition, etc.) appropriate to reducing the risk of all of the types of cracking.

Where materials may not meet the stated requirements their cracking resistance may be assessed using the test methods proposed. Guidance is given on selection of appropriate test method and acceptance criteria are suggested.

The document has been prepared by the EFC Working Party on Corrosion in the Oil and Gas Industry with input from the major oil companies worldwide plus the major industry suppliers and leading research and testing organisations. It is a valuable guide for all persons involved in materials engineering in the oil and gas industry, whether as a specifier, purchaser or supplier.

Guidelines for materials requirements for CRAs for these environments are in preparation.

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The increasing economic pressure to reduce over-design and to extend service life while maintaining acceptable safety margins demands increased reliability in prediction of the performance and lifetime of fabricated structures, components such as valves, and other equipment exposed to hostile environments. Environment-assisted cracking of metals due to absorbed hydrogen has been a major cause of failure of components, structures, pipelines and pressure vessels with sometimes catastrophic results.

Hydrogen is generated by corrosion, by galvanic interaction between dissimilar metals, by cathodic protection, by welding and by electroplating. The hydrogen atoms produced on the surface can enter the metal and will localise in regions of hydrostatic stress and at microstructural sites. Cracking occurs when critical combinations of local hydrogen concentration, stress, strain and microstructural sensitivity are achieved.

This volume is based on a conference held at the National Physical Laboratory, Teddington, UK on 13–14 April 1994. It summarises the extensive research undertaken in Europe to quantify hydrogen uptake and transport in metals in laboratory and field situations and to improve understanding and prediction of cracking in service.
Forthcoming

EFC 19: Sea Water Corrosion of Stainless Steel – Mechanisms and Experiences

This publication contains the papers presented at a workshop in 1995 organised by SINTEF Corrosion and Surface Technology (Trondheim) in co-operation with the EFC Working Parties on Marine Corrosion and Microbial Corrosion. The workshop also formed a closing seminar for the MAST (Marine Science and Technology) Project on ‘Marine Biofilms on Stainless Steels’ – a project funded by the European Communities and involving research laboratories from across Europe.

Particular attention was given to biofilms, their causes, effects and prevention, as well as to the behaviour in sea water of high alloyed austenitic stainless steels including 6Mo, and super duplex stainless steels. The titles in this volume are as follows:

- Comparison of seawater corrosivity in Europe.
- Effect of marine biofilms on stainless steel: Results from a European exposure programme.
- Mechanism and prevention of biofilm effects on stainless steel corrosion.
- Biocide options in the offshore industry.
- Practical consequences of the biofilm in natural seawater and of chlorination on the corrosion behaviour of stainless steels.
- Corrosion behaviour of stainless steel in thermally altered sea water.
- Statistical approach of pitting initiation of stainless steel in flowing sea water.
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