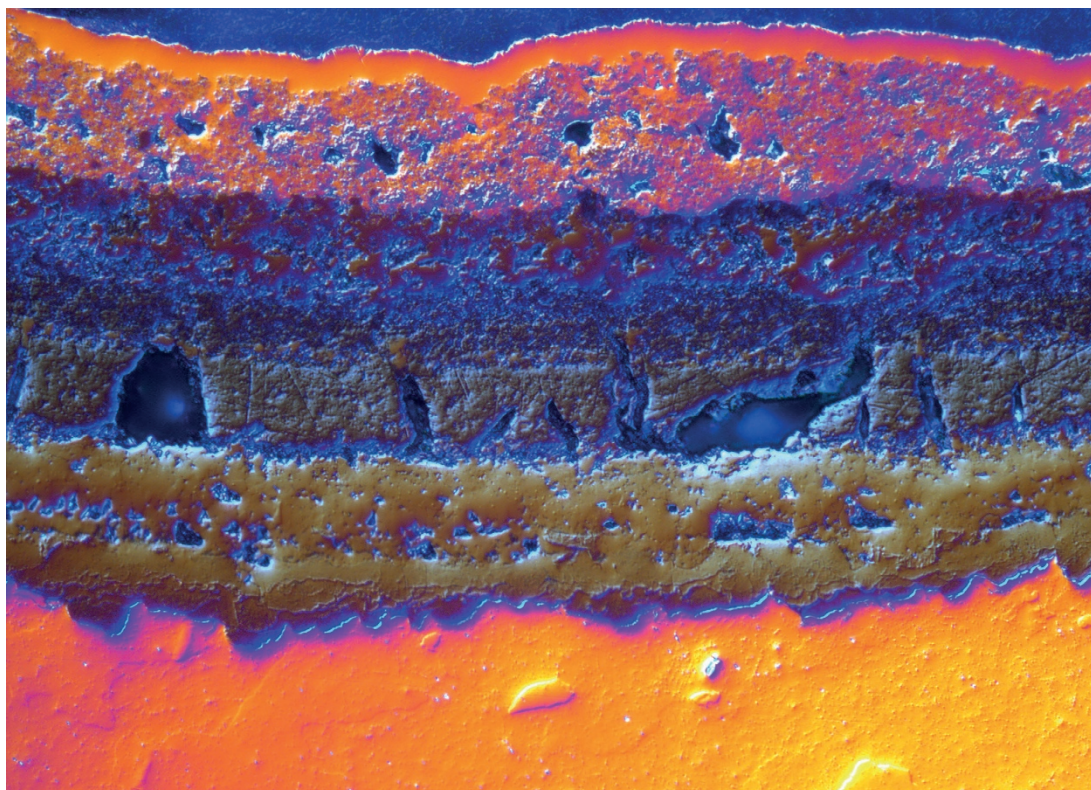


Edited by Michael Schütze,
Marcel Roche, and Roman Bender

WILEY-VCH

Corrosion Resistance of Steels, Nickel Alloys and Zinc in Aqueous Media

Waste Water, Seawater, Drinking Water,
High-Purity Water



DECHEMA the prime source
of corrosion expertise

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and Zinc in Aqueous Media**

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and Roman Bender

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Editors

Prof. Dr.-Ing. Michael Schütze
DECHEMA-Forschungsinstitut
Chairman of the Executive Board
Theodor-Heuss-Allee 25
60486 Frankfurt am Main
Germany

Marcel Roche
President of CEFRAFOR
French Corrosion Society
28 rue Saint Dominique
75007 Paris
France

Dr. rer. nat. Roman Bender
Chief Executive of GfKORR e. V.
Society for Corrosion Protection
Theodor-Heuss-Allee 25
60486 Frankfurt am Main
Germany

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Frankfurt (Main), Germany

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Preface

Practically all industries face the problem of corrosion – from the micro-scale of components for the electronics industries to the macro-scale of those for the chemical and construction industries. This explains why the overall costs of corrosion still amount to about 2 to 4% of the gross national product of industrialised countries despite the fact that billions of dollars have been spent on corrosion research during the last few decades.

Much of this research was necessary due to the development of new technologies, materials and products, but it is no secret that a considerable number of failures in technology nowadays could, to a significant extent, be avoided if existing knowledge were used properly. This fact is particularly true in the field of corrosion and corrosion protection. Here, a wealth of information exists, but unfortunately in most cases it is scattered over many different information sources. However, as far back as 1953, an initiative was launched in Germany to compile an information system from the existing knowledge of corrosion and to complement this information with commentaries and interpretations by corrosion experts. The information system, entitled “DECHEMA-WERKSTOFF-TABELLE” (DECHEMA Corrosion Data Sheets), grew rapidly in size and content during the following years and soon became an indispensable tool for all engineers and scientists dealing with corrosion problems. This tool is still a living system today: it is continuously revised and updated by corrosion experts and thus represents a unique source of information. Currently, it comprises more than 12,000 pages with approximately 110,000 corrosion systems (i.e., all relevant commercial materials and media), based on the evaluation of over 100,000 scientific and technical articles which are referenced in the database.

Increasing demand for an English version of the DECHEMA WERKSTOFF-TABELLE arose in the 1980's; accordingly the first volume of the DECHEMA Corrosion Handbook was published in 1987. This was a slightly condensed version of the German edition and comprised 12 volumes. Before long, this handbook had spread all over the world and become a standard tool in countless laboratories outside Germany. The second edition of the DECHEMA Corrosion Handbook was published in 2004. Together the two editions covered 24 volumes.

Water is commonly described either in terms of its nature, usage, or origin. The implications in these descriptions range from being highly specific to very general. The present handbook compiles new and updated information on the corrosion behaviour of iron, nickel, zinc and their alloys in contact with the following water

grades: drinking water, sea water, industrial and municipal waste water and high purity water.

All water contains some dissolved oxygen and is therefore somewhat corrosive. The rate of corrosion depends on many factors including the water's pH, electrical conductivity, oxygen concentration, and temperature. In addition to corrosion, metals dissolve when the water is extremely low in dissolved salts and in the presence of certain water-borne ions.

Understanding how to improve the corrosion resistance of iron, nickel, zinc and their alloys used in construction, transport and storage vessels and structures against this omnipresent chemical is crucial for all industries involved. This book is therefore an indispensable tool for all mechanical, civil and chemical engineers, material scientists and chemists working with these materials.

This handbook highlights the limitations of iron, nickel, zinc and their alloys in various water grades and provides vital information on corrosion protection measures. The chapters are arranged by the media leading to individual corrosion reactions, and a vast number of alloys are presented in terms of their behaviour in these media. The key information consists of quantitative data on corrosion rates coupled with commentaries on the background and mechanisms of corrosion behind these data, together with the dependencies on secondary parameters, such as flow-rate, pH, temperature, etc. Where necessary this information is complemented by more detailed annotations and by an immense number of references listed at the end of each chapter.

An important feature of this handbook is that the data was compiled for industrial use. Therefore, particularly for those working in industrial laboratories or for industrial clients, the book will be an invaluable source of rapid information for day to day problem solving. The handbook will have fulfilled its task if it helps to avoid the failures and problems caused by corrosion simply by providing a comprehensive source of information summarising the present state of the art. Last but not least, in cases where this knowledge is applied, there is a good chance of decreasing the costs of corrosion significantly.

Finally the editors would like to express their appreciation to Dr. Rick Durham and Dr. Horst Massong for their admirable commitment and meticulous editing of a work that is encyclopaedic in scope.

Michael Schütze, Marcel Roche and Roman Bender

How to use the Handbook

The Handbook provides information on the chemical resistance and the corrosion behaviour of iron, nickel, zinc and their alloys in contact with the following water grades: drinking water, sea water, industrial and municipal waste water and high-purity water.

The user is given information on the range of applications and corrosion protection measures.

Research results and operating experience reported by experts allow recommendations to be made for the selection of materials and to provide assistance in the assessment of damage.

The objective is to offer a comprehensive and concise description of the behaviour of these materials in contact with a particular aqueous medium.

The information on resistance is given as text, tables, and figures. The literature used by the authors is cited at the corresponding point. There is an index of materials as well as a subject index at the end of the book so that the user can quickly find the information given for a particular keyword.

The Handbook is thus a guide that leads the reader to materials that have already been used in certain cases, that can be used or that are not suitable owing to their lack of resistance.

The resistance is labeled with three evaluation symbols in view of concise presentation. Uniform corrosion is evaluated according to the following criteria:

Symbol	Meaning	Area-related mass loss rate		Corrosion rate
		x		y
		$\text{g/m}^2 \text{ h}$	$\text{g/m}^2 \text{ d}$	mm/a
+	resistant	≤ 0.1	≤ 2.4	≤ 0.1
⊕	moderately resistant	$> 0.1 \text{ to } \leq 1.0$	$> 2.4 \text{ to } \leq 24.0$	$> 0.1 \text{ to } \leq 1.0$
–	not resistant	> 1.0	> 24.0	> 1.0

The evaluation of the corrosion resistance of metallic materials is given

- for uniform corrosion or local penetration rate, in: mm/a and mpy
- or if the density of the material is not known, in: $\text{g/m}^2 \text{ h}$ or $\text{g/m}^2 \text{ d}$.

Pitting corrosion, crevice corrosion, and stress corrosion cracking or non-uniform attack are particularly highlighted.

The following equations are used to convert mass loss rates, x , into the corrosion rate, y :

from x_1 in $\text{g/m}^2 \text{ h}$	from x_2 in $\text{g/m}^2 \text{ d}$	where
$\frac{x_1 \cdot 365 \cdot 24}{\rho \cdot 1,000} = y \text{ (mm/a)}$	$\frac{x_2 \cdot 365}{\rho \cdot 1,000} = y \text{ (mm/a)}$	x_1 : value in $\text{g/m}^2 \text{ h}$
		y : value in mm/a
		x_2 : value in $\text{g/m}^2 \text{ d}$
		d : days
		ρ : density of material in g/cm^3
		h : hours

In those media in which uniform corrosion can be expected, if possible, isocorrosion curves (corrosion rate $y = 0.1 \text{ mm/a}$) are given.

Unless stated otherwise, the data was measured at atmospheric pressure and room temperature.

The resistance data should not be accepted by the user without question, and the materials for a particular purpose should not be regarded as the only ones that are suitable. To avoid wrong conclusions being drawn, it must be always taken into account that the expected material behaviour depends on a variety of factors that are often difficult to recognise individually and which may not have been taken deliberately into account in the investigations upon which the data is based. Under certain circumstances, even slight deviations in the chemical composition of the medium, in the pressure, in the temperature or, for example, in the flow rate are sufficient to have a significant effect on the behaviour of the materials. Furthermore, impurities in the medium or mixed media can result in a considerable increase in corrosion.

The composition or the pretreatment of the material itself can also be of decisive importance for its behaviour. In this respect, welding should be mentioned. The suitability of the component's design with respect to corrosion is a further point which must be taken into account. In case of doubt, the corrosion resistance should be investigated under operating conditions to decide on the suitability of the selected materials.

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High Purity Water

Authors: M. B. Rockel, D. Schedlitzki, R. Durham / Editor: R. Bender

Introduction

High purity water is completely demineralised water, which through additional purification processes leads to the removal of remaining electrolytes, organic substances, particles, colloidal components, microbiological impurities and dissolved gases to a very low content. Typical residual contents of electrolytes in high purity water are a few ppt, for microorganisms < 1 CFU/ml and for organic components (TOC) < 10 ppb. Until now there is no generally valid definition for the classification of high purity water, however in various applications guidelines and standards exist in which specifications for high purity water are contained [1–3]. A selection of these guidelines and standards are given in Table 1.

<i>Guideline / Standard</i>	<i>Application</i>	<i>Literature</i>
DIN ISO 3696	Analytical chemistry	[4]
ASTM D1193	Analytical chemistry	[5]
DAB 10 (German Pharmacopoeia)	Pharmaceuticals, medical products	[6]
EUAB (European Pharmacopoeia)	Pharmaceuticals, medical products, injections	[7]
NCCLS approved guideline C3–A3	Clinical laboratories	[8]
USP 27	Pharmaceuticals	[9]
VDI 2083 Sheet 9 (Draft)	Clean room technology, electronics- and pharmaceuticals industries	[10]

Table 1: Guidelines and standards concerning specifications for high purity water

To assess the quality of high purity water various parameters for the particular application are used, e.g.:

- Electrical resistance or electrical conductivity
- Cation- and anion content, salt content, silicate content (SiO_2)
- Dissolved organic carbon (DOC), total organic carbon (TOC), oxidisable substances
- microbial impurities, germ number, bacteria (living, total), bacteria endotoxins
- Particles (number, size)
- Dry residue
- pH value
- Dissolved gas content (oxygen, nitrogen, carbon dioxide)

The corrosive attack on materials by high purity water differs far more greatly from that of potable, spring or sea water, whereupon – dependent upon the type of material – both strong attack (e.g. in plastics) and also lighter corrosion attack (e.g. in some metals) by high purity water can be observed.

Physical and chemical properties

High purity water (molar mass 18.015 g/mol) is a clear, odourless and tasteless, colourless liquid, which in thick layers appears blue. Some of the physical properties are listed in Table 2.

Property		
Melting point (at 1013 hPa)	°C	0
	K	273.15
Enthalpy of fusion (at 0 °C)	kJ/mol	6.010
Boiling point(at 1013 hPa)	°C	100
	K	373.15
Enthalpy of evaporation (at 100 °C)	kJ/mol	40.651
Enthalpy of sublimation (at 0 °C)	kJ/mol	51.13
Surface tension (at 25 °C/1013 hPa)	N/m	71.96×10^{-3}
Viscosity (at 25 °C/1013 hPa)	MPa s	0.8937
Specific heat capacity	J/g K	4.1855
Dielectric constant (at 25 °C/1013 hPa)		80.18
Electrical conductivity	μS/cm	0.0555–0.0635
Electrical resistance	MΩ · cm	18

Table 2: Physical properties of high purity water [2, 11]

The temperature dependence of density and vapour pressure on high purity water in the temperature range 0–100 °C is reported in Table 3. The sharp rise in vapour pressure above around 50 °C is of particular importance for organic materials, especially for coatings and linings, since increased permeation rates are to be expected above this temperature.

Temperature °C	Vapour pressure bar	Density ¹⁾ kg/m ³
0	0.00611	999.84
10	0.01228	999.70
20	0.02338	998.20
30	0.04245	995.65
40	0.07382	992.23
50	0.12346	988.03
60	0.19936	983.19
70	0.31181	977.76
80	0.47379	971.79
90	0.70123	965.31
100	1.01325	958.36

¹⁾ at 1 atm

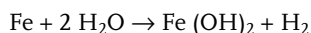
Table 3: Temperature dependence of water vapour pressure and density [12]

Unalloyed and low alloyed steels/Cast steel

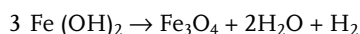
Unalloyed and low alloyed steels are significantly attacked in high purity water at room temperature up to 100 °C, so long as the water is oxygen-rich. The maximum oxygen solubility occurs at 60 °C and this is also associated with the maximum in corrosion attack. At extreme temperatures the formation of a magnetite layer acts as a protective layer. Therefore boiler steels in steam boilers are resistant up to 570 °C, as long as pulsed operation with strongly changing pressure and temperature loads (damage to the protective scale) are avoided. Also, the pH value should be neutral or slightly alkaline and the start up and shut downs should proceed with caution.

Stress corrosion cracking can be avoided if the mechanical stresses of the components remains under the yield strength ($\sigma < R_{p0.2}$) and no large compensation (yield strength too high) exists and the purity of the water is $< 0.2 \mu\text{S/cm}$ and gaseous impurities are not present. Inhibitors such as hydrazine also greatly improve the behaviour.

Carbon steels or boiler steels are only slightly attacked by distilled or deionised, oxygen free water at room temperature. On the other hand steel in oxygen containing water or at 100 °C has only limited resistance. The corrosion values reach a maximum at about 60 °C in distilled water and are practically the same at room temperature and 100 °C [13]. When iron is exposed to high purity water oxides are produced, which tend to be partly dissolved or can remain on the metal surface, whereby hydrogen will be released:



However, in boiling water Fe(II) hydroxide will be transformed to magnetite:



At higher temperatures this reaction occurs instantaneously [14]. The extensively adherent magnetite film inhibits the further attack by water. The prerequisite for good adhesion is a clean and blank metal surface, on which the Fe_3O_4 can grow. However, if the film is formed at a small distance from the metal surface, e.g. in the presence of metallic copper, then it offers no protection [15].

The oxygen content of the water plays a very large role. Thus, one finds the following corrosion rates in distilled water at 25 °C after 9 days duration [16]:

14 mg/dm² in water with 8.2 mg/l oxygen

87 mg/dm² in water with 37 mg/l oxygen.

Bare iron is only attacked until a flawlessly grown magnetite scale protects the iron underneath. Therefore, one can use deaerated deionised water in non-protected pipes, where the iron uptake is below 0.05 mg/l [17]. In a failure analysis case, after 3 years service life a steel tank used for deionised water (2 mg/l dissolved substances, pH 8.1–8.4, 60–70 °C) with unimpeded access for oxygen and carbon dioxide, a 6 mm thick deposit of a shell like brown rust with undercutting pitting corrosion had formed. In order to reduce the attack of high purity water on boiler steels, additions of hydrazine during downtime are made (27 mg/l) [18]. Further

inhibitors recommended include: 0.1 g $\text{Na}_2\text{Cr}_2\text{O}_7 \times \text{H}_2\text{O}$, 0.2 g $\text{K}_2\text{Cr}_2\text{O}_7$, 0.2 g KNO_2 , 0.2 g KCrO_4 or 0.2 g LiOH (per litre respectively) [19, 20].

The already mentioned transformation of Fe(II) hydroxide into magnetite is particularly active between 120 and 570 °C [15]. All boiler and pipe walls become covered with a uniform protective scale of magnetite during exposure, which relative to the standard hydrogen electrode shows a very noble potential from +400 to +500 mV, while for bare iron a potential of –440 mV was measured [21]. The scale thickness on the pipes reached about 0.05 mm [22], on the boiler walls up to 0.2 mm. The interior of the vessel which is protected by magnetite is practically immune to corrosion when the following conditions are filled:

- Uniform temperature, tailored to the material
- Avoidance of pulsed operation, extremely alternating loads and temperature swings (to avoid spallation of protective scale)
- Adherence of a pH value in the vessel water between neutral and slightly alkaline
- Exclusion of oxygen, chlorides and salts
- Caution with start ups and shut down

The Pourbaix diagram for iron in high purity water (for the temperatures 25, 100, 200 and 300 °C) is discussed in [23]. It shows for the dissolution quantities 10^{-6} and 10^{-8} M, that

- $\text{Fe}(\text{OH})_2$ (crystalline) is stable up to 85 °C and therefore the Schikorr reaction is thermodynamically not possible above 85 °C
- $\text{Fe}(\text{OH})_3$ (crystalline) and goethite are not stable at any temperature
- Haematite is the most stable solid product of Fe (III)
- $\text{Fe}^{3+}(\text{aq})$ is only stable at 25–100 °C and $\text{pH} > 0$
- In high purity water (10^{-8} M) due to the hydrolysis step of Fe (II), a corrosion area between iron and magnetite exists

The corrosion behaviour of steel in the cooling water of coal fired power stations was reported [24]. Hereby, aspects of the application of demineralised water with low phosphate additions (40–60 mg/l) and mechanical deaeration were summarised. The optimum conditions exist when the pH value is > 9.5 , the chloride content is < 5 mg/l and some oxygen (about 1% air saturation, which means about 0.1 mg/l) is present, thus completely anaerobic conditions should be avoided. Without giving corrosion rates, a pH value adjusted to 8.5–9.5 is expected to show very little to negligible attack (operating life at least 25 years).

The behaviour of a low alloyed steel in a test loop trial with regard to iron dissolution as well as scale formation under the conditions, such as in a pre-heater in a power station, was examined in [25]. Iron dissolution is particularly higher in de-ionised water at 150–160 °C under oxygen free conditions than with an oxygen content of 200 µg/l. Evidently in the presence of oxygen the steel exists in the passive condition, which is also concluded from the very noble potential values.

The influence of flow velocity and oxygen content (0.25–1 mmol/l) on the dissolution behaviour of iron in high purity (distilled) water was examined using the polarisation resistance of ring samples at 25 °C [26]. The initial corrosion potentials of $-450 \text{ mV}_{\text{SCE}}$ rose to values of -200 and $-100 \text{ mV}_{\text{SCE}}$, with the exception of the lowest oxygen content. Final values of about 0.5 m/s were reached. For very low oxygen contents the oxygen was cathodically reduced on the iron surface and corrosion is accelerated. For medium oxygen contents oxygen reduction is significantly slowed due to the formation of a porous scale (perhaps $\text{Fe}(\text{OH})_2$) and iron dissolution declines. For very high oxygen concentrations the corrosion potential decreases and iron dissolution increases again.

The initial dissolution rate of steel in demineralised water with $< 0.2 \text{ }\mu\text{S/cm}$ was determined radiometrically using radioisotope ^{59}Fe at 20–100 °C [27]. Although the converted corrosion rates at higher temperatures as well as at higher oxygen contents (6–8 mg/l) are initially higher than those in the deaerated state at 25 °C, nevertheless after a few minutes low values of $< 0.02 \text{ mm/a}$ were measured. The highest corrosion rate was measured in the case with an oxygen content of 8 mg/l, however, not at the higher temperature of 98 °C but rather at 25 °C (up to 0.1 mm/a). It is evident that in strongly aerated high purity water at 98 °C passivation is accelerated, which could be explained by the low corrosion rate of 0.02 mm/a.

The anodic dissolution behaviour of iron in demineralised high purity water with about $0.1 \text{ }\mu\text{S/cm}$ and oxygen contents of about 5 mg/l as well as a flow velocity of 0.8 m/s at 25–140 °C was investigated using polarisation curves [28]. From the curves illustrated in Figure 1, after holding times of several hours at 140 °C a current density of about $0.3 \text{ }\mu\text{A/cm}^2$ and thus a maximum corrosion rate of $< 0.01 \text{ mm/a}$ can be deduced. Nevertheless, these values are an order of magnitude lower than the values which have been measured by other authors using weight loss measurements.

The initial corrosion rates of steel in high purity water with $< 0.2 \text{ }\mu\text{S/cm}$ were established by means of the ^{59}Fe radioisotope method at 25 and 98 °C for 100 hours exposure. At the lowest oxygen content (here: 6 ppm) and lower temperature (25 °C), the corrosion rate is the highest (up to $100 \text{ mg/m}^2 \text{ h}$) and at higher oxygen contents, i.e. from $< 10 \text{ g/dm}^3$ it declines to $10 \text{ mg/m}^2 \text{ h}$. This low value is also reached at higher temperatures (98 °C) as well as at the above mentioned low and high oxygen concentrations (via a form of passivation of the steel) [29].

The behaviour of the carbon steels (SA106grB (0.26 C, 0.89 Mn, 0.006 P, 0.025 S, 0.16 Si) / SA333gr6 (0.18 C, 0.86 Mn, 0.006 P, 0.019 S, 0.16 Si)) against uniform and pitting corrosion as well as stress corrosion cracking in high purity water with oxygen contents of 0.02–8 mg/l at 288 °C was investigated in [30]. The corrosion potential is dependent upon the oxygen content and temperature. It increases at all temperatures with increasing oxygen content; from 0.1 mg/l oxygen a clear increase is noted. For higher oxygen concentrations (1–8 mg/l) in the measured temperature range a maximum of U_R is found at 175 °C. Accordingly, in the case of the higher oxygen contents the weight losses (200 h duration) at this maximum are high (corrosion rate up to 0.4 mm/a), see Figure 2.

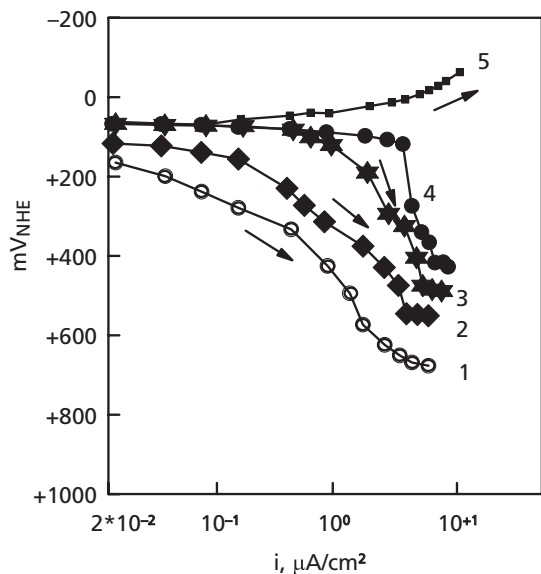


Figure 1: Anodic (1–4) and cathodic (5) polarisation curves of iron in high purity water (about 5 mg/l O₂) [28]

- 1) 25 °C
- 2) 78 °C
- 3) 118 °C
- 4) 139 °C
- 5) 140 °C

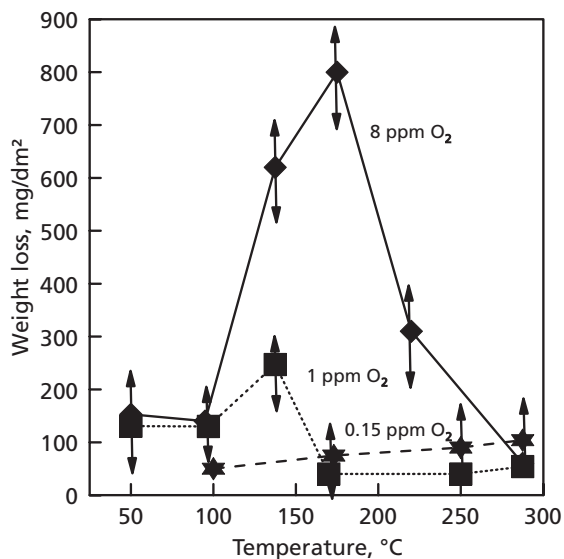


Figure 2: Weight loss of carbon steel in high purity water at 288 °C [30]

However, under normal boiling water reactor conditions (high purity water with 0.2 mg/l oxygen at 288 °C) the corrosion rates lie significantly lower (< 0.005 mm/a). Pitting corrosion in water with 1.8 mg/l oxygen was determined exclusively in the temperature range 60–225 °C and this justifies the high corrosion rates at high oxygen contents. Through pitting corrosion, induced transgranular stress corrosion cracking at high temperature and oxygen contents of 0.16, 1 and 8 mg/l was determined. In the process, in the case of 0.16 mg/l oxygen the pitting induced stress corrosion cracking occurred in the temperature range 150–265 °C.

However, cracks spread only at high stresses, i.e. close to the tensile strength. Under practical boiling water reactor conditions, stress corrosion cracking should not be a serious problem because interpretations with respect to the mechanical strength as the maximum value take the yield strength into account.

A procedure for the surface cleaning of metals as an environmentally friendly alternative to hydrofluorocarbons or other organic solvents has been developed using high purity water at high temperatures (up to 95 °C) [31]. It avoids rust residues as well as water stains (here: steel JIS G 3141, c.f.: Mat.-No. 1.0330, St 12, SAE 1008 JIS G 3141) because pure water can absorb large amounts of substances removed from the surface. The water which is produced by a distillation process has a very low oxygen content, therefore attack of the metal even after long exposure times is negligible. Due to its very low surface tension and low viscosity, high purity water covers the metal surface with a very thin film. The higher metal temperature allows the water to quickly evaporate.

Corrosion rates of carbon steels in high purity water are dependent upon oxygen contents. This was proven with tests in water with a pH value 6.5–7.2, 0.1–2.0 $\mu\text{S}/\text{cm}$ and an oxygen content in the region 0.010–8 mg/kg [32]. Measurements were made at 80 and 200 °C. At both temperatures a decrease in corrosion rate with increasing oxygen content was determined. At 80 °C with increasing oxygen content, initially one finds in the region 10 to 200/400 $\mu\text{g}/\text{kg}$ O_2 only a slight decrease, but then from 400–600 $\mu\text{g}/\text{kg}$ O_2 a steep drop in the corrosion rate. With higher conductivity the curves shift to slightly higher corrosion rates. The trend of the curves for the accumulation of corrosion products in water is similar. The results show that there is a critical oxygen content, above which the formation of a protective oxide scale (about 0.2–0.3 μm thick) and therefore higher corrosion resistance is ensured. In the case of higher conductivity the critical oxygen content lies at higher values, while it decreases with increasing temperature.

The behaviour of low alloyed steels for rotors for steam turbines (3.5 NiCrMoV) to the vulnerability of pitting corrosion in deionised water with 0.3 $\mu\text{S}/\text{cm}$ as well as with the addition of 1mg/l Cl^- at 80 °C was investigated [33]. Hereby the purity of the steel should be assessed; therefore samples from conventional production, from used materials as well as in super pure quality were tested, with exposure times up to 600 hours. Pit formation and growth were determined metallographically and optically. One finds, that non-metallic inclusions such as MnS are the cause for pitting corrosion. The pit growth rate is higher in chloride containing water and greatest in stagnant water. Pit growth is a function of time, the pit intensity is not. In

each case the super pure steel behaved the best in all conditions, both as regards to pit intensity and pit dimensions.

In relation to the use of oxidising materials and their influence on the corrosion behaviour of steel in power stations, electrochemical measurements in high purity water with 0.07 $\mu\text{S}/\text{cm}$, pH 6.75–7.25 as well as 0.7–1.0 g/l oxygen content at 20–25 °C were conducted (water flow: 3.6–9.6 l/h). Independent of surface preparation (cathodic reduction, long time oxidation in dry air, processing with abrasive materials) comparable corrosion potentials occurred after 2 hours. Galvanostatically determined current density-voltage curves show in the whole potential region up to oxygen development at 1.25 V a monotonous increase in the anodic current density, however the values do not exceed $5 \times 10^{-7} \text{ A}/\text{cm}^2$ ($0.5 \mu\text{A}/\text{cm}^2$) [34].

In [35] the erosion corrosion of carbon steels in superheated steam tubes in power stations was reported. The cause for the corrosion was assumed to be localised attack of the protective magnetite scale (preferably between this and the steel), namely the result of lightly acidic water that formed in the pipes when the plant was shut down. After turning it on again, the highly pure condensate can no longer form the magnetite scale on such corroded locations. The result is localised corrosion. A remedy can be achieved by the controlled introduction of Si-containing water. Evidently, this acts as a kind of inhibitor, by which silicon closes the pores of the magnetite scale and therefore the corrosive solution does not reach the underlying steel.

For existing knowledge about stress corrosion cracking and corrosion fatigue of carbon steel (as well as austenitic steel and nickel alloys) in high purity water with 300 $\mu\text{g}/\text{l}$ oxygen and temperatures up to 320 °C see [36]. In a variety of diagrams, stress-cycles as well as stress-strain curves are shown; crack growth rates and crack depths as a function of the mechanical stress are shown. Also, the effect of radiation as well as weld beads is also addressed.

Crack growth on smooth samples always occurs on microscopic surface discontinuities such as slip bands, grain boundaries, phase boundaries, secondary phase, carbides etc. Crack rates as a function of operating life were determined firstly for fine microscopic cracks, and later (i.e. after about 60% of the maximum operating life) from small mechanical stress cracks, so long as a sufficiently high enough mechanical stress was present. Micropores such as those formed by the dissolution of MnS inclusions are always the starting point of corrosion fatigue cracks. Pitting corrosion does not occur on low alloyed and carbon steels under practical pressurised water reactor/boiling water reactor conditions at temperatures above 200 °C and up to 0.2 mg/l oxygen. Crack depths increase with cycles and occur at high oxygen contents, even after relatively low cycles, see Figure 3.

Crack rates, da/dN , spread over the crack depths, increase in the range 10 to 1000 μm from 10^{-2} up to 10 and $10^2 \mu\text{m}/\text{cycle}$ and most pronounced in high oxygen containing water. Crack rates as a function of stress intensity, determined for steel A 533-B (c.f.: 1.5403, 1.6310) for various oxygen contents lie higher than the values of the ASME Section XI reference curve. A test method used to determine the potential at the crack tip of steel (here: pressure vessel steel A 533-(B) (UNS K12539, c.f.:

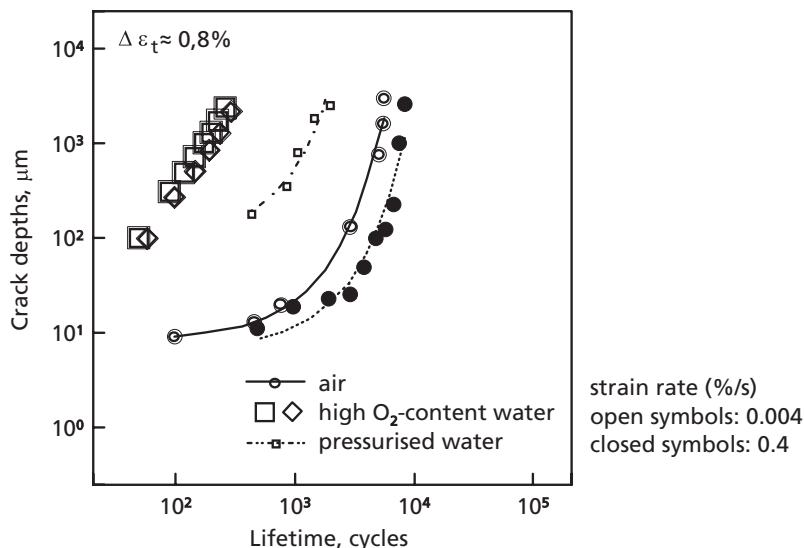


Figure 3: Depth of longest cracks as a function of cycles for steel A 533-B (c.f.: 1.5403, 1.6310) [36]

Mat.-No. 1.5403, 1.6310) was developed in demineralised water with oxygen contents of 10 mg/l and 5–6 mg/l at a water temperature of 93 °C. The potentials that were ascertained were discussed as a function of crack depth, load frequencies, wave form and oxygen content. Subsequently, the potential differences between the metal surface and the crack tip increased with decreasing load frequency and for higher oxygen contents higher potential differences were also found (60 as opposed to 10 mV) [37].

Further work was concerned with the influence of MnS on stress corrosion cracking in the above mentioned steels in high temperature water [38]. Here, micro-samples of the solution were taken from the crack tip. In the case of a high oxygen content (10 mg/l) high crack rates were found, associated with relatively high sulphur contents (1–2 mg/l S), which are an order of magnitude higher than those in the case of very low oxygen contents and the associated very low crack rates.

The vulnerability of carbon steel (SA333gr6 (0.18 C, 0.86 Mn, 0.006 P, 0.019 S, 0.16 Si)) to stress corrosion cracking in high purity water is dependent upon temperature and oxygen content [39]. The investigations took place in the temperature range 300–525 °F (150–275 °C) and oxygen contents between 0.05 and 1 mg/l. With increasing oxygen content the corrosion potential increased significantly, even with 100 $\mu\text{g/l}$ oxygen to around 500 mV (from –800 to –300 mV_{SHE}). Since pitting corrosion and stress corrosion cracking were observed at the higher potentials, one has to accept these changes in potential for both types of corrosion. In order to avoid it, the conditions (temperature, medium) for carbon steels should be that a relatively low potential can be set. Dosing low temperature high purity water with H_2O_2 causes an increase in the corrosion potential and pitting corrosion. At 450 °F (232 °C) in high purity water with 0.2 mg/l oxygen, in stress corrosion cracking samples one finds a

ductility minimum, in association with observed pitting corrosion and transgranular stress corrosion cracking. The dependence of ductility on oxygen content is shown in Figure 4.

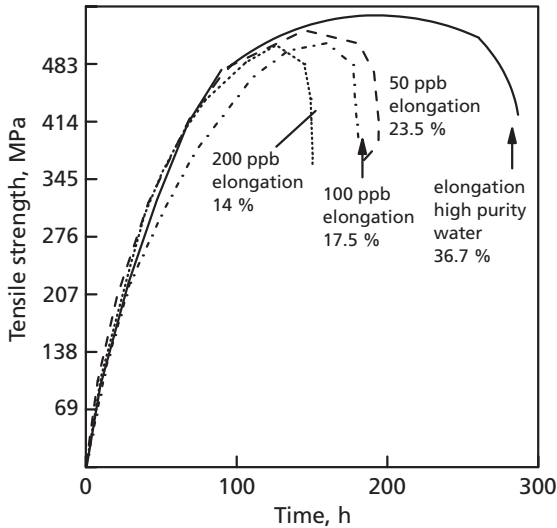


Figure 4: Stress-strain curve (2×10^{-5} /min) for carbon steel in high purity water at 450 °F (232 °C) as a function of oxygen content [39]

From CERT testing one can conclude that below 400 °F (204 °C) practically no stress corrosion cracking susceptibility exists, since all fractures were ductile. On U-bend test samples one generally finds no stress corrosion cracking. When strong mechanical damage to the surface exists stress corrosion cracking can occur rapidly (here at 525 °F/275 °C), but not through light surface damage or light pitting corrosion. Galvanic contact with nobler metals (here: titanium), similarly with high oxygen contents leads to potential increases and thus accelerated stress corrosion cracking.

In [39] the stress corrosion cracking behaviour of carbon steel in high purity water at high temperature, whose dependence on oxygen content, potential and other influences was determined using U-bend test samples, CERT measurements and stress-strain curves.

The crack formation of stress corrosion cracking loaded low alloyed steels in high purity water is dependent upon its conductivity. This was shown in tests on the steel WB 36 (Mat.-No. 1.6368, 15NiCuMoNb5-6-4, 0.10 C, 0.25 Si, 0.80 Mn, 1 Ni, 0.25 Mo, 0.5 Cu, 0.015 Nb) in high purity water with 0.06 $\mu\text{S}/\text{cm}$, whose conductivity was varied through additions of H_2SO_4 up to 0.5 $\mu\text{S}/\text{cm}$ [40]. At a test temperature of 177 °C, with increasing conductivity the corrosion fatigue lifetime decreases. A similar effect was also observed with the addition of oxygen (here: 8 mg/l O_2). At the same time pitting corrosion is not a prerequisite for crack formation and prior pitting corrosion does not reduce the corrosion fatigue lifetime. For this steel all values lie above the curve according to ASME Section XI as well as above that of steel A 533-(B) (UNS K12539, c.f.: Mat.-No. 1.5403, 1.6310).

Corrosion fatigue testing was performed on the steel A 508 (2) (UNS K12766, c.f.: Mat.-No. 1.5403, 1.6368, 0.88 Ni, 0.35Cr, 0.65 Mo, 0.68 Mn, 0.2 C) in high purity water with 0.5 $\mu\text{S}/\text{cm}$, 0.1–0.3 mg/l oxygen, < 0.1 mg/l Cl^- as well as pH 6.5 at 550 °F (288 °C) [41]. The results show that increased crack growth velocities at higher mechanical loads and with increasing frequency, in particular at the beginning of the test, occur when the stress intensity and crack lengths are still low. For larger crack depths, the influence of frequency declines because of the occurrence of secondary cracks. An interruption to the test slows down crack growth. As the load spectrum in practice is also discontinuous, a lower crack growth velocity is expected than that from the value derived from the model. Welded material differs only negligibly from the base material.

Sulphur impurities (0.007–0.013% S) in the low alloyed forging steel (0.38 Cr, 0.71 Ni, 0.62 Mo, 0.22 C) lead to increased corrosion fatigue rates in high purity water (45 $\mu\text{S}/\text{cm}$, 8 $\mu\text{g}/\text{l}$ O_2) at 149 °C and 260 °C [42]. The addition of oxygen containing water shifts the corrosion potential above $-250 \text{ mV}_{\text{SCE}}$ and increases the crack rate by a factor of four. Determination of the area fractions of sulphide inclusions on fracture surfaces led to the conclusion that below a value of 0.006% sulphur the corrosion fatigue susceptibility is very low (see also [43]).

It has been reported in [44] that the sulphur content of low alloyed steels has a strong influence on the stress corrosion cracking behaviour in high purity water (< 0.07 $\mu\text{S}/\text{cm}$) at 288 °C. In an investigation on steel A 533-(B) (UNS K12539, c.f.: Mat.-No. 1.5403, 1.6310; 0.021% S), the sulphur content at the crack tip, the influence of sulphate doping, the water flow velocity as well as the corrosion potential were examined, the corrosion potential being set by N_2 - or O_2 -dosing. The high/noble potentials occurring at high oxygen contents correlate with high crack propagation velocities and these with high sulphur contents at the crack tip. In contrast, one finds at low/ignoble corrosion potentials (set by deaerating with nitrogen purging) low crack propagation velocities and low sulphur contents at the crack tip. If the crack is cleansed in aerated water (10 mg/l O_2) then the sulphur content sinks to a level below that of deaerated conditions and the crack rate sinks considerably. As earlier investigations have shown, direct addition of H_2S in the crack tip leads to strongly increased crack propagation velocities. This means that the corrosion potential present at the crack tip is not of great importance for stress corrosion cracking but rather the local chemistry at the crack tip.

In order to determine clear technical data for the corrosion fatigue behaviour of pressurised water reactor steels (e.g. for ASME Section XI), round robin tests in numerous laboratories on the steel A 533-(B) (UNS K12539, c.f.: Mat.-No. 1.5403, 1.6310) in high purity water at 288 °C were conducted [45]. In doing so, the following parameters were precisely matched in detail:

- Oxygen content (up to 100 mg/l)
- Water purity (0.1–5 $\mu\text{S}/\text{cm}$)
- Frequency and R value
- Sine wave of applied stress

- Hydrodynamic conditions
- Galvanic effects (rare: isolated samples)

From the results one finds a relatively narrow scatter band of values in the da/dN diagrams for various frequencies (0.1–1 Hz) and R values (0.2–0.7). Furthermore, the stress corrosion cracking behaviour was determined using CERT tests; here electrochemical potentials as well as fracture type and crack growth rates were determined.

Due to deviating test parameters (see above) in the initial tests, a large scatter band of corrosion fatigue crack rates as a function of stress intensity (da/dN – dK diagrams) was found, in the subsequent tests agreement was considerably better with stricter consideration and adjustment of all the test parameters in the laboratories performing the test, see Figure 5.

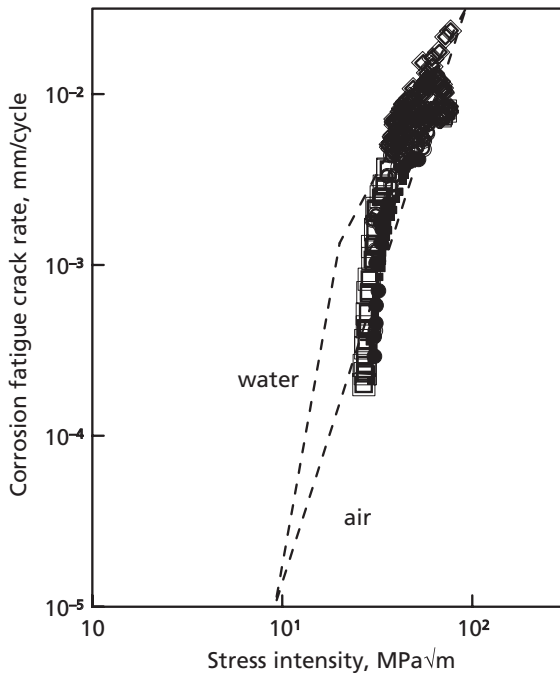


Figure 5: Corrosion fatigue crack growth rates as a function of stress intensity for carbon steel A533-B (c.f.: 1.5403, 1.6310) in high purity water at 288 °C, 0.017 mHz, $R = 0.2$. Compilation of crack rates from 20 various laboratories (round robin test) with coordinated conditions [45]

This is valid for constant load, starting at 27.5 MPa $\sqrt{m}$, a relatively low sine frequency of 0.017 Hz as well as a stress ratio of $R = 0.2$.

In the case of a higher frequency (1 Hz), the scatter band is much narrower, see Figure 6.

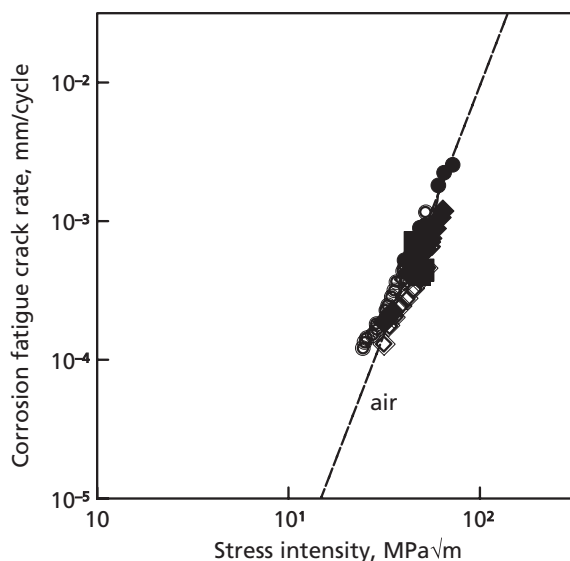


Figure 6: Corrosion fatigue crack growth rates as a function of stress intensity for carbon steel A 533-B in oxygen free high purity water at 288 °C, 1 Hz, $R = 0.2$. International round robin test (8 participants) [45]

Unlike at low frequencies, a triangular shaped alternating load instead of a sine shaped load does not lead to a lower crack rate and the oxygen content in the range 0–100 $\mu\text{g/l}$ also has no effect. Generally, one finds under all conditions an influence of the water flow velocity on the measured values, whereby turbulent flows lead to lower crack rates than for the case with laminar flow as well as for stagnant conditions.

Galvanic coupling between the test sample and the test equipment influences the crack rate, in particular at high potential differences. With an increasing ratio between crack rates in corrosive medium and in air (factors in the range 2–20) one also finds an increase in the amount of brittle cleavage on the fracture surface (20–90%). Under pressurised water reactor conditions the differences in the crack rates to those in air are marginal, provided that the region of 11–20 $\text{MPa } \sqrt{\text{m}}$ will be tested. Furthermore, the crack rates increase rapidly, namely by a factor of 10. Therefore a limit of the stress intensity (for $R = 0.7$) at about 20 $\text{MPa } \sqrt{\text{m}}$ has to be applied.

In this round robin test program the stress corrosion cracking behaviour was investigated using CERT tests. The individual test parameters for the 10 participants were: high purity water at 288 °C, 100–400 $\mu\text{g/l}$ oxygen, 0.1 $\mu\text{S/cm}$, pH 6.5–7.5; strain rate $10^{-6}/\text{s}$. On the basis that the smallest measurable crack length is only 20 μm , one arrives at a lower measuring limit of crack growth velocity, this being $3 \times 10^{-7} \text{ mm/s}$. This means that below this value no stress corrosion cracking is expected. For up to 50 $\mu\text{g/l}$ oxygen such values were achieved, while values above this led to crack rates of $> 10^{-6}$ to 10^{-5} mm/s being recorded. If the corrosion poten-

tial is applied against the oxygen content, one obtains a rough, i.e. strongly scattered increase, and the resting potential at 10 $\mu\text{g/l}$ oxygen is $-700 \text{ mV}_{\text{SHE}}$ and increases in the range 100–500 $\mu\text{g/l}$ oxygen to $+100 \text{ mV}_{\text{SHE}}$. Correspondingly, the dependence of crack growth velocity on resting potential is as follows: it increases from 10^{-7} at $-700 \text{ mV}_{\text{SHE}}$ to values up to 10^{-5} mm/s at $+100 \text{ mV}_{\text{SHE}}$, though rapidly first from $-200 \text{ mV}_{\text{SHE}}$, i.e. under this potential value hardly any stress corrosion cracking will be found. Thus one can expect stress corrosion cracking resistance for a steel of type A 508 (3) (forging material, c.f.: 1.5403, 1.6310) so long as the steel is loaded to a strain rate of $10^{-6}/\text{s}$ parallel to the direction of longitudinal inclusions and a resting potential more negative than $-200 \text{ mV}_{\text{SHE}}$ exists. On the other hand, inherent potentials above $-100 \text{ mV}_{\text{SHE}}$ lead to very rapid stress corrosion cracking.

The influence of oxygen (here: 50–2500 $\mu\text{g/l}$) on the corrosion behaviour and in particular the formation and type of surface film formed on a carbon steel (0.07 C, 0.4 Mn, 0.007 P, 0.021 S, 0.02 Cu, 0.02 Ni, 0.06 Cr) in high purity water ($< 1 \mu\text{S/cm}$) at 60–250 °C was reported [46]. Corrosion rates increase with increasing temperature and oxygen content. Oxide films consisted mainly of Fe_3O_4 , which partly transforms into Fe_2O_3 in the upper scale when oxygen contents are greater than 200 $\mu\text{g/l}$. From 1000 $\mu\text{g/l}$ oxygen the surface film consists of a powdery $\alpha\text{-Fe}_2\text{O}_3$ scale with an underlying thin scale of Fe_3O_4 . With an increasing corrosion rate the scales become thicker. With increasing oxygen contents the corrosion potential increases.

On a carbon steel (0.1 C, 0.3 Mn, 0.018 P, 0.016 S, 0.016 Co, $< 0.01 \text{ Si}$) the mechanism of film growth under boiling water reactor conditions was investigated. Also, the mechanism for the uptake of cobalt from ultrahigh purity water with $< 0.1 \mu\text{S/cm}$ and 200 $\mu\text{g/l}$ oxygen at 288 °C was followed up [47]. The weight loss after 1000 h exposure was determined (metal loss 7.02 g/m^2 , of which 6.95 g/m^2 was converted into oxide film) and the composition of the oxide scale after dissolution in a HCl solution and subsequent absorption analysis. The results show that for the carbon steel only 1% of the corrosion products were dissolved (quite the contrary to 18Cr8Ni steel: 12%); on the other hand 99% in oxide scale formation. Scale growth occurred on the interface film/substrate and grew inwards. The main components of the surface film are Fe_3O_4 , $\alpha\text{-Fe}_2\text{O}_3$ and hydroxide. Cobalt was absorbed into the film and formed CoFe_2O_4 .

The origin of transgranular stress corrosion cracking of carbon steels in high purity water at high oxygen contents and temperatures are pitting corrosion sites. This occurs in CERT tests in water with 8 mg/l oxygen at 288 °C or 250 °C from 15% strain [48]. The stress corrosion cracking susceptibility is dependent on the microstructure: it must be predominantly pearlite and the grain size must be at least 200 μm^2 . For weld metal which does not have a pearlite structure but rather a fine grained ferrite structure due to the low carbon content, no transgranular stress corrosion cracking was found.

The corrosion fatigue behaviour of two pressure tank steels (Table 4) under pressurised water conditions was investigated [49]. As well, crack propagation velocities (V_R) were measured as a function of stress intensity, frequency (0.001–10.0 Hz) as well as the R ratio (0.16–0.72), namely in high purity water with 0.10 mg/l Cl^- , $< 0.01 \text{ mg/l O}_2$ at pH 6–9 and at 288 °C. Crack propagation depends mainly on the

stress intensity, less so on the test frequency and the R ratio and is not dependent upon mechanical preloading or crack length. In comparison to high purity water (here without boric acid additions and a conductivity 20 times lower than under pressurised water reactor conditions) the crack growth velocities at high frequencies are comparable, but not at low frequencies. Here, the velocities in high purity water are considerably higher than under practical conditions.

	<i>C</i>	<i>Mn</i>	<i>P</i>	<i>S</i>	<i>Si</i>	<i>Ni</i>	<i>Cr</i>	<i>Mo</i>	<i>Cu</i>
SA508-2	0.22	0.64	0.007	0.012	0.28	0.63	0.34	0.58	0.022
SA533B-1	0.19	1.28	0.009	0.013	0.25	0.61	0.04	0.55	0.100

Table 4: Compositions of pressure tank steels [49]

Stress corrosion cracking can occur on burst discs made from low alloyed steel (typical analysis: 3.5 Ni, 1.7 Cr, 0.4 Mo, 0.25 C) which are used for low pressure turbines. Experiences were summarised in a literature review (37 literature sources) [50]. Accordingly, stress corrosion cracking is dependent upon:

- The presence of a liquid phase, also steam condensate
- The oxygen concentration or the corresponding corrosion potential
- The yield strength of the used steels
- The temperature of the burst disc
- The mechanical stress
- Cracks and localised corrosion in cracks
- The combination between mechanical stress and cracks which have the shape and size to produce a critical stress intensity factor $> 7.2 \text{ MPa}\sqrt{\text{m}}$

Generally, the stress corrosion cracking susceptibility increases with increasing oxygen content, temperature and the yield strength of the steel. Preferential sources for stress corrosion cracking are cracks as well as those in proximity to holes, dents with a splint and clamping edges on burst discs. For crack widths $> 0.04 \text{ mm}$ the stress corrosion cracking susceptibility decreases. The cause of stress corrosion cracking is quite independent of the steel composition, inclusions and pitting corrosion, although it can also occur at pitting corrosion sites. The crack propagation velocity is independent of the applied stress or stress intensity factor. Only increased yield strengths and higher temperatures lead to increased crack velocities.

Intergranular stress corrosion cracking has been observed on shrink fit low alloyed 3%NiCrMoV quench and tempered steel for steam turbine discs and vanes. Only in a few cases could stress corrosion cracking initiating steam impurities such as NaOH, H₂S, Na₂CO₃, Na₂SO₄ or NaCl be identified. Therefore, the stress corrosion cracking behaviour of these types of steels with various analyses and yield strengths was examined in high purity ($< 1 \text{ }\mu\text{S/cm}$) oxygen saturated (about 8 mg/l) water at 80 °C for times up to 32,000 hours [51]. The steels examined were 34CrNi-Mo6 (1.6582; 1.41 Cr, 1.53 Ni, 0.35 Mo, 0.37 C), 28NiCrMoV8-5 (1.6932; 1.22 Cr, 2.02 Ni, 0.41 Mo, 0.32 C) as well as 27NiCrMoV15-6 (1.6957; 1.6 Cr, 3.64 Ni, 0.39

Mo, 0.10 V, 0.28 C). The samples were tested using the CERT method in the as-delivered condition as well as after a heat treatment. The results show that the chemical composition has no influence on crack initiation. After a tempering to the normally applied 0.2% yield strength of about 850 N/mm² in high purity water, no crack initiation was detected. If the steel is tempered to a very high 0.2% yield strength (1250 N/mm²) which is uncommon in practice then crack initiation is detected. If sharp cracks exist (notched specimens), crack growth through stress corrosion cracking occurs. The investigations showed that stress corrosion cracking of turbine discs can be avoided through compliance with procedures for steam purity with a conductivity of < 0.2 µS/cm.

Continuing this research the influence of CO₂ on the stress corrosion cracking behaviour of a low alloyed quenched and tempered steel 27NiCrMoV15-6 (1.6957) in high purity water at 80 °C was examined [52]. Gaseous impurities as well as other unspecified impurities can increase water conductivity, leading to crack initiation through stress corrosion cracking, and can also increase the crack growth velocity of stress corrosion cracks, in particular if the corrosion potential is located in the transitional active-passive region. Furthermore, unfavourable crack conditions must be avoided. If, during operating phases in which poor water quality exists cracks initiate, these can also grow further when high purity conditions again exist. By raising the pH value and shifting the corrosion potential into the passive region, stress corrosion cracking can be avoided.

Stresses in boiler walls can cause the magnetite scale to spall. In the process the small exposed areas of the steel surface become anodic with respect to the large cathodically acting undamaged surfaces so that rapid corrosion of the unprotected surface is likely to occur [53].

However, from experience, uniform boiler operation under normal tensile stresses does not lead to damage because the exposed areas heal quickly under normal operating temperatures and in boiling boiler water no aggressive materials are present. A further cause for the spallation of the protective scale comes from oxygen or weakly acidic reactions of the boiler water [54]. Also, between cold and hot surfaces of the same steel, potential differences occur, whereby the hot metal becomes the anode and corrodes, if it is surrounded by a large surface of the colder metal [21]. Also, for temperature jumps of 130–260 °C the protective magnetite scale spalls. The resulting fresh magnetite does not adhere strongly on the wall surface and becomes anodic. For the protective scale tensile strains above 0.2% and compressive strains above 0.3–0.4% are damaging [53].

Opinions vary concerning the observed pH value (set at room temperature) in boiler water. There is consensus that the pH value should never lie below 7 since then the magnetite scale will be attacked. In practice and research a pH value of 9.6 is seen as optimum. However, from other sources a pH value of 10.5 is considered as a prerequisite that a protective, adherent magnetite scale exists and stress corrosion cracking does not occur [55].

At 315 °C the corrosion rate in the pH range 7.0–10.6 under operating conditions after 100 days goes from 42 down to 6 g/m² a (< 0.01 mm/a), and then remains constant. For boiler water feed pumps a pH value between 8.3 and 9.0 has proven

itself. Damage occurs to 80% on the rotors. Additives suitable to maintain a lightly alkaline pH values include volatile materials such as ammonia, morpholine, hydrazine and cyclohexamine [55]. Furthermore, hydrazine also functions as an inhibitor against pitting corrosion [56].

For boiler feed water degassing to 0.02 mg/l oxygen is required. Oxygen contents > 0.1 mg/l are damaging because they cause the formation of haematite (Fe_2O_3) as well as FeOOH and leads to pitting corrosion [21, 55]. The addition of hydrazine enables the oxygen content in the boiler water to be held at a value of 0.003 mg/l while ammonia reduces it to only 0.01 mg/l [57].

The ingress of oxygen to the boiler interior should also be avoided during down-times. Therefore, the decommissioned boiler is filled with nitrogen and volatile reducing materials are added to the high purity degassed hot water, e.g. 27 mg/l hydrazine [21, 55]. In order to avoid stresses, the cold drum of the steam boiler is not allowed to be charged with hot water; therefore one restarts with cold boiler water and purges with an inert gas (N_2) [58].

For normal operation and during downtime conditions prevail that do not favour stress corrosion cracking [53]. In the liquid phase of high purity water with oxygen contents of < 0.1 mg/l, carbon steels lose about $30 \text{ g/cm}^2 \text{ a}$ (< 0.05 mm/a) in 12 days at 250 °C, in 375 days at the same temperature $12 \text{ g/m}^2 \text{ a}$ (< 0.02 mm/a) [59].

The previously feared caustic embrittlement of steel boilers has practically vanished after the introduction of high purity, i.e. deionised water [60]. Low carbon steels are sufficient for those sections of the steam boiler which come into contact with liquid water less than 330 °C. For the hot side of turbines a steel with 12% Cr is recommended. The remaining sections of the steam boiler system consist of carbon steel or low alloyed steel [22]. Steam boiler operation in the super heater section (500–600 °C) affects the diffusion of hydrogen in the steel, and will thereby be decarburised [14]. The methane that is formed cannot escape from the iron, stresses are formed and the formation of cracks and blisters occurs. A remedy was found by adding 0.5% Mo and 1% Cr, whose carbides at boiler temperature do not transform into methane [14, 61]. The limit of the use of these steels is portrayed in Figure 7.

In atomic power stations (pressurised water and boiling water reactors) carbon steels are mostly used in the secondary cycle, especially for cooled and heated water [62]. In the primary cycle of pressurised water reactors the corrosion rate is 5 to 10 times higher than the losses of the most commonly used austenitic stainless chromium-nickel steels. The corrosion of the carbon steels increases with increasing water velocity, since the resulting protective scale of Fe_2O_3 is not adherent enough and is therefore abraded away [60]. Furthermore, it was determined that mild steels in boiling high purity radiated water are not attacked intergranularly when $11 \pm 1 \text{ mg/l}$ ammonia is present in the circulating cooling water [16, 63].

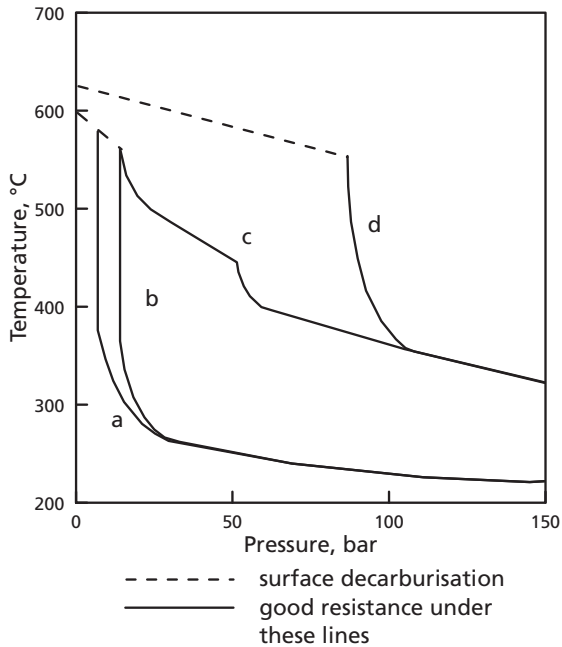


Figure 7: Hydrogen attack of unalloyed and low alloyed steel for hydrogen partial pressures from 0 to 50 atm and temperatures between 200 and 600 °C [61]

- a) carbon steel, welded or hot formed
- b) carbon steel
- c) steel with 0.5% Mo
- d) steel with 1% Cr and 0.5% Mo

The dissociation of water into hydrogen and oxygen (0.07 ml O₂/kg) by radiation is inhibited by the injection of additional hydrogen and the addition of ammonia or morpholine and reduces to 0.01 mg/kg. Without these measures significant amounts of corrosion products would form through the oxygen [60, 57].

Non-alloyed cast iron

Since cast iron forms no protective scale in distilled water, it is very strongly attacked [64]. The behaviour of grey cast iron samples in distilled and triple distilled water is highlighted in Figure 8 [65].

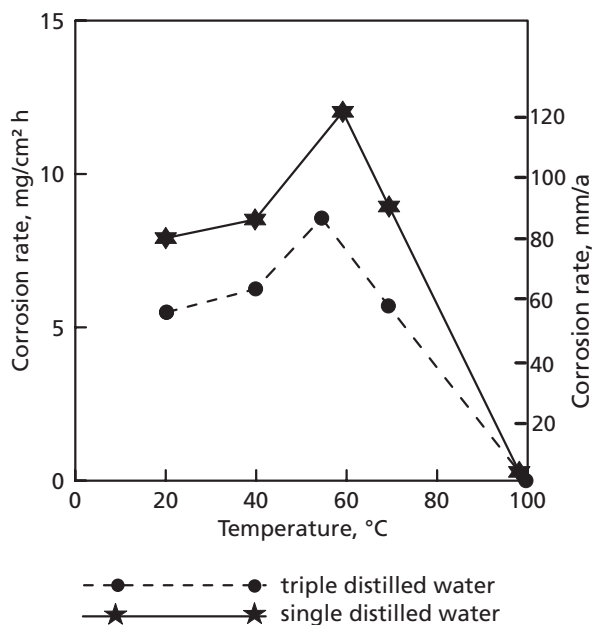


Figure 8: Corrosion behaviour of grey cast iron in distilled water at 20–100 °C [65]

One observes an increase in the corrosion rate up to an extremely high value of 100 mm/a up to 60 °C, which is due to the high solubility with oxygen. In practice such values are by no means acceptable. Only when close to the boiling point of water do the corrosion rates decrease to appropriate levels since the oxygen is driven out.

Investigations with white malleable iron showed that after 210 days exposure in distilled water at 20 °C and pH 6.5 with constant aeration, the tensile strength decreased by 5 to 8% and the elongation reduced by up to 28%. In the process strong rust formation was observed and the surface below the rust scale was very heavily fissured [66].

High-alloyed cast iron

The austenitic cast iron Ni-Resist 1 (Mat.-No. 0.6655, EN-JL3011) has good resistance in distilled water up to 100 °C [67].

Ferritic chromium steels with < 13% Cr

Together with exposures in synthetic ash mixtures (simulating the fire side) made in connection with examinations of the high temperature resistance of the ferritic steel T 91 (1.4903, X10CrMoVNb9-1) for use in oil fired power stations, an examination

was made in steam from high purity water with $0.084 \mu\text{S}/\text{cm}$ and $100\text{--}140 \mu\text{g}/\text{l}$ oxygen at 540°C for 4000 h [68]. One finds a parabolic increase in the oxide scale thickness with time with end values of $70 \mu\text{m}$ and a corrosion rate of $100 \mu\text{m}/\text{a}$. Such a value is an indication for the good stability of the oxide scale. The behaviour of this ferritic steel does not differ from that of the austenitic SAE 304 (1.4301) which was tested for comparison. It is then possible that this steel can be used in conventional boilers up to temperatures of 538°C in place of the austenitic steels based on 18Cr8Ni.

A martensitic steel with 13% chromium is significantly more resistant to stress corrosion cracking when the nickel and carbon contents are optimally set. This was shown through CERT tests in high purity water with $1 \mu\text{S}/\text{cm}$, $8 \text{ mg}/\text{l}$ oxygen and pH 6.5 at $150\text{--}288^\circ\text{C}$ [69]. Steels with increased nickel contents (3.5–5.5%) showed very good mechanical properties, but are considerably vulnerable to intergranular corrosion and intergranular stress corrosion cracking. Hydrogen embrittlement is very dependent upon the heat treatment temperature (tempering) and not dependent upon the nickel or carbon contents. This is proven in Figure 9.

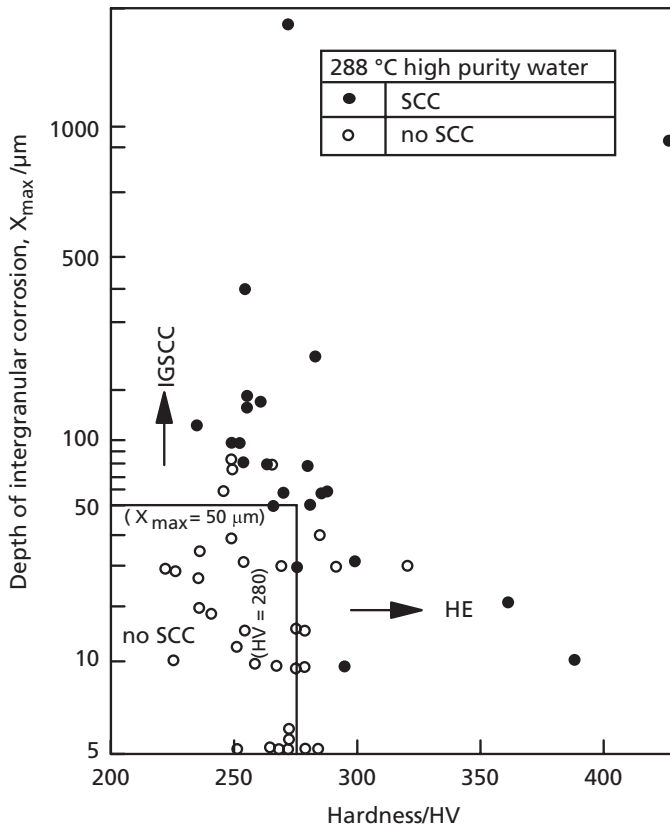


Figure 9: Critical stress corrosion cracking-hardness-Intergranular depth diagram [69]

HE: hydrogen embrittlement

Steels with < 4% nickel and < 0.08% carbon or < 2.5% nickel and < 0.17% carbon, which are tempered > 650 °C, are immune to stress corrosion cracking in high purity water. This conclusion can be made by inspection of Figure 10.

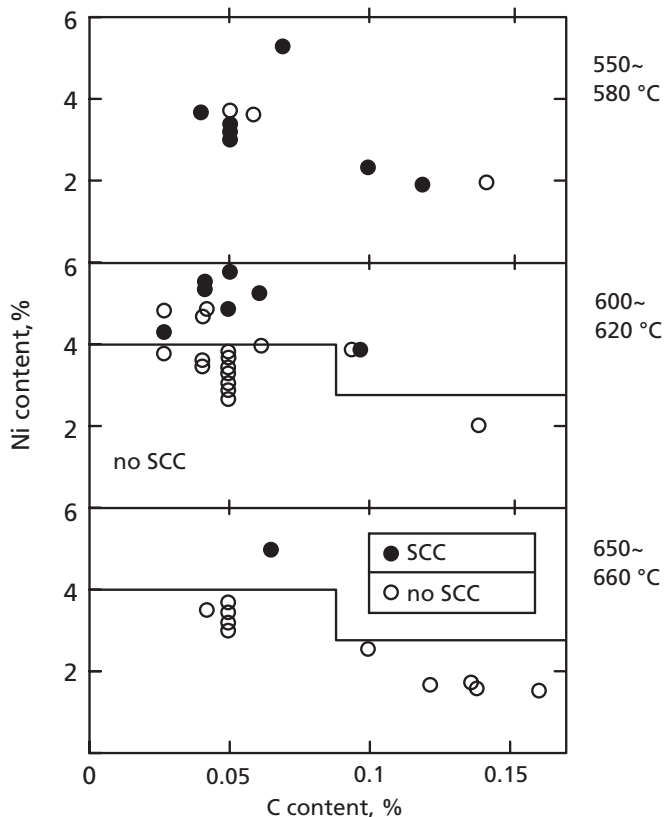


Figure 10: Stress corrosion cracking susceptibility of martensitic 13% chromium steel as a function of nickel and carbon content as well as heat treatment (tempering), according to CERT tests in high purity water at 288 °C [69]

Ferritic chromium steels with $\geq 13\%$ Cr

Low additions of titanium (about 0.6%) improve the corrosion behaviour of ferritic steels with 13 or 18% chromium, in particular after a short pre-oxidation. The influence of pre-oxidation on the corrosion behaviour of Ti-stabilised ferritic steels in high purity water with < 20 $\mu\text{S}/\text{cm}$, 5–10 $\mu\text{g}/\text{l}$ oxygen at 215 °C (488 K) up to 2000 h was investigated [70]. The steel SUS XM8 with 17% chromium and SUS 410Ti with 13% chromium and carbon contents of 0.008 and 0.006 C, respectively, as well as Ti-stabilised, each with about 0.6% titanium (see also Table 5) were examined. Pre-oxidation took place at 850 °C (1123 K) in an oxygen poor atmosphere (Ar). It was

reported that shorter oxidation times, i.e. up to 10 minutes, were more advantageous than longer times, because they reduce metal loss by up to 50% on polished surfaces; this was valid for both ferritic steels. The protective scale formed after pre-oxidation had a dual scale character, consisting of an external scale of Ti_2O_3 as well as an internal scale of MnCr_2O_3 . The titanium concentration in this oxide scale increased with increasing oxidation time. In addition, titanium suppresses the sensitisation of the ferritic steels. Decisive for the metal loss in high purity water is the thickness, density as well as the chemical composition of the surface oxide scale.

	C	Si	Mn	P	S	Ni	Cr	Ti	N
SUS XM8	0.008	0.40	0.48	0.020	0.001	0.20	17.77	0.60	0.0087
SUS 410Ti	0.006	0.46	0.41	0.026	0.001	0.17	13.08	0.56	0.0095

Table 5: Compositions of the steels SUS XM18 and SUS 410Ti [70]

In [71] the influence of water purity in the water-steam cycle of power stations on the corrosion behaviour of steels that are used in boilers and turbines (no material specified – probably 13–17% Cr-steels) was reported. The report describes the factors which can influence steam purity as well as the mechanism of accumulation of impurities. Failure analyses of turbine blades tend to be located in the region of the starting condensation and this in turn in the intermediate- and low-pressure regions. In this transition region only a small amount of condensation occurs due to the absence of nucleation sites, whose time and location vary immensely. This leads to sites with and without deposits, depending on the pressure and negative pressure sides of the turbine blades. Turbine cracks on such deposit transitions are often found. Pitting corrosion is also found under the deposits, caused by chloride enrichment. The deposits consist of silica and iron oxide, which form a porous deposit that captures impurities similar to a sponge, and are enriched after each load cycle. Impurities in the $\mu\text{g/l}$ range can be continually introduced, most often via the water treatment. Sulphuric, hydrochloric, phosphoric, acetic and organic acids were found, as well as non-ionogenic organic substances which increase corrosion upon decomposition. Due to the extreme accumulation of chlorides, a test in 22% NaCl solution at 80°C has been recommended for the qualification of turbine steels.

Acid resistant steels with 12–17% chromium have good resistance against distilled and high purity water up to 100°C , since under these conditions a sustainable protective scale of Cr_2O_3 and $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ exists; nevertheless chromium steels are only used for individual components of atomic energy plants because they are only suitable in the absence of oxygen [72–74].

The hot side of steam turbines and the blades of feed water pumps are made from 12% chromium steels, also wear resistant components such as bearings and pump shafts and valve spindles, which are sometimes hard chrome plated. Support grids for fuel rod elements are also made from chromium steel. The corrosion loss of these materials in demineralised water at 260°C is 0.007 mm/a at pH 7 and 0.11 mm/a at pH 10 [72].

In boiling water reactors chromium steels behave similarly to those in pressurised water reactors. 13% chromium steels withstand the effects of steam (700 °C) in continuous operation [75]. Chromium steels with 13–17% Cr are especially sensitive to intergranular corrosion after being welded. Also, riveted joints were seen to have pitting corrosion up to 1.7 mm in depth as well as crevice corrosion after one year [76].

The nickel containing age hardening steel grades 14-4 PH (UNS J92240) and 17-4 PH (1.4542, X5CrNiCuNb16-4) show better behaviour and are resistant in high purity water [72, 74]. Only at higher temperatures does the corrosion rate increase to 0.04 mm/a. This steel grade is however susceptible to stress corrosion cracking in demineralised water at 260 °C [72].

High-alloyed multiphase steels

Ferritic/pearlitic martensitic steels

The stress corrosion cracking behaviour of martensitic stainless steels as a function of annealing treatment in high purity water at 70–288 °C was investigated [77]. Stress corrosion cracking was initiated at pit or crevice corrosion sites. For steels with higher hardness (HV 430) the boundary stress was 300 MPa, for steels with HV 300 at their yield strength. Below hardness values of HV 270 no stress corrosion cracking was found, with the exception of steels with high nickel contents. Stress corrosion cracking susceptibility increases with increasing temperature as well as increasing hardness. Low carbon and low nickel containing steels show no signs of stress corrosion cracking in the complete solution annealed condition, also after very long exposure times up to 5000 hours in high purity water at 288 °C.

Ferritic-austenitic steels/duplex steels

The crack propagation velocity of the duplex steel Zeron 100 (c.f.: 1.4501; 24.4 Cr, 6.8 Ni, 3.7 Mo, 0.21 N with 5% austenite content) in high purity water with 5×10^4 and 2×10^5 Ohm cm as well as oxygen contents of 0.02–8 mg/l, measured at 30 °C and 5 Hz corrosion fatigue load is much higher than in air (by about a factor of 5) and comparable with that in a 3.5% NaCl solution. The unfavourable fatigue behaviour in both media is due to the cyclic tearing of the ferritic matrix with associated hydrogen absorption at the crack tip [78].

The alloy composition, austenite/ferrite ratio, heat treatment and cold deformation have a strong influence on the stress corrosion cracking behaviour of the austenitic-ferritic steel grade 18-5 (18 Cr, 5 Ni) in high purity water as well as in NaCl- and MgCl_2 -solutions [79]. The steel in the solution annealed condition (between 980–1050 °C) has significantly higher stress corrosion cracking resistance than an austenite based on 18Cr8Ni, however this is reduced considerably for the case that the austenitic-ferritic steel was annealed in the temperature range 750–900 °C because χ and γ phases precipitate at the grain boundaries. Their morphology does

however have no influence. The formation of large ferrite grains after welding or after annealing at 1300 °C is equally as damaging. Therefore the austenite/ferrite ratio must be controlled (Cr/Ni about 0.42). In contrast, a short heat treatment at 500–700 °C is less dramatic. Cold deformation produces strain induced martensite in the precipitates which increases the stress corrosion cracking susceptibility.

Austenitic CrNi steels

The literature evaluated for austenitic stainless steels is relatively comprehensive. This is related to the steels (and also NiCrMo alloys as well as Zircaloy) being used in atomic power, i.e. in pressurised and boiling water reactors (PWR, BWR) at temperatures up to 360 °C. Due to increased failures in the 1960's in particular in atomic power stations in the USA, intensive investigations began and continued well into the 1980's to understand the source of such failures. At the forefront was not the behaviour of uniform corrosion (this is negligibly small) but rather the susceptibility to stress corrosion cracking under the various water conditions as well as the microstructure of the used steels. Failures were mostly associated with welded or not optimally heat treated plant components (predominantly pipes). In the event of a sensitised microstructure as in the heat affected zone (HAZ) of a welded joint, stress corrosion cracking can occur, providing high mechanical loads are present and the high temperature water contains traces of anions, in particular chlorides. In addition, the oxygen content is of vital importance – as little as 0.2 mg/l oxygen can lead to stress corrosion cracking. From today's perspective in comparison to the steel production methods of the 1970's, considerably developed metallurgy has led to the problem of stress corrosion cracking being obsolete. The susceptibility of the earlier produced steels can be explained due to the relatively high carbon contents (0.05–0.07% C) which according to their time-temperature-precipitation diagram are inclined to chromium carbide precipitation on the grain boundaries and therefore rapid sensitisation (in solution annealed microstructure also stress corrosion cracking resistant). There are no grounds for sensitisation in reactor usage, since tests have shown that at ≤ 360 °C no susceptibility to cracking was observed. Since the mid 1970's, the modern techniques AOD and VOD (argon and vacuum oxidation decarburisation) have permitted the melting of stainless steel with very low carbon contents (so called LC grades = low carbon with 0.01% C) where sensitisation is greatly reduced after a critical heat treatment or welding.

The influence of flow velocity and the pH value on the corrosion of a 18 Cr10 Ni steel in high purity water is shown in Table 6.

The influence of a surface treatment on the corrosion behaviour can be seen in Figure 11. It can be seen that electro-polishing leads to significantly lower corrosion rates during the first 1000 hours in comparison to other surface treatments [133, 80].

Flow velocity, m/s	pH value	Total loss, mg/dm ² in 500 h	loss due to oxide
2	7	14.4	6.0
2	10	4.9	5.1
10	7	22.8	9.9
10	10	2.9	1.9

Table 6: Influence of flow velocity and pH value on electro-polished 18 Cr10 Ni steel at 300 °C in high purity water with 0.015 mg/l oxygen [133]

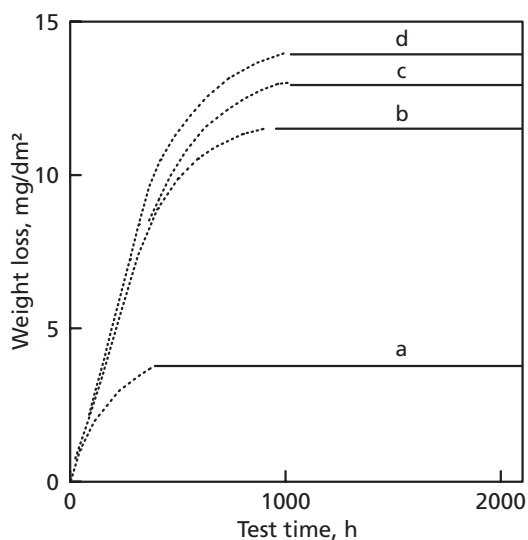


Figure 11: Influence of surface treatment on the initial corrosion of SAE 304 (Mat.-No. 1.4301) in high purity water at 300 °C (autoclave test) [133, 80]

- a) electro-polished
- b) ground (corundum, grain size 80)
- c) rolled
- d) polished (sand paper 600)

The difference in the corrosion rate of steel grades SAE 304 and SAE 316 in degassed high purity water which is either

- a) Completely free of oxygen or
- b) Contains 0.2 mg/l oxygen

is 0.21 or 0.75 mg/cm², correspondingly, after 500 hours [81].

Containers used for the long term storage of spent fuel elements in high purity water are made from steel SAE 304. Long term experiences are positive. However, isolated failures have been pointed out that can cause intergranular stress corrosion cracking to occur at relatively low temperatures (i.e. < 40 °C). So, for example in the

case of pronounced sensitisation and high mechanical loading which occurred after repeated repair welding stress corrosion cracking was observed [82]. Chlorides, which can be introduced to high purity water as a result of cleaning procedures, can further increase stress corrosion cracking susceptibility. The steel 17-4 PH (1.4542, X5CrNiCuNb16-4) proved itself over 15 years under such conditions as well as at pH 5 and high oxygen contents at 21–68 °C. The prerequisite is a correct heat treatment (4 h at 580 °C and then air cooling) and the removal of the scale layer by means of a subsequent chemical or mechanical surface treatment, in order to avoid possible stress corrosion cracking or pitting corrosion.

On the basis of AES and XPS measurements the composition of surface films on solution annealed SAE 304 (Mat.-No. 1.4301) in high purity water at 288 °C was investigated [83]. For high oxygen contents (8 mg/l) the stoichiometric mixed oxides $(\text{Fe,Ni})_2\text{O}_3$ and $(\text{Fe,Ni,Cr})_3\text{O}_4$ form, on the other hand at low oxygen contents (10 µg/l) high defect oxyhydroxides of the types Cr_2O_3 and CrOOH with NiFe_2O_4 are formed.

Defect oxide formation means poor repassivation behaviour and supports the film rupture mechanism for transgranular stress corrosion cracking which has been observed on solution annealed steels in high purity water, particularly at low oxygen contents.

On components used for boiling water reactors, accelerated intergranular stress corrosion cracking caused by crevice corrosion has been observed. Therefore, the conditions with regard to potential as well as pH in a crevice on an 18CrNi steel SAE 304 (Mat.-No. 1.4301) as well as the nickel alloy Alloy 600 (2.4816, NiCr15Fe) were fundamentally investigated [84]. As well, reference specimens with lowered chromium contents were made in order to simulate chromium depletion caused by sensitisation: on steel 304 a variation with 8% chromium, on Alloy 600 two variations with 10 and 5% chromium. The test conditions were high purity water with controlled O_2 , H_2 and N_2 contents as well as $< 0.1 \mu\text{S/cm}$ and 280 °C. From the results a pH value in the crevice is found that is well below the pH of the external solution. Also, the crevice corrosion potential is 300–400 mV lower than on the material surface. Contrast currents were measured from the cathodic surface to the anodic crevice. Whereas for both alloys the oxide films in the crevices were thinner than on the surface, they were considerably thicker on the reference specimens with lower chromium contents and the structures between the surface and crevice were very different. Ultimately the hydrogen pressure in the crevice is considerably higher than on the surface.

The electrochemical behaviour of SAE 304 (Mat.-No. 1.4301) in demineralised water ($< 1 \text{ mg/l}$ chloride) at 25 °C was investigated and compared with the behaviour in a 3% NaCl solution [85]. Corrosion potential-time curves after mechanical activation of the surface by scratching show repassivation in the 3% NaCl solution as well as in high purity water: the corrosion potentials increase from negative values ($< -200 \text{ mV}_{\text{SCE}}$) to the positive values of around $+40 \text{ mV}_{\text{SCE}}$. However, in high purity water this process occurs faster.

The mechanism of film growth was examined on the steel SAE 304 [47]. Also, the mechanism of cobalt uptake from ultrahigh purity water with $< 0.1 \mu\text{S/cm}$ and

200 µg/l oxygen at 288 °C was followed up. Weight losses after 1000 hours exposure and the composition of the oxide scale after dissolution in a HCl solution and subsequent atomic absorption analysis were determined. The results show that for a stainless steel 12% of the corrosion products are dissolved into solution (quite contrary to carbon steel: only 1%); on the other hand 88% of the oxide scale, mainly in the form of Fe_3O_4 as spinel, with a little Fe_2O_3 on the surface.

In order to reveal the corrosion risks of an 18Cr8Ni steel in a boiling water reactor under operating conditions, electrochemical potential measurements were developed to produce a monitoring technique using a special electrode [86]. The reactor test conditions were 173 °C, oxygen contents of 180–220 µg/l, hydrogen contents of 10–15 µg/l and water purity with 0.2 µS/cm (25 °C value). Over 4 years one finds potential variations in the region from –270 to +110 mV_{SCE}, which are attributed to the fluctuating water chemistry of the boiling water reactor. Assignment of the potentials or potential variations to the behaviour of the steels with uniform general corrosion or intergranular stress corrosion cracking could not be deduced.

The influence of oxygen and temperature on the stress corrosion cracking behaviour in high purity water of sensitised (600 °C/24 h) 18Cr8Ni steel (0.07 C) for use in boiling water reactors (BWR) was examined [87]. The crack propagation velocity at 288 °C is dependent upon the oxygen content and the strain rate. Under dynamic testing conditions the velocity is many orders of magnitude larger in air saturated water (8 mg/l O_2) than in the case of deaerated water with only 0.2 mg/l oxygen. The last feature was the start up conditions of a boiling water reactor. Rapid stress corrosion cracking was however observed under dynamic strain conditions at considerably lower temperatures (about 100 °C) and at the same time moderate oxygen contents (2 mg/l). Such conditions can occur during the start up of a reactor. One can reduce the period of time during start up for the stress corrosion cracking sensitive region with corresponding deaeration procedures.

In a literature review and its subsequent evaluation, 106 individual results concerning the influence of chlorides and oxygen on the stress corrosion cracking behaviour of austenitic steels based on 18Cr8Ni (SAE 304, 304 L, 316, 347 SAE 304 L, SAE 316, SAE 347) in high purity water in the temperature range 250–350 °C were summarised [88]. Subsequently, the critical parameter for stress corrosion cracking in water at high temperature is oxygen: it is a prerequisite for stress corrosion cracking. The normal conditions for solution annealed steel in reactor practice always lie in the oxygen-chloride region, in which no stress corrosion cracking occurs, which is clearly seen in Figure 12 (marked with x). On the other hand, the region above the curve in which intergranular stress corrosion cracking on sensitised steel occurs under both laboratory as well as in practical conditions.

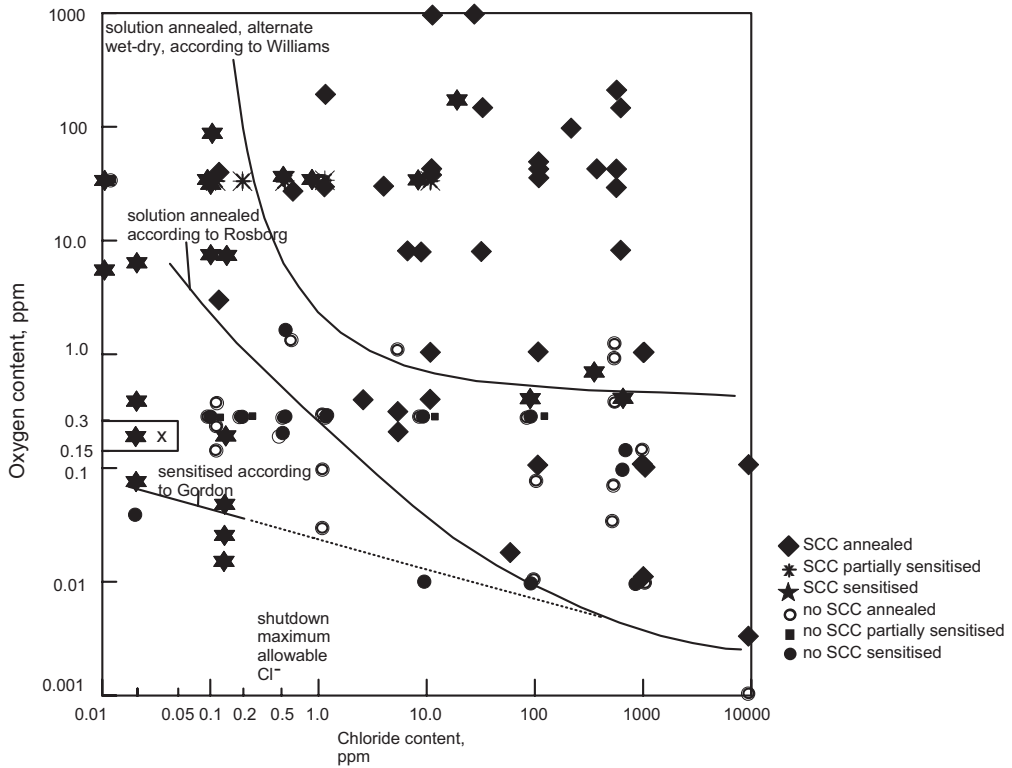


Figure 12: Influence of oxygen and chloride on the stress corrosion cracking of austenitic steels in high purity high temperature water under boiling water reactor conditions; greatly simplified – individual values see original literature [88]

The stress corrosion cracking behaviour (CERT tests) of SAE 304 (Mat.-No. 1.4301 with 0.061 C) in the sensitised condition (650 °C/1 h) in high purity distilled and demineralised water was reported in [89]. Intergranular stress corrosion cracking was found at temperatures > 150 °C and oxygen contents above 100 µg/l. For higher temperature and increasing oxygen contents the crack rate increases. Transgranular stress corrosion cracking was observed at temperatures of 150, 200, 250 and 290 °C and oxygen contents below 100 µg/l, whereby the dependence of the crack rate on oxygen content could not be determined. Transgranular stress corrosion cracking occurs when the corrosion potential is sufficiently low, i.e. when it lies in the transition active-passive region.

A test method to determine the potential dependence of the stress corrosion cracking susceptibility of sensitised 18Cr8Ni steel (0.05 C) in high purity water has been developed [90]. In the process the potential was controlled by oxygen dosing. As a result, at 200 °C CERT tests lead to a critical potential of $-250 \text{ mV}_{\text{SHE}}$, under which no intergranular stress corrosion cracking occurs, at 250 °C this values is $-300 \text{ mV}_{\text{SHE}}$.

The question was raised as to whether or not within the designated operating life of a boiling water reactor (about 40 years) the operating temperature of 288 °C could lead to sensitisation and thus to intergranular stress corrosion cracking in 18Cr8Ni steels [91]. As sensitisation tests on welded samples in the temperature range 385–500 °C show, below 450 °C chromium depletion was not found. CERT tests under start up conditions (180 °C with 1 mg/l oxygen) as well as operating conditions (288 °C with 0.2 mg/l oxygen) result in the highest crack rates in the heat affected zone (HAZ) only after sensitisation at 400 and 500 °C, however at 385 °C the rates decline rapidly and at 360 °C no further crack susceptibility was found. At very high oxygen concentrations (8 mg/l O₂-288 °C) – which however do not occur in practice – stress corrosion cracking was found. With increasing temperature as well as time the degree of sensitisation increases and thus the susceptibility to intergranular stress corrosion cracking which is illustrated in Figure 13.

In continuation of these investigations, the influence of possible sensitisation under reactor conditions at low annealing temperatures (300–500 °C) on stress corrosion racking was examined [92]. The test medium was typical of reactor water under start up conditions (180 °C/1mg/l oxygen) and continuous operating conditions (288 °C/0.2 mg/l oxygen), specimens were samples from the multiple weld layer joints of large pipes. The highest crack rates in the region of the heat affected zone were determined for those with a subsequent heat treatment at 400 and 500 °C, whereby the heat treatment time evidently showed a secondary influence. Heat treatments below 360 °C result in no stress corrosion cracking susceptibility under all test conditions. The crack rates for the simulated start up and continuous operating conditions only differ slightly. In contrast, the rates are considerably higher at a greatly increased oxygen content of 8 mg/l, for which stress corrosion cracking induced by intergranular corrosion was seen on all metallurgical sample variations, including the one in the original welded state (not heat treated). Also, a change in the water purity through the addition of sulphate 4–10 mg/l, sulphide (0.33 mg/l) or chloride (4–9 mg/l) leads to strongly increased crack growth.

Investigations on the steel SAE 304 (Mat.-No. 1.4301) concerning the dependency of the corrosion potential on oxygen content in high purity water ($< 5 \times 10^{-4}$ S/m) at 250 °C show that in the case of very low oxygen contents of 10 µg/l ignoble potentials, starting at -500 mV_{SCE} were determined. These increase above 100 µg/l to values up to -400 and -200 mV_{SCE}, in order to eventually level off at -200 mV_{SCE} for contents above 1000 µg/l and 1 mg/l, see Figure 14 [93]. The potential curve obviously presents a transition from active to passive behaviour. For this reason one can also explain the potential dependency of intergranular stress corrosion cracking in the sensitised state: stress corrosion cracking does not occur in the active state, i.e. not by the ignoble potentials caused through low oxygen contents. In contrast, at higher oxygen concentrations, here from 1 mg/l up to 36 mg/l, above which the passive state and thus self-passivation is reached, is shown in the potential jump in Figure 14. This would be consistent with the stress corrosion cracking theory of the tearing of a passive scale at the crack tip and the related formation of an active-passive cell.

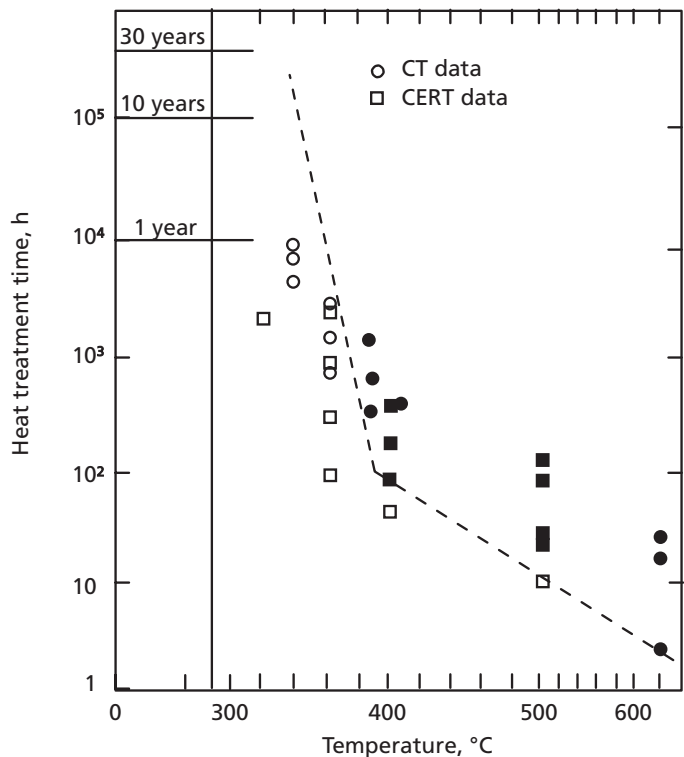


Figure 13: Time-temperature dependency of intergranular stress corrosion cracking of 18Cr8Ni steel (here with 0.068% C) in high purity water with 0.2 mg/l oxygen at 288 °C or 1 mg/l oxygen at 180 °C [91]
Filled symbols: intergranular stress corrosion cracking; open symbols: no intergranular stress corrosion cracking

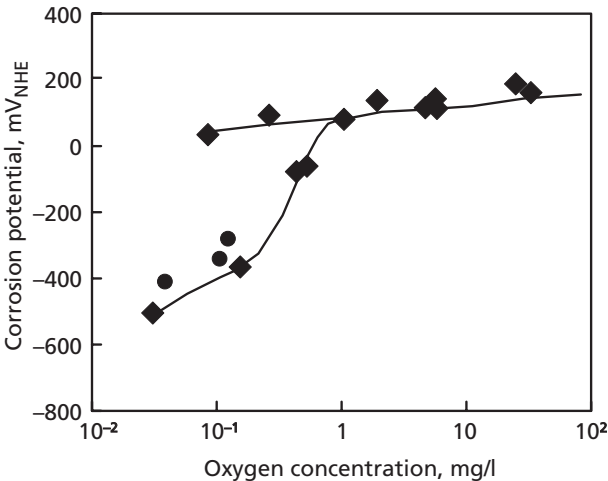


Figure 14: Dependence of corrosion potential of SAE 304 on oxygen content in high purity water at 250 °C [93]

By means of CERT tests using cyclic (trapezoidal shaped) loads, the stress corrosion cracking susceptibility of sensitised 18Cr8Ni steel (0.05 C) in high purity water with $5 \text{ M}\Omega \cdot \text{cm}$ as well as 8 mg/l oxygen at 290°C was examined [94]. The intergranular stress corrosion cracking susceptibility increases, the higher the upper load value is and for longer holding times. Higher crack rates were then determined. According to the CERT test the highest stress corrosion cracking susceptibility was found when the steel was heat treated at 600°C over 6–24 h and as a result was strongly sensitised.

In order to be able to estimate the operating life of a sensitised 18Cr8Ni steel against stress corrosion cracking, a probability analysis on the basis of measurements from tensile specimens in chloride solutions was conducted [95]. For the test of the influence of numerous factors accelerating stress corrosion cracking one concludes that the stress corrosion cracking lifetime can be illustrated using an exponential probability function and this can be directly transferred to the conditions in high purity water at high temperatures.

To determine the stress corrosion cracking susceptibility of welded tubes made from the steel SAE 304 (Mat.-No. 1.4301) for use in high purity water in boiling water reactors (here with 8 mg/l oxygen and at 288°C), a special test method was developed [96]. In order to shorten testing time, very high stresses with $1.36 \times R_{p0.2}$ were set. For commercial 18Cr8Ni grade steels with relatively high carbon contents in the range 0.055–0.075% C, one finds that from 82 tested samples, 54 cracked in the heat treated zone within about 100 hours. As a counter measure, solution annealing leads to stress corrosion cracking resistance (from 74 samples none had cracked); likewise fusion welding of the pipe exterior; also water cooling of all weld positions leads to stress corrosion cracking resistance. As alternative steel grades, the low carbon SAE 304 L (c.f. 1.4306) and 316 L SAE 316 L (c.f. 1.4404, 1.4435) were recommended. After a testing time of 2427 hours, stress corrosion cracking was not found on either steel, from 220 and 286 specimens, respectively.

In order to be able to test the stress corrosion cracking susceptibility of steels in high purity high temperature water more rapidly, a dynamic strain test under autoclave conditions was developed [97]. At low strain rates ($8 \times 10^{-4} \text{ mm/min}$) and 289°C the highest sensitivity to intergranular corrosion induced stress corrosion cracking was determined. Figure 15 shows the result of stress-strain curves, applied as stress-time curves for the various heat treatment conditions, as an example for the steel SAE 304 (1.4301, with 0.046% C). For the solution annealed condition the elongation values are the largest, in particular under inert gas conditions. With increasing sensitisation time of the steel at 620°C , the elongations decrease significantly and verify the stress corrosion cracking susceptibility. The fact that after 40 hours sensitisation the elongations, in particular in oxygen free water, increase again is due to declining intergranular susceptibility, caused by chromium homogenisation on the grain boundaries after very long heat treatment times.

Figure 16 shows the decreasing elongation with increasing temperature and the associated increase in stress corrosion cracking susceptibility.

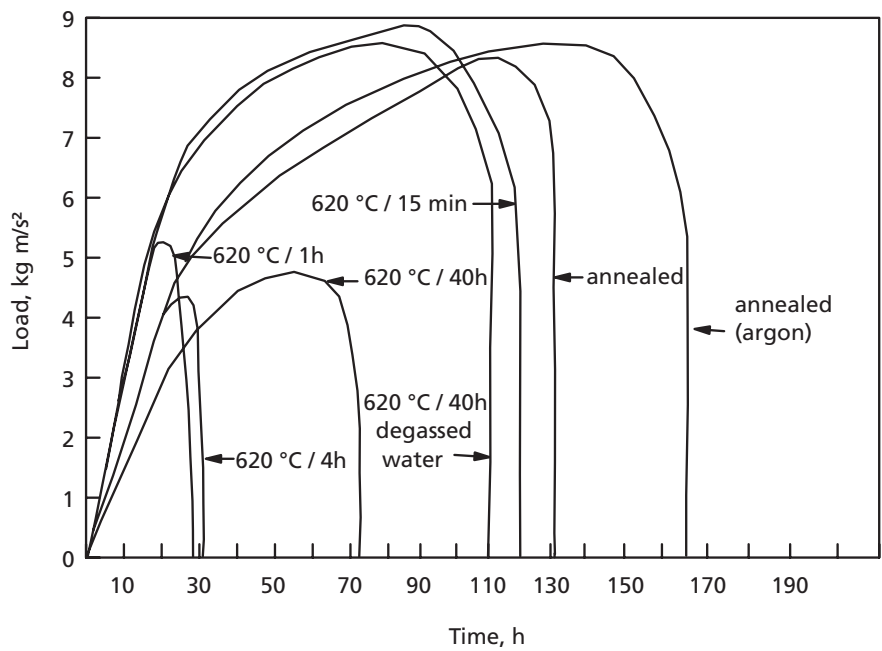


Figure 15: Stress-strain curves for the 18Cr8Ni steel SAE 304 (1.4301) with 0.046% C as-delivered and after sensitisation in high purity water with 36 mg/l oxygen at 289 °C (strain rate 8×10^{-4} mm/min) [97]

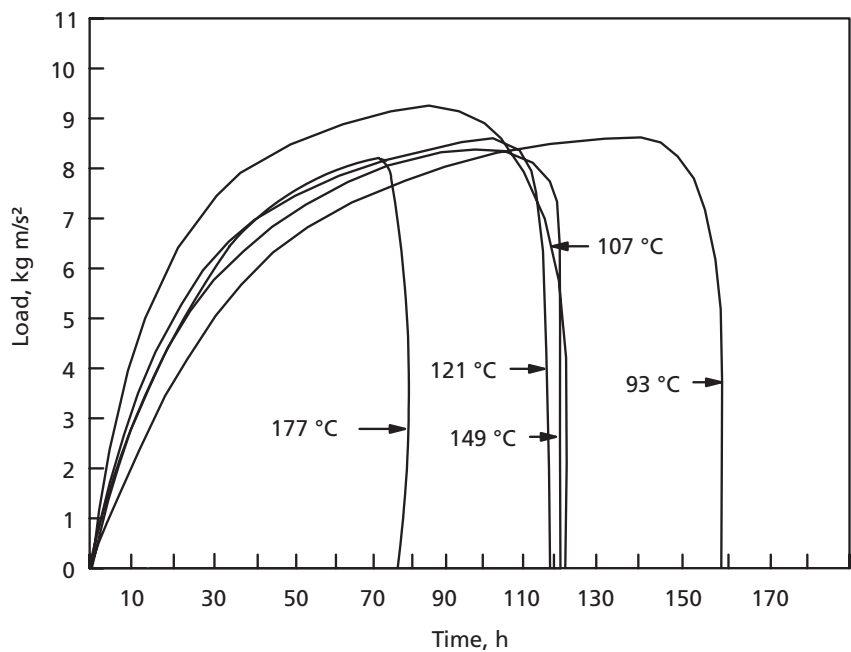


Figure 16: Stress-strain curves for 18Cr8Ni steel with 0.046% C after sensitisation at 590 °C/20 h as a function of test temperature, in high purity water with 8 mg/l oxygen (strain rate 8×10^{-4} mm/min) [97]

The method also allows the influence of the ferrite content in weld seams on stress corrosion cracking susceptibility to be determined. For a very low ferrite content the weld metal is significantly more susceptible to stress corrosion cracking, which is verified by the very low elongation values in Figure 17.

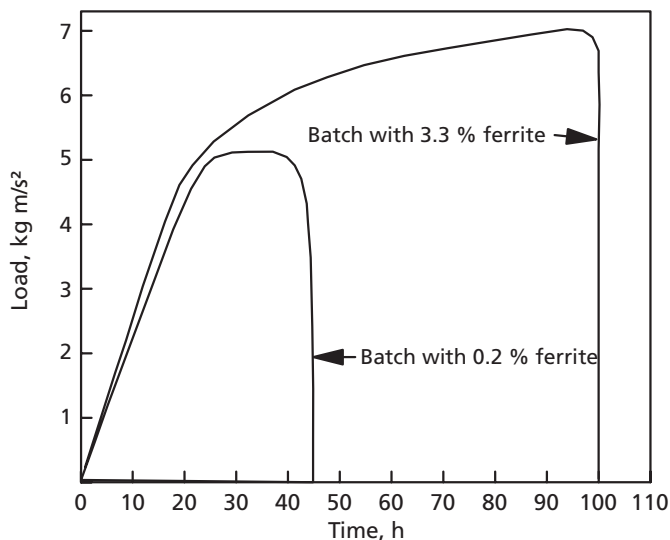


Figure 17: Stress-strain curves for a weld metal sample of 20Cr10Ni steel (SAE 308 L, Mat.-No. 1.4316, X2CrNi19-9) with 0.03% C in high purity water with 8 mg/l oxygen at 289 °C (strain rate 8×10^{-4} mm/min) [97]

Following the CERT test method, numerous austenitic steels in the conditions: solution annealed, sensitised (600 °C/24 h) and cold deformation were investigated for stress corrosion cracking in high purity water with 8 mg/l oxygen at 288 °C and 10MPa [98]. The results are presented in Table 8. For the 6 steels the best ones were the Mo-containing steel SAE 316 L (corresponding to Mat.-No. 1.4404, X2CrNiMo17-12-2 here with 0.02% C) as well as the Mn-containing XM-19 (corresponding to Mat.-No. 1.3964, X2CrNiMnMoNb21-16-5-3), the 18Cr8Ni steel SAE 304 (corresponding to Mat.-No. 1.4301, here with 0.07% C) was the worst, meaning that under all conditions it is susceptible to stress corrosion cracking, in the solution annealed conditions (transgranular stress corrosion cracking) as well as in the sensitised condition (intergranular stress corrosion cracking) and after shot peening. All other steels are resistant to stress corrosion cracking in the sensitised and solution annealed conditions. On the other hand steels become susceptible through cold forming, in particular the steels SAE 304 L (1.4306), SAE 347 (1.4550, Nb stabilised) as well as SAE 316 (1.4401, here with 0.05% C). Taking into account all treatment conditions, the order for increasing stress corrosion cracking resistance can be stated as: SAE 304, 304 L, 316 L, XM-19.

Material condition		Alloy	σ_m MPa	ε_m %	%RA	CERT Index	Fracture type, %
solution annealed	1.4301	SAE 304	468.8	46	47	1.0	85 D, 15 TG
	1.4306	SAE 304 L	386.1	44	79	1.0	100 D
	1.4401	SAE 316	482.6	52	69	1.0	100 D
	1.4404	SAE 316 L	461.9	45	70	1.0	100 D
	1.4550	SAE 347	503.3	41	63	1.0	100 D
	1.3964	XM-19	627.4	50	64	1.0	100 D
sensitised	1.4301	SAE 304	413.6	31	29	0.60	50 D, 45 IG, 5 TG
	1.4306	SAE 304 L	386.1	45	78	1.05	100 D
	1.4401	SAE 316	482.6	51	66	0.94	100 D
	1.4404	SAE 316 L	468.8	48	70	1.08	100 D
	1.4550	SAE 347	496.4	38	63	0.90	100 D
	1.3964	XM-19	634.2	54	60	1.01	100 D
blasted surface	1.4301	SAE 304	393.0	32	37	0.67	50 D, 50 TG
	1.4306	SAE 304 L	406.7	37	59	0.94	95 D, 5 TG
	1.4401	SAE 316	468.8	42	44	0.75	90 D, 10 TG
	1.4404	SAE 316 L	455.0	37	42	0.81	90 D, 10 TG
	1.4550	SAE 347	461.9	30	40	0.69	75 D, 25 TG
	1.3964	XM-19	641.1	45	54	0.96	95 D, 5 TG
stabilised + blasted surface	1.4301	SAE 304	365.4	26	26	0.53	45 D, 35 TG, 20 IG
	1.4306	SAE 304 L	386.1	30	49	0.74	60 D, 40 TG
	1.4401	SAE 316	496.4	41	51	0.86	95 D, 5 TG
	1.4404	SAE 316 L	489.5	36	38	0.90	95 D, 5 TG
	1.4550	SAE 347	461.9	29	44	0.67	60 D, 40 TG
	1.3964	XM-19	648.0	49	48	0.96	95 D, 5 TG

TG = transgranular, IG = intergranular, D = ductile

CERT Index: ratio of the respective fracture energy (surface under the stress-strain diagram) to that in the solution annealed condition

Table 7: CERT results on austenitic steels in high purity water with 8 mg/l oxygen at 288 °C [98]

Table 7: Continued

Material condition	Alloy		σ_m MPa	ε_m %	%RA	CERT Index	Fracture type, %
blasted surface + sensitised	1.4301	SAE 304	351.6	18	24	0.36	30 D, 60, IG, 10 TG
	1.4306	SAE 304 L	344.7	28	35	0.64	55 D, 35 TG, 10 IG
	1.4401	SAE 316	413.6	29	30	9.45	60 D, 20 TG, 20 IG
	1.4404	SAE 316 L	475.7	37	42	0.80	95 D, 5 TG
	1.4550	SAE 347	455.0	24	35	0.56	55 D, 45 TG
	1.3964	XM-19	634.2	44	43	0.88	95 D, 5 TG

TG = transgranular, IG = intergranular, D = ductile

CERT Index: ratio of the respective fracture energy (surface under the stress-strain diagram) to that in the solution annealed condition

Table 7: CERT results on austenitic steels in high purity water with 8 mg/l oxygen at 288 °C [98]

Using the “electrochemical noise” test method, remarks concerning the propagation of cracks in sensitised 18Cr8Ni steel in high purity water with 0.6 $\mu\text{S}/\text{cm}$ and 1 mg/l oxygen at 288 °C were made [99]. One finds that large cracks stagnate and tearing jumps over other smaller cracks. A simple model describes this jumping from one damaged grain boundary to another as well as the crack length distribution. The jumping over of cracks is higher at higher temperatures. The current density at the crack tip is 10 times higher at 288 °C than at 20 °C.

The influence of 13 various anion species on the stress corrosion cracking behaviour of sensitised SAE 304 (1.4301) in pure water with 1 $\mu\text{S}/\text{cm}$ and 0.2 mg/l oxygen at 289 °C was tested using the CERT method [100]. One finds that sulphur in the acidic form as NaS ensured relatively high stress corrosion cracking susceptibility. In the case of the presence of sulphates (0.1 and 1.0 mg/l) in the form of H_2SO_4 the intergranular crack rate in the temperature range 200–250 °C is very high. On the other hand, the rate falls substantially for temperatures > 270 °C as well as < 170 °C. At the same time, increasing transgranular stress corrosion cracking in addition to intergranular stress corrosion cracking was observed.

The resistance of SAE 304 to stress corrosion cracking in high purity high temperature water was strongly influenced by the presence of impurities such as sulphates, carbonates, nitrates and fluorides [101]. This is demonstrated with CERT tests in oxygen containing water at 274 °C with various concentrations, which were measured with a water conductivity level in the range 0.3–10 $\mu\text{S}/\text{cm}$. The reference medium was high purity water with < 0.1 $\mu\text{S}/\text{cm}$ and controlled oxygen content. During the tests the resting potential as well as the pH value was measured. The aim of the investigations was to investigate the synergistic effect of dissolved oxygen and ionic impurities on the intergranular induced stress corrosion cracking of sensitised 18Cr8Ni steel weldments. In the results one finds that sulphates and carbonates accelerate stress corrosion cracking most strongly, while nitrates are the least effec-

tive. One can largely eliminate stress corrosion cracking in the presence of corrosive sulphates and carbonates when their concentration is adjusted to a very low concentration, like that of oxygen. Thus one observes no intergranular induced stress corrosion cracking in a test solution with such low carbonate contents, which lead to a conductivity of $0.3 \mu\text{S}/\text{cm}$, with a simultaneous very low oxygen content of $21 \mu\text{g}/\text{l}$.

In order to examine the role of chromium depletion and hardening after proton radiation on the stress corrosion cracking behaviour of 18Cr8Ni steel in high temperature water, comparative investigations on model alloys with chromium contents of 15, 20 and 24%Cr were conducted – however, with a substantially increased nickel content of 24% [102]. CERT tests took place in high purity water with $0.5 \mu\text{S}/\text{cm}$ and $2 \text{ mg}/\text{l}$ oxygen at 288°C . While the ultra high purity steel SAE 304 (1.4301, 8 Ni) after radiation failed through intergranular stress corrosion cracking, the alloy variations with 24%Ni were stress corrosion cracking resistant in water with a conductivity up to $3.2 \mu\text{S}/\text{cm}$, although they showed considerable chromium depletion with up to 13% lower than the chromium concentration of the matrix. Evidently, chromium depletion is not a prerequisite for stress corrosion cracking. On the other hand, this behaviour is proof for the positive influence of higher nickel contents.

The influence of cold deformation (here 20%) on the stress corrosion cracking behaviour of 18Cr10Ni steel with and without Mo (SAE 304 (1.4301) and SAE 316 (1.4404)) was examined in high purity high temperature water ($0.1\text{--}0.3 \mu\text{S}/\text{cm}$ and $0.2\text{--}2.0 \text{ mg}/\text{l}$ oxygen) at 288°C , on the basis of crack propagation velocities [103]. The comparison with solution annealed and sensitised conditions showed that for both conditions without cold deformation, moderate susceptibility was found, but which is significantly higher for the sensitised condition, as to be expected. Cold deformed but not sensitised steel leads to similar high values, those in the case of a further sensitisation are increased further. In the temperature range $288\text{--}340^\circ\text{C}$ the crack propagation velocity of a 20% cold deformed steel (SAE 316) increased by a factor of 3.

In order to avoid intergranular corrosion induced stress corrosion cracking on SAE 304, the corrosion potential must lie below a critical value [104]. Figure 18 shows the results of investigations in high purity water with various oxygen contents and in the temperature range $150\text{--}300^\circ\text{C}$. After solution annealing ($1060^\circ\text{C}/15 \text{ min}$) the steel was sensitised at $620^\circ\text{C}/40 \text{ h}$, which led to more negative corrosion potentials. In extremely low oxygen contents (up to $10 \mu\text{g}/\text{l}$) this clearly led to no stress corrosion cracking. First, above this value the corrosion potential considerably increases and stress corrosion cracking was observed. The critical corrosion potential becomes similarly more negative with increasing temperature as well as with the addition of chlorides – both factors increase the susceptibility to stress corrosion cracking. On the other hand, U_{crit} can be increased through borate additions (at $< 250^\circ\text{C}$). An influence of the pH of the water is also possible.

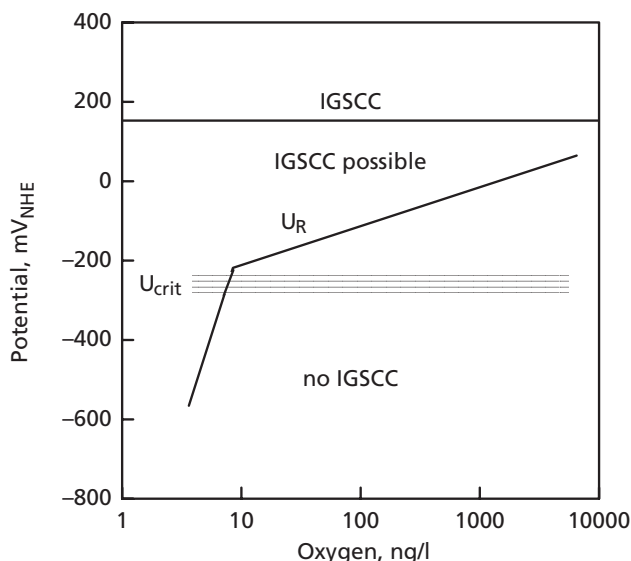


Figure 18: U_{crit} from SAE 304 in high purity water at 250 °C as a function of oxygen content [104]

Experiences from damage to welded pipes made from the steel SAE 304 (1.4301) in boiling water reactors were summarised in [105]. Under the practical operating conditions in high purity water with 0.2–0.3 mg/l oxygen, < 0.1 mg/l chloride and at 288 °C one finds:

- A) Intergranular stress corrosion cracking occurs exclusively in the heat affected zone (HAZ)
- B) The HAZ region of a welded pipe under mechanical load, which reaches the maximum load, is hardly deformed; added to this are residual stresses caused by welding – both lead to very high mechanical loads
- C) Sensitisation of the steel by welding is a more essential and sufficient factor for triggering stress corrosion cracking in case B)
- D) Waterside, the role of dissolved oxygen as an oxide scale former is of great importance
- E) Deposits on the pipe interior act as crevices, in which cracks can be triggered.

Therefore, a new stress corrosion cracking test method was developed (Crevice Bent Beam CBB test), which considers the crevice effect as well as factors B, C and D above. Bend test specimens with an artificial crevice made from graphite wool (more sensitive than those made from PFTE and especially metal-metal) were tested (both welded and non-welded but sensitised at 600 °C/2 h) in high purity water with 0.2 μ S/cm, oxygen saturated, chloride < 0.1 mg/l, pH 5.8–6.2 at 250 °C. For more than 20 steel specimens with different carbon contents (which are responsible for various susceptibilities to sensitisation) one obtains very clear conclusions: from 20 specimens each of them showed stress corrosion cracking after only 24 hours, so long as the carbon content lied in the range 0.06–0.045%. In the process cracks with

a maximum length up to 1 mm in a distance 5 mm from the fusion line of the weld seam were found. In contrast, all samples from charges with $< 0.02\%$ carbon showed the highest resistance to stress corrosion cracking: from 20 bend test specimens not a single specimen – even after a testing time of 500 hours – had cracked. The method allows for the selection of stress corrosion cracking resistant stainless steels, of which SAE 304 L (1.4306), 304 LN (1.4311), 316 L (1.4404) are the most resistant.

The process of accelerated crack initiation through the application of a crevice using graphite wool was also confirmed in another investigation SAE 304 LN SAE 316 L [106]. In comparison to the steel SAE 304, nickel base alloys such as Alloy 600 (2.4816, NiCr15Fe) have increased test sensibility up to a factor of 5–6. Good agreement with the behaviour under practical conditions was given.

The addition of precious metals (here about 3% platinum) to a 18Cr8Ni steel leads to significantly increased hydrogen oxidation kinetics as well as those for oxygen reduction in high purity high temperature water (288 °C, 200 µg/l oxygen). In the process a thermodynamically very ignoble corrosion potential of $-500 \text{ mV}_{\text{SHE}}$ is set [107].

The stress corrosion cracking behaviour of the austenitic cast steel CF3 (c.f. 1.4306, 1.4309) and CF8 (c.f. 1.4308) was tested by several methods in high purity water with $< 1 \text{ µS/cm}$ and an oxygen content of $6 \text{ mg/l} \pm 2$ at 288 °C (550 °F) [108]. In comparison to the conditions for boiling water reactions, in the present case they were significantly intensified. The results show that all cast specimens, also after various heat treatments, after sensitisation as well as welded samples, had resistance to intergranular induced stress corrosion cracking. In this case, materials with very low carbon contents (CF3 with about 0.02%) behaved most reliably. Furthermore, ferrite contents in the range 5–12% increase the stress corrosion cracking resistance for the higher carbon containing variations. For the low carbon LC-grades, stress corrosion cracking resistance was found to be independent of the ferrite content (here: 4–28%).

The susceptibility of sensitised 18Cr18Ni steel (here SAE 304) to intergranular induced stress corrosion cracking can be reduced in high purity water and at high temperatures by hydrogen dosing [109]. The prerequisite for stress corrosion cracking is the presence of a sensitised condition, high mechanical load and oxygen in the water. If the dissolved oxygen is reduced by the addition of hydrogen, the chemical driving force for the initiation of stress corrosion cracking is reduced. Under the conditions:

	Initial condition	Test conditions
Temperature	$282 \text{ °C} \pm 5 \text{ °C}$	$282 \text{ °C} \pm 5 \text{ °C}$
Dissolved oxygen	$200 \pm 100 \text{ µg/l}$	$15 \pm 10 \text{ µg/l}$
Conductivity at 25 °C	$0.6 \pm 0.3 \text{ µS/cm}$	$< 0.2 \text{ µS/cm}$
Dissolved hydrogen		$125 \pm 25 \text{ µg/l H}_2$

correspondingly lower crack rates are found, e.g. < 0.3 compared to $> 4 \times 10^{-4} \text{ mm/h}$. However, at the same time, as well as the reduction in oxygen content, the conductivity of the medium through the corresponding water chemistry is also reduced.

In order to examine the influence of water flow velocity on the stress corrosion cracking behaviour of stainless steels, CERT tests on the steel SAE 304 (1.4301) in high purity water with $< 0.2 \mu\text{S/cm}$ oxygen contents of 20–300 $\mu\text{g/l}$ and 285 °C (545 °F) were conducted [110]. The region of interest was 0.002–2 ft/s. As measurements of the stress corrosion cracking lifetime show, one finds that with increasing flow velocity, longer times (40–50%) to rupture through stress corrosion cracking are found, see Figure 19. This could be explained due to the change in chemistry in the proximity of possible forming cracks. The corrosion potentials become nobler with increasing flow velocity, in particular at oxygen contents in the range 20–300 $\mu\text{g/l}$.

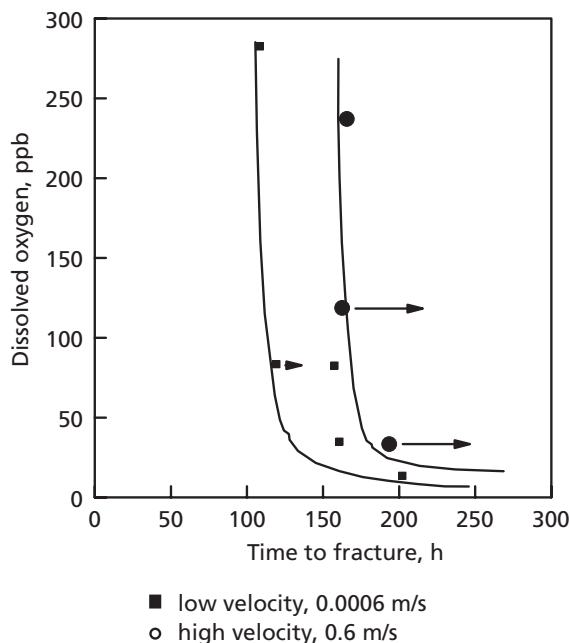


Figure 19: Influence of dissolved oxygen on the stress corrosion cracking lifetime at low and high flow velocities for a 18Cr8Ni steel in high purity water at 285 °C [110]

One can substantially reduce or almost eliminate the susceptibility to stress corrosion cracking of austenitic stainless steels based on 18Cr8Ni through additions of silicon (from 4.5%) [111]. This leads to an austenitic-ferritic matrix because silicon is a strong ferrite former. Transgranular stress corrosion cracking in the MgCl_2 test as well as intergranular stress corrosion cracking in oxygen saturated (100 mg/l) high purity water at 289 °C result in longer stress corrosion cracking lifetimes with increasing silicon contents, as seen in the values in Table 8. In contrast to the Si-free commercial 18Cr8Ni steel (here SAE 304), which cracks after a few hours and in cross-sectional micrographs shows pronounced stress corrosion cracking (triggered by intergranular corrosion), one finds no cracks in the high silicon steel grades within the testing time of 300 h. The significantly improved stress corrosion cracking behaviour is explained by the fact that during the sensitisation heat treatment car-

bides are only precipitates in the α - γ grain boundary region and not in the γ - γ grain boundary region. Despite the high silicon content which also improves the strength, the hot formability and weldability of this steel are preserved.

Sample	Si,%	δ -ferrite,%	Time to fracture, h
A	1.0	0.5–1.0	22.8; 12.0
B	2.0	0.5–1.0	65.0; 58.5
C	2.9	1.6–1.8	19.0; nB* 332**; nB 305**
D	3.8	7.5–7.6	68.0; 114
E	4.5	16.8–17.0	nB 304; nB 305
F	4.7	22.0–23.0	nB 306; nB 305
G	4.7	27.0–29.0	nB 306; nB 306
H	4.8	27.5–29.5	nB 330; nB 451
I	4.8	17.5–19.9	nB 307; nB 307
SAE 304	–	–	14.5; 13.0

* nB: no fracture in the given time

** no fracture but fine intergranular cracks

Table 8: Results of intergranular stress corrosion cracking tests with a silicon alloyed 18Cr8Ni steel and SAE 304 in water with 100 mg/l oxygen at 289 °C [111]

By means of CERT measurements, the influence of alloying elements on the stress corrosion cracking behaviour of SAE 304 (1.4301) after neutron irradiation was investigated [112]. The tests were conducted in high purity water with 0.2 μ S/cm and 32 mg/l oxygen at 300 °C. One finds:

- Samples from high purity 18Cr8Ni steel result in the highest stress corrosion cracking susceptibility
- Carbon additions (here from 0.003 to 0.10%) in the steel lead to considerably higher stresses during the CERT test (evidently carbon strengthens the hardening effect through irradiation)
- The observed elongations in the stress-strain diagram are shorter in each case
- Silicon (0.7%) reduces the maximum stresses and leads to longer elongations, and therefore improves the stress corrosion cracking behaviour
- Sulphur up to 0.03% deteriorates and phosphorus improves the stress corrosion cracking behaviour, see also Figure 20
- As well, nitrogen deteriorates the stress corrosion cracking behaviour, nickel improves it.

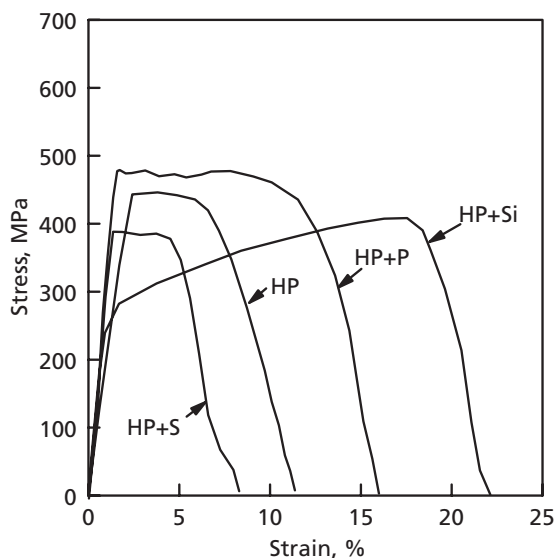


Figure 20: Stress-strain curve for SAE 304 (1.4301) (18Cr8Ni steel free of C, but with additions of S, P and Si) in high purity water with 32 mg/l O₂ at 300 °C [112]
HP = high purity

Similar claims were made in [113] concerning the influence of Cr, P, C, Si and S on the stress corrosion cracking behaviour of high purity 18Cr8Ni steels with their microstructures altered via neutron irradiation.

Neutron irradiation of stainless steels based on 18Cr8Ni without Mo (SAE 304) and with Mo (SAE 316) influenced the stress corrosion cracking behaviour via the process of hardening. This was shown in CERT tests on 23 various steel specimens with various contents of Si, P, Nb and Mo in high purity water with 32 mg/l oxygen at 288 °C [114]. Hardness and yield strengths correlate well with each other. Lower silicon and phosphorus contents suppressed the stress corrosion cracking susceptibility. Niobium has no influence. A limiting stress for the yield strength of 700 MPa was determined, above which stress corrosion cracking occurs.

The influence of proton irradiation on the stress corrosion cracking behaviour of sensitised steel SAE 304 (1.4301) in high purity water with 1 µS/cm, oxygen saturated at 288 °C was investigated using C-ring specimens, namely with electrochemical noise [115].

By means of this test method the crack propagation is verifiable via measurement of the galvanic micro-current. Irradiated material shows higher stress corrosion cracking susceptibility. However, scanning electron microscope investigations showed that the chromium depletion profile at the grain boundaries is hardly changed through low proton irradiation. Therefore, the increased stress corrosion cracking susceptibility can be justified more from hardening caused by irradiation.

To determine the influence of irradiation (fast neutrons) on the stress corrosion cracking behaviour of reactor materials (e.g. fuel casings) in high purity high pressure water, a special test device was constructed [116]. By means of CERT tests it was proven that the sensitised steel SAE 304 (1.4301) was considerably more susceptible to intergranular stress corrosion cracking than for the sensitised steel which was not irradiated. The test conditions were: high purity water with 8 mg/l oxygen at 288 °C, strain rate 1×10^{-6} /min and a radiation intensity of 3×10^{21} n/cm².

The influence of radiolysis products on the corrosion behaviour of sensitised SAE 304 (0.05% C) in high purity water (0.1 µS/cm) with various oxygen contents at 250 °C was examined [117] (see also [90]). The strong influence of the products which form was shown by H₂O₂, followed by oxygen and the lowest influence by hydrogen. This is related to the oxidising effect of H₂O₂, shown through a clear shift in the corrosion potential so that according to CERT tests intergranular stress corrosion cracking was determined from -300 mV_{SHE}. In addition, sulphates (here Na₂SO₄) have a strong influence on stress corrosion cracking, whereby they are somewhat less corrosive than in the form of H₂SO₄: a concentration equivalent with a conductivity of 10 µS/cm leads to stress corrosion cracking under oxygen free conditions (triggered by intergranular corrosion). One determines here a critical potential of -500 mV_{SHE}, above which stress corrosion cracking occurs.

The high nickel and chromium steel SCR-3 (25.13 Ni, 24.65 Cr, 2.05 Si, 1.53 Mn, 0.98 V, 0.26 Ti, 0.023 C) shows very good stress corrosion cracking behaviour in high purity water with 8 mg/l oxygen at 300 °C, also in the sensitised state (here: all specimens at 650 °C/2 h) [118]. This is the result of stress corrosion cracking tests on U-bend specimens in comparison to the steels SAE 304, Inconel® 600 as well as Incoloy® 800. From Figure 21 it can be seen that crack depths in the 18Cr8Ni steel escalate after 400 h test time, in comparison the high chromium and nickel containing SCR-3 shows no cracks after 1000 h. Its behaviour is very similar to the nickel alloy Alloy 600 (2.4816), which under these conditions is deemed as stress corrosion cracking resistant. A similar trend of curves is obtained under comparable conditions for the addition of 500 mg/l NaCl, however the values are shifted heavily to the left i.e. to shorter times. In the presence of chlorides cracks appear much earlier.

Stress corrosion cracking of components based on the 18Cr8Ni steel in high purity water in boiling water reactors is frequently observed, not only in stabilised grades or grades with high carbon contents, but even in low carbon LC grades. In the case of high carbon containing and welded steels an increase in the occurrence of intergranular stress corrosion cracking (which lies in the region of the heat affected zone) during plant operating time has been determined. Therefore a new method for the lifetime assessment of component in boiling water reactors made from austenitic stainless steel was developed: the PLEDGE model (Plant Life Extension Diagnosis of General Electric) [119]. One finds stress corrosion cracking predominantly when the water contains large amounts of oxygen, the steel has been cold formed or when grain boundary precipitations caused by heat treatment are present. Hydrogen dosing (1–2 mg/l) reduces the oxidising water conditions and therefore the danger of stress corrosion cracking. Diagrams have been presented which show good correlation between estimated and industrial crack propagation.

Inspection at regular intervals is compulsory for the recognition of cracks and their extent, in order to be able to punctually undertake component repairs and/or exchanges.

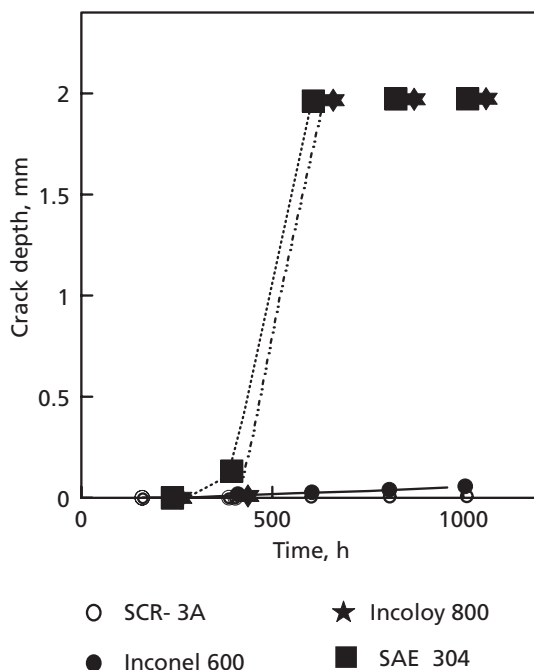


Figure 21: Stress corrosion cracking susceptibility of sensitised alloys in high purity water with 8 mg/l oxygen at 300 °C. Crack depths in mm as a function of test time in h [118]
 SAE 304 Inconel® 600 Incoloy® 800

By means of CERT tests the influence of ferrite in the austenitic matrix of steel (1.4303, X4CrNi18-12; here: 21 Cr, 19 Ni, 1.76 Mn, 0.41 Si, 0.04 C) on intergranular stress corrosion cracking in high purity water with 8 mg/l oxygen at 288 °C was investigated. For a set ferrite content of about 10%, achieved by heat treatment, one finds intergranular stress corrosion cracking only at a sensitisation temperature of 550 °C and after 24 and 48 hours – all other conditions (400–600 °C/10–200 h) show ductile fracture. The susceptibility can best be predicted using the ASTM test A 262 for the determination of intergranular corrosion [120].

The stress corrosion cracking susceptibility of sensitised 18Cr8Ni steel (SAE 304) in high purity high temperature water is dependent mainly on the combination oxygen-temperature [121]. While according to CERT tests one sees a continually increasing crack rate in the temperature range 100 to 300 °C for a very high oxygen content of 8 mg/l, in the case of only 0.2 mg/l oxygen at 200 °C the curve bends again, i.e. the crack rates decline significantly. For this reason, the susceptibility under practical conditions in boiling water reactors (288 °C, < 0.01 mg/l oxygen) fall significantly. In Figure 22 the combined regions oxygen-temperature which exist in

practice are illustrated. Since here the probability of stress corrosion cracking is given, the residence times in these regions should be kept as low as possible.

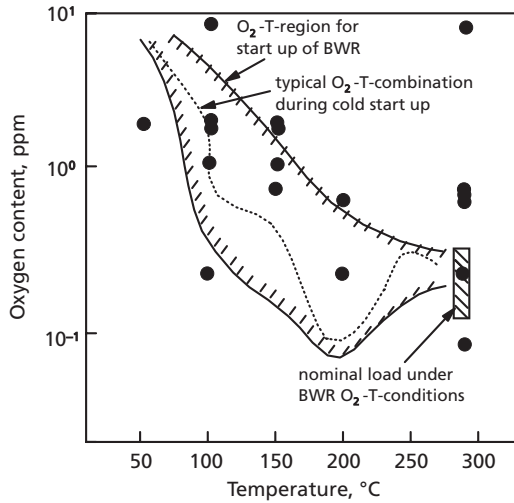


Figure 22: Tested oxygen-temperature combinations on 18Cr8Ni steel and their bearing on limitations at start up [121]

The crack propagation velocity of sensitised steel SAE 304 (1.4301, here: 0.06% C; 620 °C/24 h) was measured on samples with constant load under simulated boiling water reactor conditions at 288 °C. In order to determine the influence of H_2O_2 , oxygen and hydrogen, 10–440 $\mu\text{g/l}$ oxygen, 0–570 $\mu\text{g/l}$ H_2O_2 as well as 14–150 $\mu\text{g/l}$ hydrogen, respectively, were added to high purity deionised water [122]. The crack rates increase with increasing oxygen content, as shown in Figure 23.

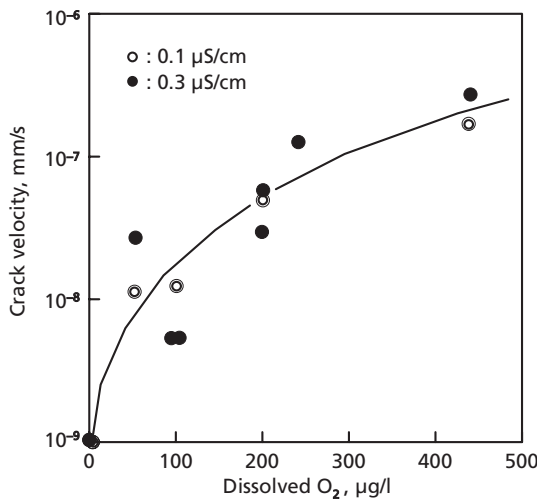


Figure 23: Influence of oxygen on the crack rate of sensitised SAE 304 (1.4301) in high purity water at 288 °C [122]

Dosing with H_2O_2 shows similar behaviour. In contrast, crack propagation was not found in the case of hydrogen additions, above 50 $\mu\text{g/l}$ hydrogen, as shown in Figure 24.

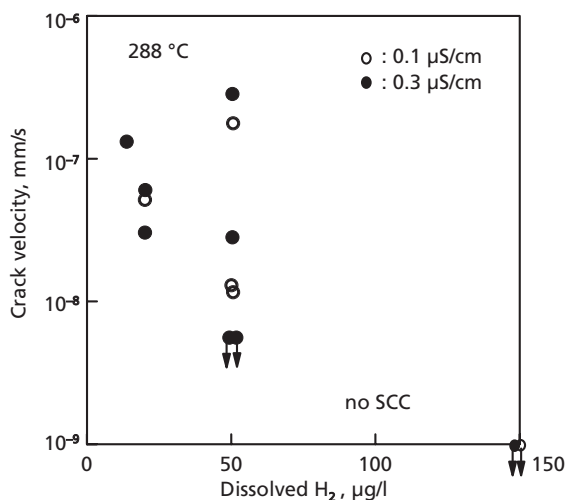


Figure 24: Influence of dissolved hydrogen on the crack rate of sensitised steel SAE 304 (1.4301) in high purity water at 288 °C [122]

With increasing corrosion potential, the crack rate increases strongly and there is a critical potential, under which the crack rate is practically zero. This limiting potential lies at $-200 \text{ mV}_{\text{SHE}}$, see Figure 25.

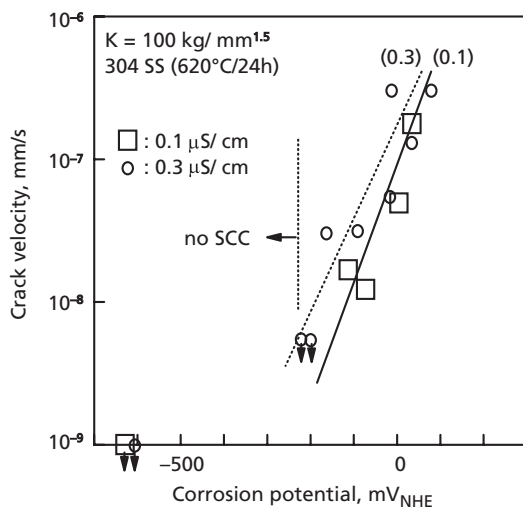


Figure 25: Influence of corrosion potential on the crack rate of sensitised steel SAE 304 (1.4301) in high purity water at 288 °C [122]

From reactor practice it is known that dosing with hydrogen reduces the stress corrosion cracking susceptibility of sensitised 18Cr8Ni because hydrogen combines with oxygen and as a result the crack propagation reduces, in particular, the cracks present are stopped from further growth.

In order to more rapidly examine the correlation between sensitisation and the tendency to intergranular stress corrosion cracking of 18Cr8Ni steel in reactor water, a new test in high purity water with 15 µg/l oxygen, pH 6.5 and 85 °C was developed. Herein the corrosion fatigue behaviour at a frequency of 1 cycle/min and stress amplitude of 23 MN/m^{3/2} was investigated, using fractographic investigations to determine the form and percentage of the fracture surface. Specimens were sensitised at 620 °C for 1, 10 and 40 h. The results for the solution annealed comparative samples show 100% ductile fracture, while for the sensitised specimens the proportion of the grain surface fractures increases with the sensitisation time and in the case of 40 h was almost 100%, i.e. no more ductile fracture was present. The results show that intergranular stress corrosion cracking in relatively mild media and at lower temperature (lower than in reactor conditions) with cyclic loading and low frequency is possible.

By means of experimental data on welded pipes made from SAE 304 (1.4301) a model for intergranular stress corrosion cracking in high purity high temperature water was derived. Crack initiation- as well as crack propagation-phases were treated. The process of sensitisation on grain boundaries, stress gradients in weldments, residual stresses and the role of surface treatments were also considered [123].

In the case of the presence of crevices on the surface, the stress corrosion cracking susceptibility of 18Cr8Ni steels (here: SAE 304, SAE 304 L, SAE 316, SAE 316 L, SAE 316 LN) in high purity high temperature water increased. This is shown by investigations on specimens with constant loading as well as U-bend specimens, which were tested with an artificial crevice [124]. One observes a considerable decrease in stress corrosion cracking lifetimes as well as the critical limiting stress at 240 °C. Intergranular stress corrosion cracking was experienced above 200 °C on specimens without a crevice, on the other hand specimens with a crevice from 175 °C. Below 150 °C no intergranular stress corrosion cracking was observed.

The crack rates for the stress corrosion cracking of the sensitised steel SAE 304 in high purity water with 0.5 mg/l oxygen at 288 °C are greatly accelerated by sulphate ions, by a factor of 4–5 [125]. This is the result of crack rate measurements as a function of the change in conductivity after the addition of H₂SO₄. However, only after numerous dosages (3–4 after one another) does one find such corresponding effects as well as after an incubation time up to 100 h. However, from the total conductivity of the test solution alone one cannot conclude the amount of damage – additionally, the length of time, the level and number of SO₄ dosages must also be considered.

In the cooling system of boiling water reactors the start up and shutdown of the plants can lead to cyclical mechanical stresses, in particular in welded pipe components. Investigations on the sensitised SAE 304 (1.4301) show that this leads to intergranular stress corrosion cracking in a short time in high purity water with 5 MΩ · cm resistance and in the case of 8 mg/l oxygen at 290 °C. At the same time the stress corrosion cracking susceptibility is dependent on the trapezoidal shape of

the load curve, i.e. from the upper and lower stresses as well as the holding times [126].

The susceptibility of welded 18Cr18Ni pipes (here: up to 100 mm diameter) to intergranular stress corrosion cracking in high purity water with 6 ± 2 mg/l oxygen at 288 °C can be considerably improved (by a factor of 15) by an inductive post-heat treatment in the weld seam region because compressive stresses are formed on the inner side of the pipe [127]. In doing so the effect of the level of mechanical load is dependent, i.e. there is a limiting stress, above which the heat treatment effect is absent. This limiting value (here: 227 MPa) lies much further above the $R_{p0.2}$ and as such in the range of mechanical component loads that are found in practice.

To determine the fatigue corrosion behaviour of boiler steels for pressurised water reactors (SA508-2 and SA533B-1, see also Table 4) in high purity water at 288 °C, crack rates were measured as a function of the stress intensity (da-dK diagrams) [128].

Microbiological influenced corrosion (MIC) was found on SAE 304 (1.4301) in relatively pure water at 80 °C [129]. A large tank failed by intergranular stress corrosion cracking. Microbes were responsible for a deposit forming on the steel surface, under which the smallest amounts of chlorides are enriched and can also penetrate the grain boundaries. When localised high mechanical stresses are present, MIC induced stress corrosion cracking can occur.

In large storage tanks ($30 \times 10 \times 10$ m) used for spent fuel rods from nuclear power plants, which are lined with stainless steel (no further details given) and filled with demineralised water, the corrosion rate after many years of service was determined [130]. Under the conditions $20^\circ\text{C} \pm 5^\circ\text{C}$, $\text{pH } 5 \pm 1$, 0.1 mg/l oxygen as well as 0.1 mg/l chloride ions a total container weight loss of 150 mg/a was found by spectral analysis, which corresponds to a corrosion rate of $0.01 \mu\text{m/a}$. This means absolutely negligible corrosion attack. Information: since only Fe, Cr and Ni, and no Mo were found in the spectral analytical data, the described stainless steel involved was assumed to be an 18/8 CrNi steel.

In another case a pump housing for a boiling water reactor was made from the steel CF-8M (1.4408; 18-21 Cr 9-12Ni, 2-3 Mo), the impeller was made from CF-8 (1.4308, GX5CrNi19-10). The niobium stabilised CrNi steel Mat.-No. 1.4550 (corresponding to SAE 347) has proven itself for use as a material for ^{235}U enriched nuclear fuel sheaths [131, 132]. The steels come into contact with high purity water or the boiling reactor water at temperatures between 260 and 350 °C. In the process, magnetite and spinel form on the metal surface of which a portion will be transported from the cooler to the hotter plant components [133]. The observation that the acid resistant CrNi steels were destroyed in water at 300 °C with 50 mg/l oxygen + 100 mg/l chloride after only 200 hours means keeping these foreign substances completely free from the circulating water. From the investigations mentioned below, the susceptibility ranges of the Mo free chromium-nickel steels for the simultaneous presence of chloride ions and oxygen were marked out:

- After the addition of 10 mg/l chloride the steel SAE 304 (Mat.-No. 1.4301) started to crack in the presence of 8 mg/l oxygen after 25.5 h [134].

- 4 commercial acid resistant chromium-nickel steels suffered no stress corrosion cracking in high purity water with 100 to 800 mg/l chloride (added as NaCl) at 300–350 °C, so long as the oxygen content remained below 0.2 mg/l. As soon as the oxygen concentration was increased to 0.3 mg/l, fracture as a result of stress corrosion cracking occurred. Solution annealed steels were destroyed by transgranular attack, in addition sensitised (welded) steels were destroyed by intergranular attack [133, 135].
- The steel SAE 304 was not attacked under load in the presence of 0.02 mg/l chloride + 0.1 mg/l oxygen at 330 °C; in water with 0.1 mg/l chloride + 3 mg/l oxygen as well as 0.02 mg/l chloride + 40 mg/l oxygen crack formation through stress corrosion cracking occurred [136].
- Mo containing austenitic chromium-nickel steels are less susceptible in the simultaneous presence of chloride ions and oxygen [133].

From these results the requirements for the purity of the circulating water can be deduced. However, in contrast to the acid resistant chromium-nickel steels, nickel alloys such as Alloy 600 (2.4816) and Alloy 800 (1.4876 c.f. A 28) withstood the exposure to water with 50 mg/l oxygen and 100 mg/l chloride at 300 °C without damage because they did not suffer from stress corrosion cracking. Therefore nuclear fuel sheaths are often made from these materials [72].

The water in secondary cycles must also be free of chloride ions, since the heat exchangers, pipes and the hot side of the turbines, which are made from acid resistant chromium-nickel steels can be heavily damaged by stress corrosion cracking [72]. The addition of phosphate is not allowed due to the risk of stress corrosion cracking. Maintaining the pH value (pH 9) can be achieved by using volatile organic compounds e.g. cyclohexamine or hydrazine [137, 138]. To prevent stress corrosion cracking one should select steels with low carbon content (ELC grade with < 0.03% C) or steels which are stabilised with titanium or niobium. The ELC steels are highly suitable for nuclear fuel sheaths from 0.1 mm wall thickness [72]. The corrosion rates for austenitic chromium-nickel steels in high purity water for pressurised and boiling water reactors are given in Table 9.

Alloy	Temperature °C	pH value	Water quality	Corrosion rate	
				mm/a	
SAE 304	100		distilled	0.13 g/m ² d	0.0005
SAE 304, SAE 316	300	6.5	degassed, distilled		0.0025
SAE 304, SAE 316	260	6.5	degassed, distilled		0.0–0.0025

Table 9: Corrosion rates of austenitic CrNi steels in high purity water under the conditions of pressurised and boiling water reactors

Table 9: Continued

Alloy	Temperature °C	pH value	Water quality	Corrosion rate	
				mm/a	
SAE 304, SAE 316	30	3.2	degassed, distilled, cation free	no attack	
SAE 304	reactor temp.			< 0.01	
SAE 347	260	5–11		0.002	
SAE 304	262–280		water + steam	0.003	
SAE 304	288		boiling water + 10 ppm NH ₃	0.1–0.2 mg/dm d	0.0027– 0.0054
In a special case exposure of the gases situated above the water surface was examined					
SAE 304, SAE 304 L	316		deionised, above 95% N ₂ + 5% O ₂	crevice depth 0.0–0.2 mm	
SAE 347	316		deionised, above 95% N ₂ + 5% O ₂	crevice depth 0.2–0.4 mm	
SAE 304, SAE 304 L	316		air	crevice depth 0.1–2.8 mm	
SAE 347	316		air	crevice depth 0.25–0.6 mm	

Table 9: Corrosion rates of austenitic CrNi steels in high purity water under the conditions of pressurised and boiling water reactors

Austenitic CrNiMo(N)steels

The Mo containing 18Cr10Ni steel grade SAE 316 LN (c.f. Mat.-No. 1.4406, 1.4429) is considerably more resistant to intergranular stress corrosion cracking in high temperature water with 0.3 µS/cm and < 1 mg/l oxygen than the Mo free 18Cr8Ni steel (SAE 304) [139]. Only after extreme heat treatments/sensitisations at 650–700 °C over 100 hours can stress corrosion cracking occur. Solution annealed material (1050–1100 °C/2–4 h) as well as subsequently annealed material (950 or 850 °C/2–4 h) lead to the desired microstructure modification such as grain growth, carbide distribution and ferrite formation (up to 8%) as well as a slight drop in strength, but an increase in ductility – however the influence on stress corrosion cracking susceptibility is negligible. In the temperature range 90–230 °C stress corrosion cracking was not observed (CERT test), so long as high purity water with < 0.3 mg/l oxygen, < 2 mg/l hydrogen and < 10 mg/l H₂O₂ is present. Also, in a neu-

tral solution with chloride, sulphate and copper ions (all to a maximum of 5 mg/l) stress corrosion cracking was not determined up to 320 °C. Only in the case of high hydrogen contents up to 30 mg/l (simulation of high water radiolysis) was stress corrosion cracking observed on sensitised samples after 1500 hours exposure. Samples which were neutron irradiated at 200 °C are resistant to stress corrosion cracking in high purity water with > 10 mg/l oxygen and > 3 mg/l hydrogen in tests with constant deformation. This is also the case for water at > 150 °C with 7 mg/l oxygen + 6 mg/l H₂O₂ + 0.1 mg/l sulphate ions, so long as cracking conditions are present. On the other hand, 60 µg/l (0.06 mg/l) chloride ions from 200 °C under such cracking conditions lead to stress corrosion cracking (however not using the CERT test). Based on previous literature the steel SAE 316 LN is considered to be resistant to intergranular stress corrosion cracking under practical conditions, also in the irradiated condition (maximum 3 dpa). A possible metallic compound with copper (mixed systems in cooling circuits) causes negligible galvanic corrosion ($i_g < 1 \mu\text{A}/\text{cm}^2$), although copper is slightly nobler and therefore is the cathode.

The influence of metallurgical factors on the stress corrosion cracking behaviour of the steel SAE 316 (1.4401) in high purity water with 8 mg/l at 288 °C was tested [140]. Subsequently, stress corrosion cracking was initiated by coating-like, amorphous CaS precipitations on the grain boundaries. On the other hand, Laves phase on the grain boundaries reduces the susceptibility. High austenite stability (measured from the Ni/Cr ratio) increases the stress corrosion cracking susceptibility.

The corrosion behaviour of the steel SAE 316 (1.4401) in deionised high purity water is influenced by high energy γ -radiation (here: 20 MeV/340 kRad/h). This is the result of potential measurements and CERT tests at 50, 90 and 130 °C [141]. As a result of the substances released by radiolysis (H₂O₂, H₂ and O₂) the corrosion potential shifts by about 100 mV to ignoble values; passive current densities are an order of magnitude lower, see Figure 26. CERT tests at 50 °C result in only small differences in the elongation values between measurements in hydrogen (1500 µg/l) and those in argon as the inert gas. Thus, under these conditions SAE 316 is not susceptible to stress corrosion cracking, which is equally valid for the sensitised (welded) condition.

Current measurements of corrosion potentials were made on the steel SAE 316 (1.4401) between stress corrosion cracking and reference specimens as a function of time in order to determine a possible effect of stress corrosion cracking under pressurised water reactor conditions (here: high purity water with < 0.1 µS/cm, > 20 mg/l oxygen, 288 °C) [142]. Indeed one finds good correlation between the current density-time curve and the observed stress corrosion cracking using the CERT method. For a sensitised (624 °C/24 h) steel SAE 316 (0.06% C) the current level or intensity (integral i - t) where stress corrosion cracking occurs is considerably more pronounced than for the solution annealed condition (1120 °C/1 h), for which stress corrosion cracking was not observed. Also, the current decline is considerably slower in the sensitised condition. The method is recommended for determining and estimating (monitoring) possible stress corrosion cracking in stainless steels in high temperature water.

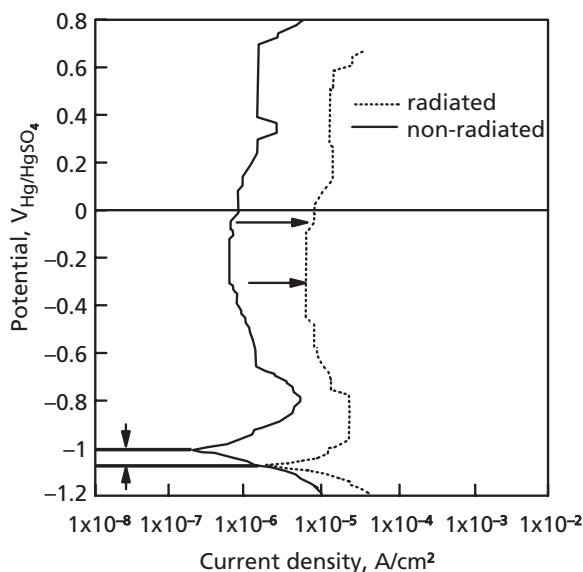


Figure 26: Potentiodynamic current density-potential curves for the steel SAE 316 (1.4401) in pure water at 50 °C deaerated with hydrogen [141]

The high-strength and manganese containing steel XM-19 (UNS S20910, 21 Cr, 12 Ni, 2.15 Mo, 5 Mn, 0.003 C) shows considerably better stress corrosion cracking resistance in high purity water with $< 0.2 \mu\text{S/cm}$ and 8 mg/l oxygen at 288 °C than SAE grades 304 and 316. This is the result of tests on flat specimens at constant load and test times up to 47,000 h [143]. On notched specimens stress corrosion cracking is also found at stresses $< R_{p0.2}$ as fine incipient cracks, also for non-cracked samples. The results on un-notched samples are shown in Table 10. Here, the factor R illustrates the ratio of applied mechanical stress to $R_{p0.2}$. One finds that classical stress corrosion cracking occurs at $R > 1.35$ with relatively short lifetimes. Below this critical value the highest lifetimes, but also at $R = 1$ fine incipient cracks were observed, which propagate slowly up to $R = 0.8$.

The blades of a pump impeller made from the Mo containing cast steel CF-8M (1.4408, UNS J92900, 17 Cr, 11.35 Ni, 2.64 Mo, 0.67 Mn, 0.42 Si, 0.075 C) failed after one year in operation through strong corrosion attack in demineralised water, however with a low pH value in the range of 2-2.5 [144]. On the underside of the blades pitting corrosion as well as incipient cracks were found, which after metallographic examination were found to be exclusively intergranular and continuous across the material thickness. Furthermore, massive carbide precipitations on the grain boundaries were found. The attack took place interdendritically with the loss of whole grains. The damage is clearly traceable to the use of an alloy with excessive carbon content. This leads to considerable chromium carbide precipitation on the grain boundaries caused by slow cooling during the production of the cast material, which then leads to sensitisation of the steel. In acidic solutions this leads to pronounced intergranular corrosion (c.f. Strauß test). Therefore, for the corresponding

application a high alloyed steel with 20 Cr, 25 Ni, 4.5 Mo, 1.5 Cu, 0.02 C (Mat.-No. 1.4539) is intended, which also has a very low carbon content.

<i>Charge</i>	<i>applied mechanical stress, MPa</i>	<i>R</i>	<i>test period, h</i>	<i>rupture</i>	<i>without rupture</i>	<i>fine cracks</i>
A	588	2.02	2060	•		
			1559	•		
			1432	•		
			1559	•		
	392	1.35	9393	•		
			11014	•		
			7192	•		
			46713		•	•
	294	1.01	47713		•	
			47713		•	
	196	0.67	47713		•	
			47713		•	
B	588	2.00	8462	•		
			7043	•		
	490	1.67	10053	•		
			9324	•		
	392	1.33	40880		•	•
			41880		•	•
	294	1.00	41880		•	•
			41880		•	•
	196	0.67	41880		•	
			41880		•	

Table 10: Stress corrosion cracking lifetimes of the steel XM-19 (UNS S20910) in high purity water with 0.2 $\mu\text{S}/\text{cm}$ and 8 mg/l oxygen at 288 °C [143]

Nickel

Nickel has been used as plating for high purity water storage [145]. An electrolytically produced nickel plating with 0.2 mm thickness has proven itself as a lining for high purity water containers due to results from tests running more than six months [146]. For electroless nickel plating, the corrosion rates after three months immersion testing in deionised water were:

aerated	RT	0.5 mm/a
non-aerated	49 °C	0.3 mm/a
non-aerated	82 °C	slight weight gain

In non-aerated distilled water the corrosion rate after one month was 0.7 mm/a, which means that electroless nickel coatings are not resistant in high purity water [147].

Nickel-chromium alloys

Nickel-chromium-iron alloys (without Mo)

From the main candidates of NiCrFe alloys, Alloy 800 (32 Ni, 20 Cr, rest Fe, Mat.-No. 1.4876) and Alloy 600 (72 Ni, 16 Cr, 9 Fe, Mat.-No. 2.4816), in the USA also the high Cr containing Alloy 690 (61 Ni, 29 Cr, 9Fe, Mat.-No. 2.4642), are used in BWR/PWR at high temperatures because they are resistant to stress corrosion cracking in high purity water up to 360 °C. Unlike stainless steels, anneals which lead to carbide precipitation on the grain boundaries, reduce stress corrosion cracking susceptibility. Also a stress relieving anneal at 340 °C after welding improves the stress corrosion cracking susceptibility. Also, cold formed material shows improved behaviour to stress corrosion cracking. High sulphur contents (0.03–0.05% S) in the alloy increase the risk of stress corrosion cracking (better: < 0.01% S). Increasing hydrogen dosing in high purity water initially leads to an increase in the stress corrosion cracking crack velocity, for very high hydrogen dosages a decrease in the velocity is seen.

Investigations on the crevice corrosion behaviour of Alloy 600 (2.4816, NiCr15Fe) in high purity high temperature water at 288 °C and 0.2 mg/l oxygen were conducted [148]. One finds that under such conditions slightly alkaline solutions form in the crevices. However, thermodynamic assessments show that the mechanism for crevice corrosion induced intergranular stress corrosion cracking is not that corresponding to the classical alkaline stress corrosion cracking. Also, the test results show that diffusion of the solution rather than the kinetics of metal dissolution control crevice corrosion. Also, the film rupture mechanism does not favour stress corrosion cracking at high temperatures.

The NiCr alloy Alloy 800 (Mat.-No. 1.4876, X10NiCrAlTi32-21) used in boiling water reactors is only susceptible to intergranular stress corrosion cracking when high oxygen contents are present in the high purity reactor water at high tempera-

tures, and only in the sensitised condition. This can be seen from the data in Table 11. Susceptibility was noted for the test samples with higher carbon contents (0.051% C) and also after an annealing treatment at 1050 °C (Sample M10). For the sample solution annealed at 1150 °C with a lower carbon content (0.035% C) stress corrosion cracking did not occur [149].

<i>Test conditions</i>	<i>M10</i>		<i>M9</i>	
	<i>delivery condition</i>	<i>sensitised 500 °C/100 h</i>	<i>delivery condition</i>	<i>sensitised 550 °C/100 h</i>
350 °C in deaerated water, after 12960 h	0/2*	0/2	0/2	0/2
350 °C water with 0.5 mg/l O ₂ , after 9160 h	0/2	0/2	0/2	0/2
290 °C water with 40-140 mg/l O ₂ , after 5661 h	0/1-480 h 0/1-5661 h	2/2-480 h	0/2	0/2
475 °C steam with 6.89 MN/m ² pressure, after 1500 h	0/4	–	–	–

*: 0/2 = number of susceptible samples in comparison to the number of investigated samples

Table 11: Stress corrosion cracking results for Alloy 800 in high purity water [149]

The stress corrosion cracking behaviour of the nickel alloys Alloy 600 (Mat.-No. 2.4816) and X-750 (Mat.-No. 2.4669) in demineralised high purity water (< 3 µg/l oxygen; 350 °C) is dependent upon the microstructure [150]. For alloy X-750 one finds that removal of the mechanical load leads to a sharp increase in the lifetime until stress corrosion cracking, which does not mean that there is a limiting load, under which cracks do not occur. Even for loads of 40% of the 0.2% yield strength, cracks were observed. Also, crack susceptibility of this alloy decreases when there are less intermetallic phases and thus lower strengths. For Alloy 600 a heat treatment leads to longer stress corrosion cracking lifetimes, if as a result carbide precipitations on the grain boundaries are produced (700 °C/1 h). Galvanic contact with noble metals such as gold or platinum improve the stress corrosion cracking susceptibility, on the other hand contact with carbon steel accelerates stress corrosion cracking (for contact with stainless steel only slightly). Cracks are mostly intergranular, in particular for Alloy 600 with grain sizes from 20–40 and 200–300 µm. The susceptibility to stress corrosion cracking is explained by the presence of granular precipitates on the grain boundary surface. These are planar or rod-shaped and occur preferentially in the crack initiation zone, on the other hand hardly in the crack edges or crack tips. EDAX analysis shows them to be highly enriched in sulphur and nickel. Thus a decrease in stress corrosion cracking susceptibility for the case of a very low sulphur content (here actual: 0.05% S; target: S < 0.01%) is ascertained. The authors point to the fact that all differences in the investigation results from industrial batches, despite having comparable as-is analyses in the main alloying elements, are due to fine differences in residual elements such as sulphur and carbon, also aluminium and titanium. Therefore, melting technology as well as pro-

cessing are key factors for semi-finished product manufacturers, which is why careful examination of these needs to be made (as-is analyses, hot deformation parameters, heat treatments).

The influence of heat treatment on the stress corrosion cracking behaviour of the age-hardenable nickel alloy X 750 (2.4669; with about 73 Ni, 15 Cr, 7 Fe, 2.5 Ti, 1 (Nb + Ti), 0.8 Al (as well as Alloy 718 (2.4668), Discaloy)) in high purity water (< 5 mg/l oxygen, pH 7) at 320–360 °C using U-bend specimens was investigated [151]. Good resistance to stress corrosion cracking was found for the solution annealed state in the range 1065–1100 °C and after age hardening at 704–732 °C. In particular, water quenching after solution annealing results in very good resistance to stress corrosion cracking. Furthermore, one finds good correlation between the form, morphology and coherence of the precipitates on the grain boundaries.

Sensitisation (700 °C/2 h) of Alloy 600 (Mat.-No. 2.4816) has only a slight influence on the corrosion fatigue behaviour in comparison to the desensitised state (700 °C/120 h) in high purity water at 288 °C and 0.2 mg/l oxygen [152]. However, the crack velocity increased with increasing oxygen content and decreasing frequency (10 or 0.1 Hz). Cathodic polarisation has very little effect – quite the contrary to the effects in acidic solution. In the sensitised as well as in the desensitised materials the type of cracking identified was transgranular.

Discontinuous grain boundary precipitation is evidently a prerequisite for Alloy 600 not having stress corrosion cracking in high purity water (quite the contrary to stainless steels). On the other hand solution annealed specimens are susceptible to stress corrosion cracking. This occurs at potentials both above and below U_R : below U_R (galvanic coupling with carbon steel) the adsorbed hydrogen plays a role; above U_R the rupture mechanism of the passive layer has an effect. Contact with carbon steel accelerates while contact with noble metals reduces the susceptibility to stress corrosion cracking. An optimal heat treatment at 982–1010 °C/1–5 min, followed by 704 °C/15 h should be conducted. As a result the highest resistance to stress corrosion cracking will be achieved. Stress corrosion cracking of nickel alloys based on Ni-16Cr-9Fe in high purity water is strongly dependent upon the crystallographic orientation of the grain boundary surfaces. This was seen from CERT tests in deaerated high purity water at 360 °C [153]. Accordingly, the percentage of cracked samples with predominantly high angle grain boundaries was considerably higher (up to about 10%) than in the case of samples with coincident site lattice boundaries – 0.1%. Samples with low angle grain boundaries showed no cracks, neither in an inert argon atmosphere nor in high purity water. Evidently, low angle grain boundaries produce sliding properties on neighbouring grains, as they absorb lattice dislocations, emit new ones and thus reduce mechanical stresses in the grain boundaries. The results show that by controlling grain boundary conditions, which can be done through corresponding annealing treatments, resistance to stress corrosion cracking can be improved.

The influence of grain boundary chemistry and structure of Alloy 600 (Mat.-No. 2.4816; here: Ni-16Cr-9Fe-C-B) on the stress corrosion cracking behaviour in high purity deaerated water with $18 \text{ M}\Omega \cdot \text{cm}$ (< 5 µg/l oxygen) at 347 °C has been reported [154]. CERT tests (1.7×10^{-7} in/s) resulted in all samples being susceptible to

cracking, due to carbide precipitation on the grain boundaries, irrespective of the heat treatment. Maximum crack depths of 100 μm were determined for the highly sensitised condition (solution annealed at 1100 °C/20 min + 550 °C/2 h). Surprisingly, for an alloy variation with extremely low carbon content (0.008 compared to 0.029%) one observed no change in behaviour – on the other hand one finds severe internal intergranular stress corrosion cracking and is explained by the increased vacancy formation on the grain boundaries. For an alloy variation doped with 50 $\mu\text{g/kg}$ boron, only investigations concerning the precipitation behaviour were conducted. Heat treatment at 873–973 °C leads to precipitation of Ni and B rich M_{23}X_6 phases. Chromium depletion was not seen.

The stress corrosion cracking of Alloy 600 (< 0.01% C) in high purity water (distilled, deionised, deaerated with < 20 $\mu\text{g/l}$ oxygen) was found to be a function of the microstructure condition [155]. Carbon found in solution (after heat treatment: 1100 °C/20 min + 850 °C/10 min) does slow the stress corrosion cracking creep rate, however at 360 °C intergranular induced stress corrosion cracking was observed. On the other hand, carbon found in the form of chromium carbides on the grain boundaries (after heat treatment: 750 °C/80 min) had a positive influence, i.e. the susceptibility to stress corrosion cracking reduced considerably.

Selected tubes made from Inconel® 600 (2.4816) for nuclear reactors were investigated for their resistance to intergranular stress corrosion cracking in high purity water with < 0.5 $\mu\text{S/cm}$ and < 5 $\mu\text{g/l}$ oxygen at 365, 345, 325 and 290 °C [156]. To determine crack propagation U-bend specimens were used, to determine crack velocities CERT tests were performed. The results on strongly deformed U-bend specimens show that in deaerated high purity water stress corrosion cracking occurs at all temperatures, at 365 °C within two weeks (otherwise up to 35 weeks). The susceptibility to cracking determined from the CERT tests occurs at considerably shorter test times and sometimes at lower elongation. Cold deformation reduces the time to crack propagation and accelerates the crack velocity. Large differences in crack propagation were found for materials from different batches. A heat treatment at 700 °C/ up to 20 h reduces stress corrosion cracking susceptibility of a batch that would normally be very susceptible. The volume of data was sufficient to establish a formula which allowed for the prediction of the lifetime of Alloy 600 (Mat.-No. 2.4816) under the corresponding conditions.

In order to avoid intergranular induced stress corrosion cracking in Alloy 690 (Mat.-No. 2.4642, NiCr29Fe; here with 28–32 Cr, 6–13 Fe, 0.5 Si/Mn/Cu, up to 0.06 C, rest Ni) in high purity water (pressurised water conditions) an anneal on semi-finished products (here: tubes) should be performed as follows: anneal in the region 954–1177 °C over 15–60 min., followed by an homogenising anneal at 704–927 °C up to max. 2 h for the purpose of producing a favourable carbide distribution on the grain boundaries [157].

By means of CERT tests the influence of microstructure on the stress corrosion cracking behaviour of solution annealed (1100 °C/20 min) Alloy 600 in deaerated (< 10 $\mu\text{g/l}$ oxygen) high purity water at 360–400 °C was examined [158]. Intergranular stress corrosion cracking is always found at these temperatures. Increased carbon contents in the matrix cause a reduction in the percentage of transgranular frac-

ture. Phosphorus and boron have a similar effect. Neither chromium depletion nor carbides on the grain boundaries increase the susceptibility to stress corrosion cracking. On the other hand cold deformation considerably increases the susceptibility to stress corrosion cracking. The extent of intergranular crack formation is larger in material with a smaller grain size (30 μm) than in a material with a larger grain size (130 μm).

Furthermore, investigations were performed on U-bend and C-ring specimens at 330 °C in deionised water with < 10 $\mu\text{g/l}$ oxygen on 180 specimens from four batches and various microstructure conditions or heat treatments (as delivered, solution annealed, sensitised, pickled, cold deformed surface). Intergranular stress corrosion cracking was sporadically found on pickled samples. In summary, for all commercially important microstructure conditions and for all mechanical stresses found in practice Alloy 600 is not susceptible to stress corrosion cracking, even after long exposure times in high purity water at 330 °C, so long as the material has a non-pickled surface condition [159].

Stress corrosion cracking can occur on Alloy 600 (Mat.-No. 2.4816) when used in pressurised water reactors when the chemistry of the high temperature water is not sufficiently controlled. The microstructure also has an influence: solution annealing (870–1100 °C) and stress relief annealing after welding (here: 1150 °F/625 °C, 18 h) must be optimal. For this purpose U-bend specimens were tested in autoclaves at 340 °C (650 °F) in high purity water [160]. Intergranular induced stress corrosion cracking can occur when annealing at > 870 °C occurs and the grain boundaries are free of precipitates. Annealing which leads to carbide precipitation reduces the susceptibility to stress corrosion cracking. Stress relief annealing after welding (post weld heat treatment) at the relatively low temperature of 340 °C (650 °F) leads to long incubation times and thus improves stress corrosion cracking behaviour.

Similar results are found in [161]. The susceptibility of X-750 (2.4669) in high purity water (< 0.5 $\mu\text{S/cm}$) at 320 °C and 100 bar to stress corrosion cracking (U-bend specimens) and also hydrogen embrittlement was found to be dependent on ageing as well as solution annealing. Both a high solution annealing temperature (> 1100 °C) before ageing as well as a single (instead of double) ageing treatment at 700 °C/ 20 h improves the resistance to hydrogen embrittlement and equally to stress corrosion cracking. The results indicate that stress corrosion cracking and hydrogen embrittlement are controlled by the same microstructural processes.

As an alternative to X-750 the equally age hardening alloys Inconel® 718 (2.4667), Incoloy® alloy 925 (UNS N09925), Incoloy® alloy 926 (UNS N09926) as well as the non age hardening alloys Inconel® 600 (2.4816), 625 (2.4856) and in particular Inconel® 690 (2.4642) were tested for their behaviour to stress corrosion cracking and hydrogen embrittlement under the conditions of a boiling water reactor, see Table 12 [162].

Alloy	UNS Nr.	C	Mn	Fe	Cr	Ni	Al	Ti	Mo	Nb+Ta
X-750	N07750	0.04	0.5	7.0	15.5	73.0	0.7	2.5	–	1.0
Inconel [®] 718	N07718	0.04	0.2	18.5	19.0	52.5	0.5	0.9	3.0	5.1
Incoloy [®] alloy 925	N09925	0.02	0.6	29.3	21.9	43.0	0.2	2.0	2.7	–
Incoloy [®] alloy 926	N09926	0.02	0.9	47.2	16.1	28.0	0.1	1.7	2.0	4 Cu
Inconel [®] 690	N06690	0.01	0.2	9.4	29.2	60.7	0.2	0.3	–	–

Table 12: Compositions of tested nickel alloys [162]

Furthermore, cold deformation processes as well as the usual hardening procedures which influence the resistance to stress corrosion cracking and hydrogen embrittlement were examined. A considerably negative influence was found for cold deformation of Inconel[®] 625 which was proven by the strong decrease in ductility after hydrogen charging. On the other hand, Inconel[®] 690 retains its relatively high ductility. As stress corrosion cracking examinations on stirrup specimens in non-deaerated water with pH 10 and at 350 °C (662 °F) show, the stress corrosion cracking lifetimes for 20 and 30% cold deformed Inconel[®] 690 are considerably higher than for the normally precipitation hardening (non cold deformed) X-750. It could be concluded that cold deformed Inconel[®] 690 is more resistant to stress corrosion cracking although it exhibits higher strength than X-750. Therefore, for practical conditions one could apply lower cold deformation and still achieve strength that would be comparable to X-750 – with improved stress corrosion cracking resistance.

The nickel based alloy X-750 is susceptible to stress corrosion cracking in high purity and deaerated water [163]. Crack formation starts at > 204 °C, crack propagation at < 145 °C. Crack propagation lies at higher temperatures at 0.1 mm/d and increases rapidly to values of 2500 mm/d at low temperatures. As a result, the heat treatment condition has a large influence: stress relief annealed material (885 °C/24 h) is the most susceptible; the conditions solution annealed with immediate tempering (1093 °C/1 h + 704 °C/20 h) as well as only tempering (704 °C/24 h) are least susceptible. A stress corrosion cracking model based on hydrogen embrittlement makes predictions for stress corrosion cracking due to grain boundary chemistry as well as chromium carbide distribution on the grain boundaries. Phosphorus increases the susceptibility to stress corrosion cracking at both lower and higher stress corrosion cracking test temperatures because it will be precipitated on the grain boundaries in all heat treatment conditions and thus reaches a concentration 100 times higher than in the matrix (measure: up to 2.4% P). The presence of M₂₃C₆ carbides and the absence of MC carbides on the grain boundaries improve the resistance to stress corrosion cracking.

The stress corrosion cracking behaviour of X-750 can be considerably increased by a heat treatment at 760 °C/96 h in combination with improved strength, as tests in high purity water with pH 10 at 360 °C have shown [164]. As well, zirconium additions to the alloy improve the resistance to stress corrosion cracking, since the γ'

phase is stabilised on the grain boundaries. For a yield strength 10% lower, the resistance to stress corrosion cracking is improved by 50%.

The influence of hydrogen on the crack propagation velocity of Alloy 600 and X-750 was tested in high purity water ($\text{pH} < 10$, $< 10 \text{ mg/l}$ oxygen) at 338 and 360 °C [165]. At 360 °C a maximum was measured, up to seven times higher, whereby the lowest crack velocities at higher hydrogen concentrations were observed. At 336 °C the crack velocity decreases with increasing hydrogen content. The results were discussed together with a literature review.

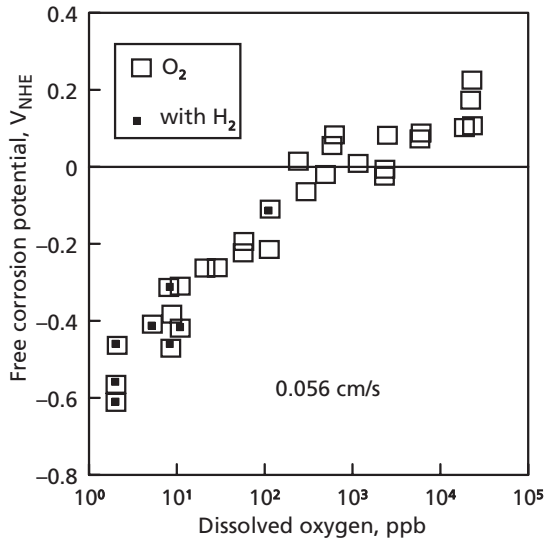
If nickel alloys such as Alloy 625 (2.4856) and Alloy 690 (2.4642) are assembled by diffusion bonding, one produces a material with higher strength so long as an intermediate layer of pure nickel of only 0.01 mm thickness is inserted before the bonding process. However, in high purity high temperature water such bonds are very susceptible to stress corrosion cracking [166, 167]. The very low chromium content in the nickel joining layer was responsible for this. After an annealing treatment at 1052 °C chromium homogenisation had taken place and the stress corrosion cracking susceptibility decreases. After 16 hours heat treatment on Alloy 625 a chromium content in the joining zone of 14% and after 36 hours 20% is found, which corresponds to the nominal content of Alloy 625. For this reason there is an accompanying decrease in the fracture percentage for intergranular stress corrosion cracking over 16% down to 0%. For Alloy 690 after 4 hours 20% chromium and after 24 hours 26% chromium were determined (nominal value for Alloy 690: 30% chromium) and the fracture percentage goes from over 14% down to 0%. One also finds good correlation to the stress corrosion cracking behaviour of other nickel alloys with low chromium contents, in accordance with intergranular crack growth using CERT tests and U-bend specimens. A longer heat treatment at relatively higher temperatures improves the resistance to stress corrosion cracking of such composite materials in all cases, so long as chromium dilution in the nickel joining layer occurs up to contents which approach those of the composite materials.

The influence of the potential on the susceptibility to stress corrosion cracking of sensitised (615 °C/10 h) filler materials made of Alloy 182 (67 Ni, 14.12 Cr, 7.44 Mn, 7.43 Fe, 0.41 Ti, 1.95 Nb) in high purity water with $< 0.2 \mu\text{S/cm}$, $\text{pH} 6$, at oxygen contents up to 200 mg/l and 288 °C was examined [168]. Test methods included CERT tests and CBB (creviced bent beam) tests. The potential was adjusted using oxygen dosing, see Figure 27.

As can be seen in Figure 28 stress corrosion cracking occurred in two regions: highest susceptibility to stress corrosion cracking using both techniques was found to be in the potential region 0 to +50 mV_{SHE}, in the potential region -400 to -550 mV_{SHE} slight susceptibility to stress corrosion cracking was observed, however only according to CERT tests. In the potential region 0 bis -350 mV_{SHE} stress corrosion cracking was not detected, neither by CERT tests nor by CBB tests.

In order to improve the stress corrosion cracking resistance of age hardening nickel alloys (based on Ni, Cr, Mo, Fe) for use in boiling water reactors, alloys with various chromium and molybdenum contents were melted on a laboratory scale and in the form of notched stirrup samples, were tested in high purity water with 8 mg/l oxygen at 288 °C for 500 h [169]. Within the 500 h test time molybdenum free sam-

ples with 15 and 20% chromium failed by stress corrosion cracking. Together with the dissolution rates as well as the repassivation potentials in strongly diluted Na_2SO_4 solutions at 250°C the results show that for the age hardening nickel alloys an optimal matrix is one that contains 20–25% Cr, 2–4.5 Mo and 10–30% Fe.



The influence of structure and composition of the nickel alloys Alloy 600 (c.f. 2.4816) and 690 Alloy 690 (c.f. 2.4642) on the stress corrosion cracking behaviour in high purity water with $< 5 \mu\text{g/l}$ oxygen at 365°C has been thoroughly investigated using SEM and TEM images [170]. Intergranular precipitates exist predominantly as chromium rich carbides, possibly with boron impurities. Higher chromium contents in the alloy improve the behaviour of intergranular stress corrosion cracking which is probably based on inner oxidation. A high density of precipitates on the grain boundaries reduces crack propagation in Alloy 600.

The intergranular stress corrosion cracking of alloy 600 in high purity water at $315\text{--}365^\circ\text{C}$ is strongly dependent upon temperature: with increasing temperature the lifetimes of U-bend specimens (0.01% C) up to stress corrosion cracking failure in the above mentioned region decrease by an order of magnitude, as shown in Figure 29.

Furthermore, stress corrosion cracking is observed at both above and below the corrosion potential. The presence of hydrogen accelerates stress corrosion cracking, as shown in Figure 30. It shows the dependence of stress corrosion cracking rates on temperature under various water conditions [171].

A newly developed welding electrode made from Inconel[®] Filler Metal 52 (UNS N06052) is recommended for the gas shielded welding of nickel alloy Inconel[®] alloy 690 (2.4642) [172]. According to a new alloy digest the alloy's chromium content is decisive for the resistance to stress corrosion cracking in high purity water in pressurised water reactors (in addition also for use in strongly oxidising acids as well as containers for the final storage of nuclear waste). The most important alloying elements of the Filler Metal 52 are: 28–31.5 Cr, 7–11 Fe, 1 Mn, 1.5 (Ti + Al), 0.04 C, rest Ni.

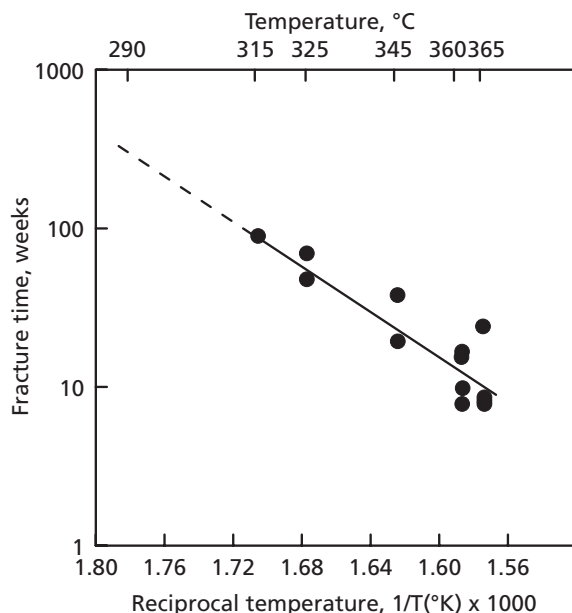


Figure 29: Lifetimes of U-bend specimens made from Alloy 600 (0.01% C) up to stress corrosion cracking failure in high purity deaerated water [171]

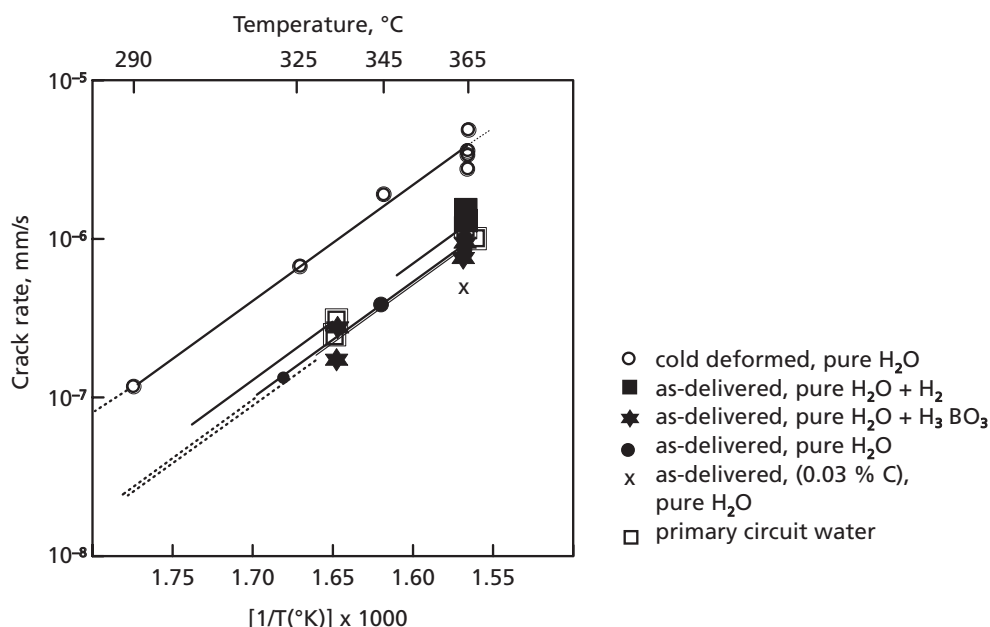


Figure 30: Influence of hydrogen dosing on the crack rate of Alloy 600 (0.01 and 0.03% C) at various temperatures; according to CERT tests [171]

A further alloy digest addressed a sheathed rod electrode for the same purpose [173]. The analysis of these sheathed rod electrodes used for electrode manual welding essentially differed in the alloying elements manganese (5%) and, due to the possible burn off of titanium, through a higher niobium content with 1.0–2.5 (Nb + Ta).

Nickel chromium iron alloys are very resistant to high purity water in a wide temperature range. Since these alloys are well suited for the plating of steel, alloys such as Alloy 600 (Mat.-No. 2.4816) and Alloy 800 (Mat.-No. 1.4876) are resistant to moderate oxygen and chloride quantities, and are used in nuclear reactors. Alloy 600 is used as a lining for steel tanks [174] as well as for tubing and pipes in heat exchangers [72, 175]. The behaviour of nickel and a few of its alloys is summarised in Table 13.

<i>Metal</i>	<i>Temperature °C</i>	<i>Water quality</i>	<i>Corrosion rate mm/a</i>
Nickel	< 204	high purity water	hardly any attack
Nickel	> 315	high purity water	> 36 g/m ² a > 0.004 mm/a

Table 13: Behaviour of nickel and nickel alloys in deaerated high purity water [72, 175]

Table 13: Continued

Metal	Temperature °C	Water quality	Corrosion rate mm/a
Inconel	260	high purity water	no attack
Monel	360	high purity water	> 0.004 mm/a
Nickel	room temperature	distilled or high purity water	> 0.003 mm/a
Inconel® 600 (2.4816)	316	distilled, deionised water, above 95% N ₂ + 5% O ₂ , pH 10	crack depth 0.0–2.8 mm
Inconel® 600 (2.4816)	316	the same as above, however with air	crack depth 1.0–2.8 mm
Nickel	room temperature	distilled water	0.0002 mm/a
Inconel® 600 (2.4816)	24	flowing distilled water	no attack in the course of 2 years
Monel® 400 (2.4360)	room temperature	aerated distilled water	0.003 mm/a
Incoloy® 800 (1.4876)	316	high purity water with 8.6 g boric acid per kg, 2.4 ppm LiOH, pH 5.5; flow velocity 6 m/s	1.2–1.7 g/m ² a
Inconel® 600 (2.4816)	290	high purity water with 0.4 ppm oxygen, pH 10, flow velocity 7.5 m/s	0.00119 mm/a
Inconel® 600 (2.4816)	300	high purity water with 5 ppm Cl ₂ + 0.06 ppm oxygen, pH 5.0–7.4, still	0.00097 mm/a

Table 13: Behaviour of nickel and nickel alloys in deaerated high purity water [72, 175]

Alloy 600 and Alloy 800 withstand exposure to high purity water at 300 °C with 100 mg/l chloride and 50 mg/l oxygen (test time 80 days). Thus both these alloys are superior to the acid resistant chromium nickel steels [72, 76]. Under reactor conditions stress corrosion cracking was not observed on the nickel alloys in high purity water, however these metals are inclined to undergo crevice and pitting corrosion, also in oxygen free water [76]. Radiation in the nuclear reactor has a positive impact on the resistance. In the presence of 10 mg/l NH₃ or 10 mg/l nitrate in the reactor water crevice or pitting corrosion on Alloy 600 or Monel® 400 are of no concern [57, 63].

Steam created in boiling water can become overheated so that the materials can come into contact with steam with a temperature of at least 560 °C, which contains up to 20 mg/l oxygen and 2.5–3.5 mg/l hydrogen. Figure 31 describes the weight loss of a few alloys under these conditions in the steam section of a superheated steam reactor [133].

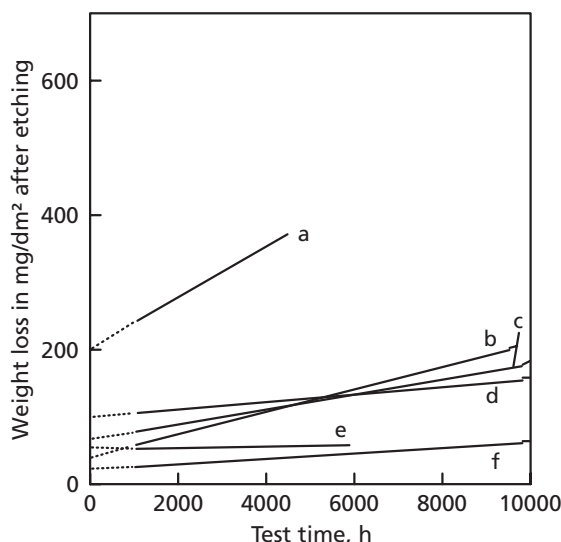


Figure 31: Behaviour of chromium steel (13% Cr), 18Cr8Ni steel SAE 304 and nickel alloys in flowing superheated steam at 560 °C [133]

- a) 18Cr8Ni steel SAE 304 (1.4301, X5CrNi18-10)
- b) Incoloy® 825 (2.4858, NiCr21Mo)
- c) Hastelloy® X (2.4665, NiCr22Fe18Mo)
- d) Incoloy® 800 (1.4876, X10NiCrAlTi32-21)
- e) Inconel® alloy 625 (2.4856, NiCr22Mo9Nb)
- f) Inconel® alloy 600 (2.4816, NiCr15Fe)

Nickel-chromium-molybdenum alloys

The NiCrMo(Fe) alloys of the type Hastelloy with molybdenum contents between 9 and 16% (Mat.-No. 2.4819, 2.4610, 2.4605, 2.4856 amongst other new developments with comparable compositions) are resistant to high purity water, also at high temperatures so long as they are in a solution annealed condition. Molybdenum improves the resistance to stress corrosion cracking in these alloys, similar to the stainless steels.

Nickel-copper alloys

Monel® 400 (NiCu 30 Fe) are used for floors in heat exchangers as well as for linings in steel tanks used for high purity water in nuclear reactors [177].

The NiCu alloys (typical candidates: Mat.-No. 2.4360, NiCu 30 Fe) are used in nuclear reactors for cooling circuits and therefore have excellent corrosion resistance in high purity water up to high temperatures.

Nickel-molybdenum alloys

The main representatives of the nickel molybdenum alloys, Alloy B-2 (70 Ni, 28 Mo, 0.7 Cr, 1.7 Fe; Mat.-No. 2.4617) as well as improved variations such as Alloy B-4 (68 Ni, 28 Mo, 0.7 Cr, 1.7 Fe; Mat.-No. 2.4600) have excellent resistance to strongly reducing media such as hydrochloric acid and highly concentrated sulphuric acid, also at high temperatures. Nevertheless they are very susceptible to corrosion when oxygen ingress through ventilation, oxidising heavy metal ions as well as other oxidising agents are present. Therefore, nickel molybdenum alloys should have good resistance to high purity water under non-oxidising conditions, also at high temperatures.

Zinc

The Pourbaix diagram for zinc at 25 and 300 °C was revised in 1997, namely for the concentrations 10^{-5} , 10^{-6} and 10^{-8} M, whereby the last concentration corresponds to high purity water. For the first time the neutral aqueous hydrolysis complex $\text{Zn}(\text{O}-\text{H})_2(\text{aq})$ was taken into account. Accordingly, zinc passifies in the solution at 25 °C and 10^{-6} M not due to the neutral complex but rather first above $10^{-5.7}$ M. The oxide and not the hydroxide is the stable phase of zinc at 25 and 300 °C [176].

Since zinc does not form a protective scale, it is attacked by distilled and high purity water [64]. The corrosion products in distilled water at room temperature are zinc hydroxide and a little zinc oxide, at 85 °C zinc oxide which can contain zinc hydroxide [177]. In high purity water dissolved carbon dioxide attacks zinc; however as soon as the CO_2 content reaches 27 mg/l a protective scale of zinc carbonate is formed [178]. The corrosion behaviour of zinc in distilled water (up to 3 bar, up to 100 °C) free from air and aerated shows two corrosion maxima: one at 30–40 °C which increased with increasing pressure; and another at 65–70 °C which decreased with increasing pressure [179]. Paint containing a zinc pigment on steel does not give adequate protection to distilled water.

Bibliography

- [1] Bendlin, H.
Reinstwasser von A bis Z; Grundlagen
und Lexikon
VCH Verlagsgesellschaft mbH,
Weinheim, 1995
- [2] Georg Thieme Verlag
Römpp Online (Online im Internet):
Reinstwasser; Wasser
<<http://www.roempp.com/prod/roempp.php>>
(Stand 2004, Abruf 03.03. und
06.03.2004)
- [3] Koepsell, M.; Peil, S.
Herstellung von Reinstwasser mit Hilfe
eines kombinierten Elektrolyse-/
Brennstoffzellenverfahrens
Abschlussbericht vom 28.07.2003 zum
AiF-Forschungsvorhaben Nr. 34Z,
Institut für Energie- und Umwelttechnik
e. V., Duisburg
- [4] DIN ISO 3696 (06/1991)
Wasser für analytische Zwecke;
Anforderungen und Prüfungen
Beuth Verlag GmbH, Berlin
- [5] ASTM D 1193 (1999)
Wasser für Analysezwecke
Beuth Verlag GmbH, Berlin
- [6] Deutsches Arzneibuch 10. Ausgabe
(DAB 10) (1991-2003)
Deutscher Apotheker Verlag, Stuttgart
- [7] Europäisches Arzneibuch; amtliche
deutsche Ausgabe; 4. Ausgabe
Grundwerk (2002)
Deutscher Apotheker Verlag, Stuttgart
- [8] NCCLS approved guideline C3-A3 (1997)
Preparation and Testing of Reagent Water
in the Clinical Laboratory,
National Committee for Clinical
Laboratory Standards, Wayne (PA/USA)
- [9] USP 27 (2004)
United States Pharmacopeia
(Amerikanisches Arzneibuch)
United States Pharmacopeial
Convention, Inc. Rockville (MD/USA)
- [10] (Entwurf) VDI 2083 Blatt 9 (09/1991)
Reinraumtechnik; Qualität, Erzeugung
und Verteilung von Reinstwasser
Beuth Verlag GmbH, Berlin
- [11] Lenntech Wasseraufbereitung und
Luftreinigung, Delft/Niederlande
Deionisiertes und demineralisiertes
Wasser (Online im Internet)
<<http://www.lenntech.com/deutsch/>>
(Stand 2004, Abruf 02.06.2004)
- [12] Weingärtner, H. et al.
Water
in: Elvers, B.; Hawkins, S.
Ullmann's Encyclopedia of Industrial
Chemistry, 5. Aufl., Bd. A 28
VCH Verlagsgesellschaft mbH,
Weinheim, 1996, S. 4 ff
- [13] Splittgerber, A.; Ulrich, E. A.
Wasseraufbereitung im
Dampfkesselbetrieb
Springer, Berlin, 1963, S. 97
- [14] Pollmann, S.
Korrosionsvorgänge auf der Innenseite
thermisch hochbelasteter Siederohre in
Dampfkraftwerken
Werkst. Korros. 22 (1971) 1, S. 8–16
- [15] Evans, U. R.
Engineering, London, 1953, 8. Mai
- [16] Coriou, H. et al.
Corrosion et Anticorrosion 12 (1964) 8,
S. 358–370 (360)
- [17] Stolzenbach, C. F.
Solve atomic power plant problems
Chem. Engng. 66 (1959) 8, S. 127
- [18] Ferrara, M.
Termotecnica 14 (1960), S. 425–458,
(n.C.: A. 55 (1961) 3397i/3398c)
- [19] Richmann, R. B.
US Atomic Energy Comm. BNWL-29
(1965), 19 S. (n.C.A. 63 (1965)15939c)
- [20] Gadiyar, H. S.; Blachandra, J.
Influence of organic inhibitors on the
corrosion of mild steel in distilled water
at 85°C
Trans.Indian Inst. Met. 19 (1966),
S. 189–194
- [21] Holmes, D. R.; Mann, G. M. W.
A critical survey of possible factors
contributing to internal boiler corrosion
NACE Corrosion 21 (1965) 11, S. 370–377
- [22] Voyles, D. E.; Fiss, E. C.
Water conditions for high pressure
boilers
NACE Corrosion 13 (1957) 9,
S. 589t–590t

- [23] Beverskog, B.; Puigdomenech, I.
Revised Pourbaix diagrams for iron at 25–300°C
Corrosion Science 38 (1996) 12, S. 2121–2135
- [24] Kelly, G. J.
Demineralised Water for Power Station Auxiliary Cooling Circuits
Corrosion Australasia 16, (1) Feb. 1991, S. 12–15
- [25] Rohlf, U.; Kaesche, H.
Scaling and Corrosion of Preheater Steel Tubes in High-Pressure, High-Temperature Feedwater
Conference: Metallic Corrosion, 8th International Congress on Metallic Corrosion, 1981, Vol.II, Mainz, Germany, 6–11 Sept. 1981
DECHEMA e.V., 1981, S. 1588–1593
- [26] Foroulis, Z. A.
The Influence of Velocity and Dissolved Oxygen on the Initial Corrosion Behaviour of Iron in High-Purity Water
NACE Corrosion 35 (1979) 8, S. 340–344
- [27] Moskvina, L. N. et al.
Measurement of the Initial Corrosion Rate of Steel in High-Purity Water
Protection of Metals (Russia) 28 (1992) 2, S. 167–170
- [28] Sirota, A. M.; Latunin, V. I.; Donnikov, V. E.
Experimental Investigation of Electrode Potentials and the Polarisation Curves of Metals in a Flow of Demineralized Water
Therm. Eng. (USSR) 3 (1990), S. 117–119
- [29] Moskvina, L. N.
Measurements of the Initial Corrosion Rate of Steel in High-Purity Water
Protection of Metals (Russia) 28 (1992) (2), S. 167–170
- [30] Mizuno, T. et al.
Corrosion and Stress corrosion Cracking of Carbon Steel in Oxygenated High-Purity Water at Elevated Temperatures, Conference: Environmental Degradation of Materials in Nuclear Power Systems–Water Reactors, Myrtle Beach, S.C. USA, 22–25 Aug. 1983
National Assoc. of Corrosion Engineers, Houston, Texas USA, 1984, S. 395–422
- [31] Shimizu, S.; Yagi, T.; Sawada, H.
The effect of high-temperature pure water rinsing on metal corrosion
Hitachi Zosen Tech. Rev. 56 (1), April 1995, S. 43–47
- [32] Belous, V. N.
The Corrosion of Carbon Steel in High-Purity Oxygen-Containing Water
Teploenergetika (12), Dec. 1983, S. 58–59
- [33] Gabetta, G. et al.
Investigation on Pit Susceptibility in Low Pressure Rotor Steels
Conference: Materials for Advanced Power Engineering 1994, Liege, Belgium, 3–6 Oct. 1994
Kluwer Academic Publishers Group, Dordrecht, NL, 1994 Part I, S. 209–218
- [34] Sirota, A. M.
Laboratory Investigation of the Potentials and Galvanostatic Polarisation Curves of Iron and Steel in Demineralized Water at Room Temperature
Therm. Eng. (USSR), 33, (2), Feb. 1986, S. 94–99
- [35] Lichti, K. A.; Bacon, L. G.
Corrosion in Wairakei steam pipelines
Corrosion Reviews 17 (1999) 3–4, S. 219–236
- [36] Chopra, O. K. et al.
Current research on environmentally assisted cracking in light water reactor environments
Conference. 25th Water Reactor Safety Information Meeting, Bethesda, Maryland, USA, 20–22 Oct. 1997
Nuclear Engineering and Design 194 (1999) (2–3), S. 205–223
- [37] Gabetta, G.; Rizzi, R.
Electrochemical Potential Measured at the Tip of a Growing Fatigue Crack in Demineralized Water at 93°C: the Effect of Frequency, Wave Form and Oxygen Content
Corrosion Science 23 (1983) 6, S. 613–620
- [38] Andresen, P. L.; Young, L. M.
Crack Tip Microsampling and Growth Rate Measurements in Low-Alloy Steel in High-Temperature Water
NACE Corrosion 51 (1995) 3, S. 223–233

- [39] Indig, M. E.; Weber, J. E.; Weinstein, D.
Environmental Aspects of Carbon Steel Stress Corrosion in High-Purity Water
Rev. Coatings Corros. 5 (1–4), 1982, S. 173–225
- [40] Solomon, H. D.; DeLair, R. E.; Unruh, A. D.
Crack initiation in low alloy steel in high temperature water
in: Conference: Effects of the Environment on the Initiation of Crack Growth, Orlando, Florida, USA, 20–21 May 1996
ASTM, West Conshohocken, PA, USA, 1997, S. 135–149
- [41] Hale, D. A.; Kass, J. N.
Fatigue Crack Growth of Low Alloy Steel in a High-Temperature, High-Purity Oxygenated Water Environment.
Conference: Corrosion '79, Atlanta, Ga., 12–16 Mar 1979
NACE, Katy, Tex., 1979, Paper No. 225
- [42] Auten, T. A.; Hayden, S. Z.; Emanuelsen, R. H.
Fatigue Crack Growth Rate Studies of Medium Sulphur Low Alloy Steels Tested in High Temperature Water
Conference: Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water reactors, San Diego, California, USA, 1–5 Aug. 1993
The Minerals, Metals & Materials Society, Warrendale, Pennsylvania, 1993, S. 35–41
- [43] Auten, T. A.; Monter, J. V.
Temperature and environmentally assisted cracking in low alloy steel
Conference: Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors. Vol. 2, Breckenridge, Colorado, USA, 7–10 Aug. 1995
NACE, Houston, TX, USA, 1995, S. 1145–1155
- [44] Young, L. M.; Andresen, P. L.
Crack Tip Microsampling and Growth Measurements in a 0,021% S Low Alloy Steel in High Temperature Water
Conference: Seventh International Symposium on Environmental Degradation of Materials in Power Systems-Water Reactors. Vol. 2, Breckenridge, Colorado, USA, 7–10 Aug. 1995
NACE, Houston, TX, USA, 1995, S. 1193–1204
- [45] Jones, R. L.; Hurst, P.; Scott, P. M.
International Cooperative Group on Cyclic Crack Growth
Int. J. Pressure Vessels Piping 40 (1989) 5, S. 375–395
- [46] Mabuchi, K. et al.
Effects of Oxygen Concentration on the Corrosion Behaviour of Carbon Steel in High Temperature Water
Conference: Critical Issues in Reducing the Corrosion of Steels, Nikko, Japan, March 1985
NACE Editors: Leidheiser, H.; Haruyama, S. 79–88
- [47] Honda, T. et al.
Corrosion of Ferrous Materials and Deposition of Trace Metal Ions in High Temperature and High Purity Water
Boshoku Gijutsu 36 (1987) 5, S. 267–274
- [48] Kuniya, J. et al.
Observations on Stress Corrosion Cracking Initiation Sites in Carbon Steel
Conference: Corrosion '94, Paper No. 234
NACE, Houston, TX, USA, 1994, 13 S.
- [49] Van der Sluys, W. A.; DeMiglio, D. S.
Use of a Constant Delta Test Method in the Investigation of Fatigue Crack Growth in 288 deg C Water Environments. Conference: Environment-Sensitive Fracture; Evaluation and Comparison Test Methods, Gaithersburg, Maryland, USA, 26–28 Apr. 1982
ASTM, Philadelphia, Pennsylvania, USA, 1984, S. 443–469
- [50] Lyle jr., F. F.
Stress Corrosion Cracking in Low-Pressure Steam Turbines – an Overview
Conference: Corrosion '94, Paper No.: 219
NACE, Houston, TX, USA, 1994 18 S.
- [51] David, W.; Schleithoff, K.; Schmitz, F.
Spannungsrißkorrosion in hochreinem Wasser von 3-3½% NiCrMoV-Vergütungsstählen für Dampfturbinen-Scheiben und Wellen. Teil 1
Mater. Wiss. Werkst. Tech. 19 (1988) 3, S. 43–50

- [52] David, W.; Schleithoff, K.; Schmitz, F. Spannungsrißkorrosion in hochreinem Wasser von 3-3½% NiCrMoV-Vergütungsstählen für Dampfturbinen-Scheiben und Wellen. Teil 2 Mater. Wiss. Werkst. Tech. 19 (1988) 3, S. 95–104
- [53] Bachmair, A.; Hömig, H. E.; Kaes, H. Mitt. Vereinigung Großkesselbetreiber (1966), S. 106–114
- [54] Ulrich, E. A. The relationship between corrosion, stress and the Fe₃O₄ layers Techn. Überwach. 8 (1967) 1, S. 17–20
- [55] Richtlinien für die Aufbereitung von Kesselspeisewasser und Kühlwasser in: Vereinigung der Großkesselbetreiber Vulkan W.Classen, Essen, 1958, S. 113, 115, 123, 126, 127, 141, 211
- [56] Ahrnborn, L. Techn. Überw. 11 (1970) 9, S. 314–316
- [57] Le Surf, J. E.; Bryant, P. C. E.; Tanner, M. G. At. Energy Can. Ltd., Chalk River 2562 (1962) 12 S. (n.C.A. 66 (1967) S. 9435, 100675e)
- [58] Henjes, G.; Rese, H.; Krause, R. Filling, preheating, and preserving steam boiler drums and headers Mitt. Vereinigung der Großkesselbetreiber 50 (1970) 5, S. 394–410
- [59] Bloom, M. C.; Krulfeld, M.; Fraser, W. A.; Vlannes, P. N. Corrosion studies in high temperature water by a hydrogen effusion method NACE Corrosion 13 (1957) 5, S. 297t–302t
- [60] Tödt, F.; Splittberger, A.; Freier, R. Korrosion und Korrosionsschutz, 2. Aufl. W. de Gruyter u. Co., Berlin, 1961, S. 854, 856, 863, 899
- [61] Nelson, G. A.; Anwendungsgrenzen für Stähle in Kontakt mit Wasserstoff Werkst. Korros. 14 (1963), S. 65–69
- [62] Muller, A. C. Indian point nuclear power plant Ind. Engng. Chem. 51 (1959) 10, S. 1254–1258
- [63] Bryant, P. E. C.; Le Surf, J. E. At. Energy Can. Ltd. Chalk River (1968) AECL – 2800, 31 S. (n.C.A. 69 (1968) Nr. 16, S. 5720, 61025h)
- [64] Fabian, R. J. Mater. Design. Engng. 58 (1963/Jan.) M/DE Special Report Nr. 202, S. 107
- [65] Wiegand, H.; Piltz, H.-H. Über das Zusammenwirken von Kavitation und Korrosion Werkst. Korros. 15 (1964), S. 212–216
- [66] Roll, F. Werkst. Korros. 12 (1961), S. 212–213
- [67] Chem. Processing (London), Corrosion Chart, Beilage Dez. 1955
- [68] Livraghi, M. et al. Characterisation of the High Temperature Corrosion Behaviour of the Modified 9Cr-1 Mo Steel Conference: Process 6 Materials: Innovation Stainless Steel. Vol. 3, Florence, Italy, 11–14 Oct. 1993 Assoziatione Italiana di Metallurgia, Milano, Italien, 1993 S. 3.133–3.138
- [69] Ozaki, T.; Ishikawa, Y. Intergranular Stress corrosion Cracking and Hydrogen Embrittlement of Martensitic Stainless Steels in High-Temperature-High Purity Water Conference: Stainless Steels '91. Vol. 1, Chiba, Japan, 10–13 June 1991 Iron and Steel Institute of Japan, Tokyo, Japan, 1991, S. 176–180
- [70] Yamanaka, K.; Matsuda, Y. Relationship Between Pre-Oxidised Film Structure and Corrosion Resistance of Ferritic Stainless Steels in High Temperature Pure Water Materials Transactions Jim 32 (1991) (4), S. 360–367
- [71] Schleithoff, K. Corrosive Environment in Steam Turbines Conference: Corrosion Fatigue of Steam Turbine Blade Materials, Palo Alto, Calif., USA, 21–24 Sept. 1981 Pergamon Press, Maxwell House, Elmsford, N.Y., USA, 1983, Paper 2.2, S. 2-19–2-28
- [72] Grützner, H.; Jesper, H. Werkstofffragen beim Einsatz nichtrostender Stahlbleche und -rohre im Reaktorbau Blech 11 (1964) 10, S. 503–511

- [73] Heitmann, H. G.
in: Tödt, F.
Korrosion und Korrosionsschutz
W. de Gruyter, Berlin, 1961, S. 942, 948
- [74] Firmenschrift
Apparate und Anlagen für die chemische Industrie
Werkschrift Edelstahlwerke Buderus AG.,
Wetzlar, Druckschrift 1 663, S. 85
- [75] Hömig, H. E.
Physikochemische Grundlagen der
Speisewasserchemie, VGB
Vulkan W.Classen, Essen, 1963, S. 256
- [76] de Paul, D. J.
Corrosion engineering problems in high
purity water
NACE Corrosion 13 (1957) 1, S. 75 ff
- [77] Ozaki, T.; Ishikawa, Y.
Stress Corrosion Cracking Behaviour of
Martensitic Stainless Steels Under Static
Load in High Temperature High Purity
Water
J. Iron Steel Inst. Jpn. 75, (8), Aug. 1989,
S. 1338-1345
- [78] Marrow, T. J.; King, J. E.
Microstructural and environmental effects
on fatigue crack propagation in duplex
stainless steels Fatigue and Fracture of
Engineering Materials and Structures 17
(1994) 7, S. 761-771
- [79] Wang, X. et al.
Stress Corrosion Cracking Behaviour of
18-5 Type Duplex Stainless Steel
Iron Steel (China) 17 (1982) 5, S. 47-54
- [80] Warzee, H. et al.
J. Electrochem. Soc. 112 (1965), S. 670-
674
- [81] Roebuck, A. H.; Breden, C. R.;
Greenberg, S.
Corrosion of structural materials in high
purity water
NACE Corrosion 13 (1957) 1, S. 71-74t
- [82] Czakowski, C.; Weeks, J. R.; Protter, S. R.
Corrosion of Structural and Poison
Material in Spent Fuel Storage Pools
Conference: Corrosion '81, Toronto,
Ontario, Canada 6-10 Apr. 1981
NACE, Houston, TX, 1981, Paper 13
- [83] Lumsden, J. B.; Stocker, P. J.
Characterisation of Passive Films Formed
on Stainless Steel in High-Temperature
Water
Conference: Passivity of Metals and
Semiconductors, Bombannes, France,
30. May-3 June, 1983
Elsevier Science Publishers BV,
Amsterdam, NL, 1983, S. 579-584
- [84] Saito, N.; Sakamoto, H.
Electrochemical Study of Crevice
Environment in High-Temperature Water
- Corrosion Potential and pH
Measurements
in: Conference: Corrosion 94
NACE, Houston, TX, USA, Paper No.
233, 27 S.
- [85] Cavalcanti, E. et al.
Electrochemical and Electronoptical
Observations of the Behaviour of Type
304 Stainless Steel in Sodium Chloride
and Demineralized Water Under Natural
Immersion Conditions
Conference: Electrochemical Methods in
Corrosion Research-Proceedings of the
3rd International Symposium, Zürich,
Switzerland, 12-15 July 1988
Mater. Sci. Forum 44-45 (1989)
ISSN: 0255-5476, S. 235-246
- [86] Leibovitz, J. et al.
Development and Qualification of High-
Temperature Reference and
Measurement Electrodes for In-Plant Use
Conference: Corrosion '83, Anaheim,
Calif. USA, 18-22 Apr. 1983
NACE, Houston, TX., USA, 1983
- [87] Ford, F. P.; Povich, M. J.
The Effect of Oxygen /Temperature
Combinations on the Stress Corrosion
Susceptibility of Sensitised 304 Stainless
Steel in High-Purity Water. Conference:
Corrosion '79, Atlanta, Ga.,
12-16 Mar 1979
NACE, Katy, Tex., 1979, Paper No. 94
- [88] Gordon, B. M.
The Effect of Chloride and Oxygen on the
Stress Corrosion Cracking of Stainless
Steels: Review of Literature
Mater. Perform. 19 (1980) 4, S. 29-38
- [89] Welch, G. A. et al.
Stress Corrosion Cracking of Sensitised
Type 304 Stainless Steel in High Purity
Water
Conference: Corrosion '79, Atlanta, GA.
12-16 Mar. 1979
NACE, Katy, TX., 1979, Paper 48

- [90] Rosborg, B.; Rosengren, A.
Slow Strain Rate Testing in High-Purity Water at Controlled Electrode Potentials Conference: Laboratory Corrosion Tests and Standards, Bal Harbour, Florida, USA, 14-16 Nov. 1983
ASTM, Philadelphia, Pennsylvania, USA, 1985, S. 415-427
- [91] Schmidt, C. G. et al.
Low Temperature Sensitisation of Type 304 Stainless Steel Pipe Weld Heat Affected Zone
Metall. Trans. A 18A (1987) 8, S. 1483-1493
- [92] Schmidt, C. G.; Caligiuri, R. D.; Eiselstein, L. E.
Intergranular Stress Corrosion Cracking of Low-Temperature Sensitised Type 304 Stainless Steel Pipe Welds Conference: Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors Myrtle Beach, S. C. USA, 22-25 Aug. 1983 NACE, Houston, TX, USA, 1984, S. 423-437
- [93] Takabayashi, J. I.; Hishida, M.
Corrosion Potential Dependency on Dissolved Oxygen Concentration and a New Type Reference Electrode in High Purity Water
Conference: Predictive Methods for Assessing Corrosion Damage to BWR Piping and PWR Steam Generators, Fuji, Japan, 28 May-2 June 1978
NACE, Houston, TX, USA, 1982, S. 116-119
- [94] Takaku, H.; Tokiwai, M.; Hirano, H.
Effects of Cyclic Loading on Stress Corrosion Cracking Susceptibility for Sensitised Type 304 Stainless Steel in 290°C High-Purity Water
NACE Corrosion 35 (1979) 11, S. 523-531
- [95] Nakayama, G.; Akashi, M.; Ohtomo, A.
A Probabilistic Assessment for the Stress Corrosion Cracking Lifetime of Sensitised 304 Stainless Steel in Sodium Chloride Solution
ISIJ International 31 (1991) 2, S. 223-228
- [96] Danko, J. C. et al.
A Pipe Test Method for Evaluating the Stress Corrosion Cracking Behaviour of Welded Type 304 Stainless Steel Pipes Properties of steel weldments for elevated temperature pressure containment applications, 1978, 91-101 – Met. A., 7911-72 0370
- [97] Clark, W. L.; Cowan, R. L.; Danko, J. C.
Dynamic Straining Stress Corrosion Test for Predicting Boiling Water Reactor Materials Performance
Conference: Stress Corrosion Cracking – The Slow Strain-Rate Technique, Toronto, Canada, 2-4 May 1977
ASTM, Philadelphia, Pa., 1979, S. 149-169
- [98] Povich, M. J.; Broecker, D. E.
The Stress Corrosion Cracking of Austenitic Stainless Steel Alloys in High-Purity Temperature Air-Saturated Water Mater. Perform. 18 (1979) 10, S. 41-48
- [99] Stewart, J. et al.
Electrochemical Noise Measurements of Stress Corrosion Cracking of Sensitised Austenitic Stainless Steel in High-Purity Oxygenated Water at 288°C
Corrosion science 33 (1992) 1, S. 73-88
- [100] Ruther, W. E.; Soppet, W. K.; Kassner, T. F.
Effect of Temperature and Ionic Impurities at Very Low Concentrations on Stress Corrosion Cracking of AISI 304 Stainless Steel
NACE Corrosion 44 (1988) 11, S. 791-799
- [101] Davis, R. B.; Indig, M. E.
The Effect of Aqueous Impurities on the Stress Corrosion Cracking of Austenitic Stainless Steel in High-Temperature Water
Conference: Corrosion 83, Anaheim, Calif., USA, 18-22 Apr. 1983
NACE, Houston, TX, 1983, 25 S.
- [102] Cookson, J. M. et al.
The Role of Microchemical and Microstructural Effects in the IASCC of High Purity Austenitic Stainless Steels
Conference: Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water reactors, San Diego, California, USA, 1-5 Aug. 1993

- The Minerals, Metals & Materials Society, Warrendale, Pennsylvania, 1993, S. 573–581
- [103] Andresen, P. L. et al.
Effect of Deformation on SCC of Unsensitised Stainless Steel
Conference: Corrosion 2000, Orlando, FL., USA, 26–31 Mar. 2000
NACE, Houston, TX
- [104] Rosborg, B.
Critical Potentials for Intergranular Stress Corrosion Cracking of Austenitic Stainless Steels in High Temperature Water Conference: Stainless Steels, 84, Chalmers University of Goteborg, Sweden, 3–4 Sept. 1984
The Institute of Metals, London, UK, 1985, S. 423–427
- [105] Akashi, M.
CBB Test Method for Assessing the Stress Corrosion Cracking Susceptibility of Stainless Steels in High-Temperature, High-Purity Water Environments in: Localized Corrosion 175-196
Elsevier Applied Science, Barking, Essex, UK, 1988
- [106] Akashi, M.
Acceleration of Stress Corrosion Cracking Test for High-Temperature, High-Purity Water Environments by Means of Artificial Crevice Application
Conference: Application of Accelerated Corrosion Tests to Service Life Prediction of Materials, Miami, Florida, USA, 16–17 Nov. 1992
ASTM, Philadelphia, PA, USA, 1994, S. 313–324
- [107] Kim, Y.-J.
Effect of noble metal addition on electrochemical polarisation behaviour of H₂-oxidation and O₂-reduction on 304 SS in high temperature water
Conference: Corrosion 98, San Diego, Ca, USA, 22-27 Mar. 1998
NACE, Houston, TX, USA, Paper 127, 12 S.
- [108] Hughes, N. R.; Clarke, W. L.; Delwihe, D. E.
Intergranular Stress Corrosion Cracking Resistance of Austenitic Stainless Steel Castings
in: Conference: Stainless Steel Castings, Bal Harbour, Fla., 12–13 Nov. 1980
American Society for Testing and Materials, Philadelphia, Pa., USA, 1982, S. 26–47
- [109] Jewett, C. W.; Pickett, A. E.
The Benefit of Hydrogen Addition to the Boiling Water Reactor Environment on Stress Crack Initiation and Growth in Type 304 Stainless Steel
J. Eng. Mater. Technol. (Trans. ASME) 108 (1986) 1, S. 10–19
- [110] Hettiarachchi, S. et al.
Effect of Flow Velocity on Crack Initiation
Conference: Corrosion '98, San Diego, CA, USA, 22–27 Mar 1998
NACE, Houston, TX, USA, 1998, Paper No 143, 11 S.
- [111] Wilde, B. E.
Making AISI Type 304 Stainless Steel Immune to Stress Corrosion Cracking
Conference: Critical Issues in Reducing the Corrosion of Steels, Nikko, Japan, 11–13 Mar. 1985
NACE, Houston, TX, USA, 1986, S. 145–158
- [112] Tsukada, T.; Miwa, Y.; Nakajima, H.
Stress Corrosion Cracking of neutron irradiated Type 304 stainless steels,
Conference: Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors. Vol 2, Breckenridge, CO, USA, 7–10 Aug. 1995
NACE, Houston, TX, USA, 1995 S. 1009–1019
- [113] Cookson, J. M. et al.
Irradiation Assisted Stress Corrosion Cracking of Controlled Purity 304L Stainless Steels
Journal of nuclear materials 202 (1993) 1–2, S. 104–121
- [114] Fukuya, K. et al.
Mechanical Properties and IASCC Susceptibility in Irradiated Stainless Steels
Conference: Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water reactors, San Diego, California, USA, 1–5 Aug. 1993
The Minerals, Metals & Materials Society, Pennsylvania, 1993, S. 565–572

- [115] Wang, L. H. et al.
Comparison of stress corrosion cracking susceptibility of thermally-sensitised and proton-irradiated 304 stainless steel using electrochemical noise techniques
Journal of Nuclear Materials 258–283 (Part B), Oct. 1998, S. 2046–2053
- [116] Clarke, W. L.; Jacobs, A. J.
Stress Corrosion Test Facility for Studying Irradiated Materials
Conference: Materials in Nuclear Energy, Huntsville, Ont., Canada, 29 Sept.–2 Oct., 1982
ASM, Metals Park, Ohio, 1983, S. 153–160
- [117] Molander, A.; Rosborg, B.
Influence of Radiolysis Products and Impurities on the Critical Potential for IGSCC of Type 304 Stainless Steel in Water at 250°C
Conference: Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Traverse City, Michigan, USA, 30 Aug–3 Sept. 1987
The Metallurgical Society/AIME, Pennsylvania, USA, 1988, S. 333–340
- [118] Kowaka, M.; Fujikawa, H.; Kobayashi, T.
Alloy SCR-3 Resistance to SCC.
Conference: Predictive Methods for Assessing Corrosion Damage to BWR Piping and PWR Steam Generators, Fuji, Japan, 28 May–2 June 1978
NACE, Houston, TX, USA, 1982, S. 353–356
- [119] Horn, R. M. et al.
Experience and assessment of stress corrosion cracking in L-grade stainless steel BWR internals
Nuclear Engineering and Design, 174, (3), Oct. 1997, S. 313–325
- [120] Devine, T. M.; Drummond, B. J.
Use of Accelerated Intergranular Corrosion Tests and Pitting Corrosion Tests to Detect Sensitisation and Susceptibility to Intergranular Stress Corrosion Cracking in High-Temperature Water
NACE Corrosion 37 (1981) 2, S. 104–115
- [121] Ford, F. P.; Povich, M. J.
The Effect of Oxygen Temperature Combinations on Stress Corrosion Susceptibility of Sensitised Type 304 Stainless Steel in High-Purity Water
NACE Corrosion 35 (1979) 12, S. 569–574
- [122] Kikuchi, E. et al.
Intergranular Stress Corrosion Crack Growth of Sensitised Type 304 Stainless Steel in an Simulated Boiling-Water Reactor Environment
NACE Corrosion 53 (1997) 4, S. 306–311
- [123] Hannemann, R. E.; Rao, P.; Danko, J. C.
Intergranular Stress Corrosion Cracking 304 SS BWR Pipe Welds in High Temperature Aqueous Environments
Conference: Environment-sensitive fracture of engineering Materials; Chicago, Illinois, USA, Oct. 1977, S. 153–177 ISSN: 089520353 1979
- [124] Tsuruta, T.; Okamoto, S.
Stress Corrosion Cracking of Sensitised Autenitic Stainless Steels in High-Temperature Water
NACE Corrosion 48 (1992) 6, S. 518–527
- [125] Lidar, P.
Influence of sulphate transients on crack growth in Type 304 stainless steel in water at 288°C
in: Conference: Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors. Vol 1, Breckenridge, CO, USA, 7–10 Aug. 1995
NACE, Houston, TX, USA, 1995, S. 597–607
- [126] Takaku, H. et al.
Effects of Load Waveform for Assessing Corrosion Damage to BWR Piping and PWR Steam generators, Conference: Predictive Methods for Assessing Corrosion Damage to BWR Piping and PWR Steam Generators, Fuji, Japan, 28 May–2 June 1978
NACE, Houston, TX, USA, 1982, S. 271–276
- [127] Hughes, N. R.; Diaz, T. P.; Pestanas, V. V.
Qualification of Induction Heating Stress Improvement for Mitigation of Stress Corrosion Cracking
J. Pressure Vessel Technol. Trans. ASME 104 (1982) 4, S. 344–350

- [128] Van der Sluys, W. A.; Demiglio, D. S.
Use of Constant DeltaK Test Method in the Investigation of Fatigue Crack Growth in 288 °C Water Environment
Conference: Environment-Sensitive Fracture: Evaluation and Comparison of Test methods, Gaithersburg, Maryland, USA, 26–28 April 1984
ASTM, Philadelphia, Pennsylvania, USA, 1984, S. 443–469
- [129] Stoecker, J. G.; Pope, D. H.
Study of Biological Corrosion in High Temperature Demineralized Water
Mater. Perform. 25 (1986) 6, S. 51–56
- [130] Kaneko, A. et al.
The Evaluation of the Pool Components' Integrity by the Concentration of the Corrosion Products in the Pool Water.
Conference: VTT Symposium 63 IAEA Technical Committee Meeting on the Methods Used in Design of Spent Fuel Storage Facilities, Espoo, Finland, 30 Sept.–3 Oct. 1985
Technical Research Centre of Finland, Espoo, 1985, S. 169–176
- [131] Friend, W. Z.
The importance of high purity water data to industrial applications
NACE Corrosion 13 (1957) 1, S. 81t ff
- [132] Coriou, H. et al.
Corrosion et anticorrosion 12 (1964) 8, S. 358–370
- [133] Herbsleb, G.
Behaviour of stainless steels, nickel and zirconium alloys in the primary systems of nuclear power plants
Mitt. Vereinigung Großkesselbetreiber 50 (1970) 2, S. 132–151
- [134] Staehle, R. W.
US At. Energy Comm., Rep. C 00-1319-32, 1965, Nov., 47 S.
- [135] Ito, G.; Ishikawa, T.; Shimuzu, Y.
Tran. Nat. Res. Inst. Metals, Japan 9 (1967) 2, S. 87–94 (n.C.A. 7 (1968) Nr. 2, S. 93
- [136] Gerasimov, V. V. et al.
Teploenergetika (1968) 6, S. 40–41 (n.C.A. 69 (1968) Nr. 8, S. 2773, 29584d)
- [137] Heitmann, H. G.
in Tödt, F.
Korrosion und Korrosionsschutz II. Aufl., W. de Gruyter, Berlin, 1962, S. 938, 941, 945, 946
- [138] Heitmann, H. G.
in Tödt, F.
Korrosion und Korrosionsschutz, II. Aufl., W. de Gruyter, Berlin, 1962, S. 938, 941, 945, 946
- [139] Belous, V. et al.
Assessment of the corrosion behaviour of structural materials in the water coolant of ITER
Conference: Fusion Reactor Materials VIII, Part A, Sendai, Japan, 26–31 Oct. 1997
Journal of Nuclear Materials 258–263, Part A, S. 351–356
- [140] Akashi, M. et al.
Metallurgical Factors Influencing the Susceptibility of Non-sensitised Stainless Steel to Intergranular SCC in High-Temperature Water
Conference: Corrosion 99, San Antonio, TX, USA, 25–30 Apr. 1999
NACE, Houston, TX
- [141] Duquette, D. J.; Steiner, D.
Effects of Radiolysis on the Corrosion and Stress Corrosion Behaviour of 316 Stainless Steels
Gov. Res. Announc. Index (1993), 14 S.
- [142] Watanabe, Y.; Shoji, T.; Kondo, T.
Electrochemical Noise Characteristics of IGSCC in Stainless Steels in Pressurised High-Temperature Water
Conference: Corrosion '98, San Diego, CA, USA, 22–27 Mar 1998
NACE, Houston, TX, USA, 1998, Paper 129, 7 S.
- [143] Yamamoto, M.; Kuniya, J.; Uchida, S.
Stress Corrosion Cracking Initiation Behaviour of XM-19 Stainless Steel Under Long-Term Uniaxial Constant Load Testing in High-Temperature Water
NACE Corrosion 60 (2004) 7, S. 681–688
- [144] Firmenschrift
Balbi, M.
Causes of Failure of an Austenitic Stainless Steel Pump Impeller
Avesta Stainless Bull., (4), 1982, S. 12–13
- [145] Firmenschrift
Corrosion-Resisting Characteristics of Wiggins Nickel Alloys, Nr. 3003, Nov. 1962
H. Wiggins u. Co Ltd., Hereford (U.K.)
- [146] Dlesk, R. R.
The storage of high purity water
NACE Corrosion 13 (1957) 9, S. 585t–588t

- [147] Mapp, C. T.
Corr. Technology 3 (1956) 10, S. 335
- [148] Taylor, D. F.
Crevice Corrosion of Alloy 600 in High-Temperature Aqueous Environments
NACE Corrosion 35 (1979) 12, S. 550–559
- [149] Hurst, P.
The Sensitisation and Intergranular Corrosion of alloy 800
ALLOY 800 (Proc. Conf.) Petten, The Netherlands, Mar. 1978, S. 271–280
- [150] Blanchet, J. et al.
Historical Review of the Principal Research Concerning the Phenomena of Cracking of Nickel Base Austenitic Alloy.
Conference: Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, Unieux-Firminy, France, 12–16 June, 1973
NACE, Houston, TX, 1977, S. 1149–1160
- [151] Yonezawa, T.; Onimura, K. et al.
Effect of Heat Treatment on Stress Corrosion Cracking Resistance of High-Nickel Alloys in High-Temperature Water
in: Conference: Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, Myrtle Beach, S. C. USA, 22–25 Aug. 1983
National Assoc. of Corrosion Engineers, Houston, Texas, USA, 1984, S. 345–367
- [152] Latanision, R. M.
Physical Metallurgy of Nickel-Base Alloys as it Relates to Corrosion
J. Mater. Eng. 10 (1988) 2, S. 143–162
- [153] Crawford, D. C.; Was, G. S.
The Role of Grain Boundary Misorientation in Intergranular Cracking of Ni-16Cr-9Fe in 360°C Argon and High-Purity Water
Metallurgical Transactions A 23A (1992) 4, S. 1195–1206
- [154] Was, G. S.
The Influence of Grain Boundary Chemistry and Structure on the Intergranular Attack and Intergranular Stress Corrosion Cracking of Austenitic Alloys
Report DOE/ER/45184–3; DE88 002436 für U.S. Department of Energy, Oct. 1987, 10 S. 11 Tab. 1 Abb..
- [155] Was, G. S.; Paraventi, D. J.; Hertzberg, J. L.
Mechanism of environmentally-enhanced deformation and intergranular cracking of Ni16Cr9Fe alloys
in: Conference: Second International Conference on Corrosion-Deformation Interactions, CDI '96, Nice, France, 24–26 Sept. 1996
Institute of Materials, London, UK 1997, S. 410–420
- [156] Bulischek, T. S.; Rooyen, D. van
Stress Corrosion Cracking of Alloy 600 Using the Constant Strain Rate Test
NACE Corrosion 37 (1981) 10, S. 597–607
- [157] Martin, J. M. et al.
Nickel-Base Alloy Heat Treatment Inco Alloys International, Patent US4798633, USA, 25 Sept. 1986 OFF. GAZ. 17 Jan. 1989, ISSN: 0360-5132
- [158] Sung, J. G.; Was, G. S.
Intergranular Cracking of Ni-16Cr-9Fe Alloys in High Temperature Water
NACE Corrosion 47 (1991) 11, S. 824–834
- [159] Pement, F. W.; Graham, N. A.
Stress Corrosion Cracking in High-Purity Water
Corrosion problems in energy conversion and generation electrochemical society, Princetown, N.J., 1974, S. 423–441
- [160] Domian, H. A. et al.
Effect of Microstructure on Stress Corrosion Cracking of Alloy 600 in High Purity Water
in: Conference: Corrosion 76
NACE, Houston, TX, Paper 99, 20 S.
- [161] Kekkonen, T.; Hänninen, H.; Tähtinen
A Comparison of the HE and SCC Susceptibility of an Age Hardenable Nickel-Base Alloy
Conference proceedings: 1986 Workshop on Advanced High-Strength Materials, Clearwater Beach, FL, USA, 12–13 Mar. 1986
Electric Power Research Institute, Palo Alto, California, 1989, report no. EPRI NP-6363, S. 13.1–13.19
- [162] Crum, J. R.; Lemke, T. F.
SCC and Hydrogen Embrittlement Testing of Candidate High Strength Nickel Alloys

- Conference: Proceedings of 1986 Workshop on Advanced High-Strength Materials, Clearwater Beach, Fla., USA, 12–13 Mar. 1986 Pub: Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, California 94304, USA, 1989, S. 25.1–25.11
- [163] Grove, C. A.; Petzold, L. D.
Mechanism of Stress Corrosion Cracking of Alloy X-750 in High-Purity Water
Conference: Corrosion of Nickel-Base Alloys Cincinnati, Ohio, USA, 23–25 Oct. 1984
American Society of Metals, Metals Park, Ohio, USA, 1985, S. 165–180
- [164] Floreen, S.; Nelson, J. L.
The Effects of Heat Treatment and Composition on the Stress Corrosion Cracking Resistance of Inconel Alloy X-750
Metall. Trans. A 14A (1983) 1, S. 133–139
- [165] Morton, D. S. et al.
Influence of Dissolved Hydrogen on Nickel Alloy SCC in High Temperature Water
in: Conference: Corrosion 99, San Antonio, TX, USA, 25–30 Apr. 1999
NACE, Houston, Paper No. 447, 12 S.
- [166] Stress Corrosion Performance of Diffusion Bonded Base Nickel Alloys
Knolls Atomic Power Laboratory, Paper 24, 1989 Report No.: DE90008130/XAB
- [167] Prybylowski, J. W. et al.
The Stress Corrosion Performance of Diffusion-Bonded Nickel-Base Alloys
NACE Corrosion 47 (1991) 3, S. 210–215
- [168] Nakayama, G.; Akashi, M.
Effect of Electrode Potential on the Susceptibility of Alloy 182 Weld Metal to Stress-Corrosion Cracking in Simulated BWR Environment
Conference: Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, San Diego, CA., USA, 1–5 Aug. 1993
The Minerals, Metals and Materials Society, Warrendale, Pennsylvania, USA, 1993, S. 883–888
- [169] Hattori, S. et al.
Development of Corrosion Resistant High Strength Nickel Base Alloys. I
Matrix Composition of Corrosion Trans. Iron Steel Inst. Jpn, 24, (12), B–403, Dec. 1984
- [170] Stiller, K.; Nilsson, J.-O.; Norring, K.
Structure, chemistry and stress corrosion cracking of grain boundaries in alloys 600 and 690
Metallurgical and Materials Transactions A 27A (1996) 2, S. 327–341
- [171] Bandy, R.; Rooyen van D.
Mechanism of Intergranular Failures in Alloy 600 in High-Temperature Environments
Conference: International Congress on Metallic Corrosion, Vol. 2, Toronto, Canada, 3–7 June 1984
National Research Council of Canada, Ottawa, Canada, 1984, S. 202–209
- [172] Alloy Digest
Inconel Filler Metal 52, Filling Code Ni-412, Sept. 1992, Alloy Digest, Inc./ 201-677-9161, Orange, N.J., USA
- [173] Alloy Digest
Inconel Welding Electrode 152, Filling Code Ni-406, July 1992
Alloy Digest, nc./ 201-677-9161, Orange, N.J., USA
- [174] Splittberger, A.
priv. Mitteilung, Nov. 1954
- [175] Firmenschrift
Nr. 19, Juni 1967
Inco Nickel, S. 1, 3
- [176] Beverskog, B.; Puigdomenech, I.
Revised Pourbaix diagrams for Zinc at 25 and 300°C
Corrosion Science 39 (1997) 1, S. 107–114
- [177] Gilbert, P. T.
J. Electrochem. Soc. 99 (1952), S. 16–21
(n.C.A. 47 (1953) 18, 9183h)
- [178] Zink-Taschenbuch, Herausgeber
Zinkberatung e.V.
Metall-Verlag GmbH, Berlin-Grünwald, 1959, S. 93
- [179] Grubitsch, H.
Über die Heißwasser-Druckkorrosion von Zink
Werkst. Korros. 20 (1969) 11, S. 949–954

Drinking Water

Authors: G. Heim, K. Reeh / Editor: R. Bender

Drinking Water – Survey Table

The table below contains general data on the corrosion behaviour. For additional comments, refer to the corresponding text.

Type	Behaviour*
Unalloyed steels and cast steel	⊕
Unalloyed cast iron	⊕
High-alloy cast iron, high-silicon cast iron	
Structural steels with up to 12% chromium	⊕
Ferritic chromium steels with more than 12% chromium	+ to ⊕
Ferritic-austenitic steels with more than 12% chromium	+ to ⊕
Austenitic chromium-nickel steels	+ to ⊕
Austenitic chromium-nickel-molybdenum steels	+ to ⊕
Austenitic chromium-nickel steels with special alloying additions	+ to ⊕
Special iron-based alloys	
Nickel	
Nickel-chromium alloys	
Nickel-chromium-iron alloys	
Nickel-chromium-molybdenum alloys	
Nickel-copper alloys	
Nickel-molybdenum alloys	
Other nickel alloys	
Zinc, cadmium and their alloys	+ to –

* + resistant/ ⊕ fairly resistant/ – unsuitable. Where no indication of corrosion resistance is made, experimental data are not available.

Introduction

– General –

Drinking water is water suitable for human consumption and use. When materials or coatings come into contact with it, no substances should be released which lead to a deterioration in its quality. The EC Directive [1] and the drinking water legislation specify limiting values both for toxic and non-toxic substances. These define a restricting framework for drinking water which must be observed within the European sector. Differences exist between the EC Directive and the drinking water legislation, which will be referred to where necessary. The parameters relevant to corrosion have been taken from [2] and summarised in Tables 1, 2 and 3.

Chemical substance	Limiting value mg/l	Calculated as	Corresponding to approximately mmol/m³	Allowance in measured value ± mg/l
Arsenic	0.04	As	0.5	0.015
Lead	0.04	Pb	0.2	0.02
Cadmium	0.005	Cd	0.04	0.002
Chromium	0.05	Cr	1	0.01
Cyanide	0.05	CN ⁻	2	0.01
Fluoride	1.5	F ⁻	79	0.2
Nickel	0.05	Ni	0.9	0.01
Nitrate	50	NO ₃ ⁻	806	2
Nitrite	0.1	NO ₂ ⁻	2.2	0.02
Mercury	0.001	Hg	0.005	0.0005

Table 1: Limiting values for chemical substances in drinking water [2]

Parameter	Limiting value	Allowance in measured value
Temperature	298 K (25 °C)	± 1 K (1 °C)
pH	not below 6.5 and not above 9.5 a) the pH of the water in the range 6.5–8.0 with metallic or cement-containing materials should not be more than 0.2 pH units below the pH of calcium carbonate saturation	± 0.1
Electrical conductivity	2000 $\mu\text{S}/\text{cm}$ at 298 K (25 °C)	± 100 $\mu\text{S}/\text{cm}$
Oxidisability (calculated as O_2)	5 mg/l	–

marble = calcium carbonate

Table 2: Physico-chemical parameters of drinking water [2]

Chemical substance	Limiting value mg/l	Calculated as	Corresponding to approximately mmol/m³	Allowance in measured value $\pm$ mg/l	Remark
Aluminium	0.2	Al	7.5	0.04	–
Ammonium	0.5	NH_4^+	30	0.1	except with water from a strongly reducing soil
Iron	0.2	Fe	3.5	0.01	does not apply for the addition of iron salts in the treatment of drinking water
Potassium	12	K	300	0.5	except with water from a potassium-containing soil
Magnesium	50	Mg	2050	2	except with water from a magnesium-containing soil
Manganese	0.05	Mn	0.9	0.01	–
Sodium	150	Na	6500	6	–

Table 3: Limiting values for chemical substances in drinking water [2]

Table 3: Continued

Chemical substance	Limiting value mg/l	Calculated as	Corresponding to approximately mmol/m ³	Allowance in measured value $\pm$ mg/l	Remark
Silver	0.01	Ag	0.1	0.004	does not apply by the addition of silver or silver compounds in the treatment of drinking water
Sulphate	240	SO ₄ ²⁻	2500	5	except with water from a calcium-containing soil

Table 3: Limiting values for chemical substances in drinking water [2]

The limiting values referred to clearly differentiate drinking water from all other types of water.

When evaluating the suitability of materials, the deterioration described in the corrosion medium drinking water due to the release of constituents of the material must also be taken into account in the sense of DIN EN ISO 8044 [3], as well as the corrosive attacks leading to weakening of walls or wall fractures. In the majority of cases drinking water comes into contact with the inner surfaces of pipes, tanks and fittings made of various materials. Under these circumstances, as well as depending on the quality of the drinking water, the corrosion behaviour of the individual materials is determined by other influencing parameters, such as the operating conditions (flow rate, temperature), construction and installation [4].

Since the influencing parameters referred to are not always constant and known, only probability statements can be made on the resistance of materials [3]. The possibility of corrosion damage to the outer surfaces of the components must be taken into account when evaluating the resistance of materials [5]. This particularly applies to underground pipelines and components, which may be attacked on the outer surfaces by aggressive soils, by the formation of electrochemical cells [6] or by stray currents [7]. In the case of plastic pipes, substances of a dubious hygienic nature may pass from contaminated soils through the pipe wall into the drinking water.

The pipelines and components which come into contact with drinking water on their inner surfaces can be briefly described as follows in the sequence following drinking water treatment by the water supply companies (WSC): drinking water tanks, long-distance lines, distribution lines, domestic service lines, domestic installation (consumer).

– Water quality –

Drinking water contains dissolved ions and gases which largely determine its corrosion-influencing properties. This is always caused by the interaction of several contents in the water. It is not possible to make statements which apply universally to

all materials. The following comments are a brief review of the main contents of water which can be used to evaluate the behaviour of the material.

The content of dissolved ions is summarised by the electrical conductivity, which according to Table 2 should not exceed the limiting value of 2000 $\mu\text{S}/\text{cm}$ at 298 K (25 °C). It is influenced particularly by the content of hydrogen and hydroxyl ions, and by cations (mainly Ca^{2+} , Mg^{2+} and Na^+) and anions (mainly Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} and NO_3^-). The pH within the limits of 6.5 to 9.5 permitted according to Table 2 and the cations and anions mentioned have various effects on the corrosion behaviour of the individual materials.

Of the dissolved gases, oxygen (O_2) and carbon dioxide (CO_2) should be mentioned above all. On metallic materials – depending on the conditions which exist – oxygen can either promote corrosion or have the effect of forming a surface layer. CO_2 is particularly important for evaluating the resistance of cemented materials in connection with the bicarbonate content.

To evaluate the corrosion properties of drinking water on metallic materials, the following data are necessary according to [8];

water temperature, pH, acid capacity $K_A4.3$, Ca^{2+} , SO_4^{2-} , Cl^- , NO_3^- , O_2 , DOC, Na^+ , Mn^{2+} , Fe^{2+} , SiO_2 and P.

In the case of cemented materials, such as, for example, the cement mortar linings on steel and cast iron pipes, according to [9] the following data must be known:

pH, $Q_c = K_A4.3 + K_B 8.2$, SO_4^{2-} , excess CO_2 , saturation index I_s .

– Temperature –

According to the data in Table 2, drinking water intended for immediate human consumption should not exceed a temperature of 298 K (25 °C). Within the temperature range of about 283 to 298 K (10 to 25 °C) stated for cold water, the temperature does not have a very substantial influence on the corrosion behaviour of materials.

If drinking water is heated for human consumption, an increased risk of corrosion compared with cold water can be expected on ferrous materials, especially unalloyed ferrous materials, because of the increased temperature. In contrast, copper materials tend to be less at risk from corrosion in hot water than in cold water.

At higher temperatures, agents which cause hardness precipitate as the temperature rises, depending on the hardness of the cold water. The deposits formed on the surfaces of materials by this process can lead to the formation of electrochemical cells, especially if the surfaces are not coated uniformly, with the consequence of increased local corrosive attack. However, even if the surfaces are coated uniformly, pitting phenomena may occur due to the concentration of anions, especially chloride. This should be remembered, for example, in the case of heat exchanger pipes made of stainless steel.

– Flow conditions –

Static drinking water initially leads to non-uniform general corrosion on unalloyed ferrous materials, leading to the development of non-protective surface layers and therefore the formation of anodic and cathodic regions. The consequence is then the occurrence of local corrosive attack in the form of wide or deep pitting. The pH drops in the pitting regions and rises in those regions outside the pitting, that is to say an electrochemical cell forms as a result of different pH values (Evans cell). At relatively high flow rates, differences in pH cannot always develop, so that in these cases it is often not local corrosion but uniform corrosion which can occur [10].

In domestic installations, there are alternating periods of static, gently flowing and faster flowing water, depending on what is being drawn off for use. The corrosion conditions are thus less clear, so that no general statements can be made, only material-specific statements.

– Installation –

In the construction of systems for drinking water transport and distribution, connection elements, for example pipe connections, whose design can significantly affect the corrosion phenomena, must be made. This is clear particularly in the case of domestic installation, where pipe connections are made in the form of screwed, soldered or welded joints [11].

In a domestic installation, a combination of different metallic materials is unavoidable, that is to say the possibility of contact corrosion must be taken into account. Indications of the contact corrosion risk are contained in [12].

Another aspect of constructing a drinking water installation in buildings is the introduction of solids, such as, for example, sand, iron filings etc., into the pipelines. If solids are deposited at certain points on the inner surfaces and remain there, the formation of a protective layer is prevented here. Pitting at these points can cause fractures in the pipe wall.

– Overview of the use of materials and material protection measures –

Practical experience with materials used for the drinking water supply has shown that the use of a material, as already stated, is largely determined both by the operating conditions and the production possibilities for the components and the production costs. The historical development is outlined and the materials and coatings currently used are mentioned in the following paragraphs.

Unalloyed ferrous materials, that is to say cast iron and steel materials, are predominantly used in drinking water plants in association with active and passive protective measures. Suitable active measures are cathodic corrosion protection (preferably in water tanks) and the addition of inhibitors to the drinking water. Passive measures include coatings using organic and inorganic coating materials, and metallic coatings.

Unalloyed ferrous materials are used without additional protective measures to a strictly limited degree. The reason for their limited use is the lack of resistance of these materials to local attack, such as wide or deep pitting. In domestic installations, it is the brown discolouration and change in taste of drinking water (rusty water), above all, which are unacceptable to the public – although they are not a health hazard.

– Long-distance pipelines

Pipes made of unalloyed ferrous material, that is to say, cast iron and steel pipes, are used for strength in long-distance pipelines, because of the larger pipe dimensions and the high pressures. Unalloyed steel and cast iron materials are protected by linings because of the possible brown discolouration due to even relatively small amounts of iron dissolving out into the drinking water.

Unalloyed steels and cast steel

The corrosion behaviour of unalloyed steels without protective measures is of importance in respect of evaluation of older long-distance and distribution lines. This also applies to older pipelines in domestic installations, especially in cases where the hot-dip galvanised layer is worn away non-uniformly and too rapidly, so that formation of a good surface layer is no longer possible.

The fundamental importance of acids and bases of high ionic strength in corrosion on unalloyed steel has been demonstrated by laboratory experiments [13]. For local corrosive attack due to electrochemical cell formation, anions such as Cl^- and SO_4^{2-} are needed for stabilisation of the anode. However, the cathodes must also be stabilised, which requires the presence of alkali metal ions (not alkaline earth metal ions). The site of formation of $\text{Fe}(\text{OH})_2$ is important in the formation of protective layers. At low flow rates, $\text{Fe}(\text{OH})_2$ is oxidised by O_2 in the water, that is to say surface coatings which provide little protection are formed. At high flow rates, O_2 arrives at the steel surface and oxidises $\text{Fe}(\text{OH})_2$ here, so that the conditions for the formation of protective surface layers exist.

Steel pipes according to DIN EN 10255 which were pickled and scaled were tested in hard and partly softened drinking water (Table 4) at continuous flow rates of 0.5 and 1.5 m/s in field experiments [14].

The increase in iron corrosion products in the surface layers shown in Figure 1 gives an indication of the corrosion processes. Under the intermittent flow conditions which were also investigated similarly, there was a significantly increased amount of iron compounds in the surface layers. The finding that as the hardness decreases more calcium is incorporated into the surface layers was remarkable (Fig. 2). This resulted in a significant reduction in the protective action of the surface layers, i.e. less impervious, inhomogeneous surface layers which tend to flake off resulted, pustules being formed. The start of wide pitting with pit diameters of up to 1 mm was found in the water softened the most, with $K_A 4.3 = 2.5 \text{ mol/m}^3$. No

reliable conclusions could be made on the influence of the neutral salt content. The fact that practically no naturally occurring inhibitors (which – as other experiments show – have a significant influence, especially on local corrosion attacks) are present in the water samples analysed is important.

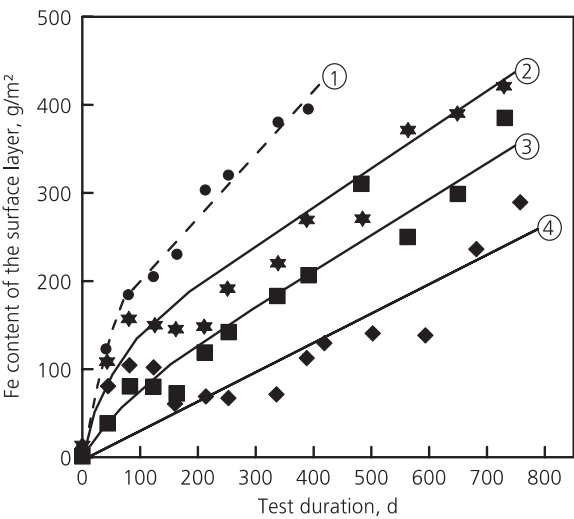


Figure 1: Influence of pH on the accumulation of iron corrosion products during protective layer formation on an unalloyed steel pipe at a flow rate of 0.5 m/s [14]
 ① pH 7.2; intermittent flow rate
 ② pH 7.9
 ③ pH 7.6
 ④ pH 7.2

<i>pH and contents mol/m³</i>	<i>Untreated water Rheinau waterworks (hard)</i>	<i>Water partially softened (medium-hard)</i>	<i>Water partially softened (soft)</i>
pH	7.2	7.6	7.9
Calcium	3.2	2.4	1.9
Magnesium	1.0	1.0	1.0
Hydrogen carbonate	5.3	3.5	2.5
Sodium	0.8	0.8	0.8
Chloride	1.8	1.8	1.8
Sulphate	1.0	1.0	1.0
Nitrate	0.4	0.4	0.4

Table 4: Test values from test waters in Mannheim (RHE) [14]

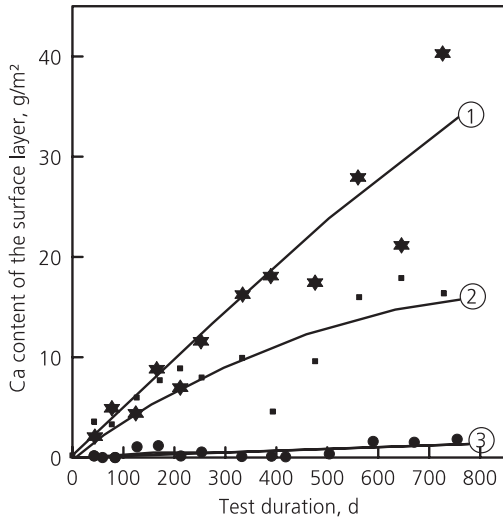


Figure 2: Influence of a pH increase on the incorporation of CaCO_3 into the protective layers during a reduction in the hardness [14]

- ① pH 7.9; flow rate 1.5 m/s
- ② pH 7.6; flow rate 1.0 m/s
- ③ pH 7.2; flow rate 1.5 m/s

By recording the cell distribution in the rust spots which formed in the field experiments described in [14] using a microprobe, it was possible to detect the accumulation of chlorides on the steel surface in [15]. On the other hand, no Cl^- ions were detectable on the cathodes. Little calcium was determined in the upper region of the surface layers in hard water of $K_{\text{A}4.3} = 5.3 \text{ mol/m}^3$, while a large quantity of calcium was present in the entire surface layer in softened water of $K_{\text{A}4.3} = 2.5 \text{ mol/m}^3$. The calcium content in a surface layer is therefore no measure of its protective action, and thus justifies abandoning of the term lime-rust protective layer for unalloyed steels. This is also shown in the standard DIN EN 12502-5 [16], in which, in contrast to the previous version, this term is no longer used for evaluating the corrosion behaviour of unalloyed and low-alloy ferrous materials.

The formation of surface layers in synthetic waters was investigated in laboratory experiments in [15], a distinction between the following surface layers being possible:

- in water of high salt content containing Ca^{2+} and HCO_3^- ions, rust layers of low impermeability form almost regardless of the flow rate, Cl^- ions promoting local corrosion.
- at flow rates of 0.35 to 1.5 m/s in ND 20 steel pipes, good surface layers are formed in Cl^- -low or Cl^- -free equilibrium water; the decreases in thickness here are 5 to 10 μm .
- in Ca^{2+} -free, acidic, CO_2 -containing water, as in Ca^{2+} - and HCO_3^- -free water, no protective layers form.

- in Ca^{2+} -free equilibrium water containing NaHCO_3 , the reproducibility of protective layer formation is low.

The results reported apply to inhibitor-free water.

The influence of O_2 content, pH and flow rate in drinking water given the following parameters was investigated in a field experiment lasting 3.5 years [17]:

- steel pipes DIN EN 10255, scaled and pickled,
- O_2 content 0.02, 1, 2 and 4 g/m³,
- flow rate 0.03, 0.1 and 0.5 m/s (constant) and 0.5 m/s intermittently,
- pH 7.2 and 8.0,
- chemical composition of the original water, see Table 5.

The following ratings are used to evaluate the corrosion state:

1 = general corrosion, roughening < 50 μm

2 = general corrosion, isolated wide pits < 100 μm

3 = general corrosion, wide pitting < 200 μm

4 = wide pitting corrosion > 200 μm

Measurable variable	Average	Standard deviation	Units
Temperature	286.1 (13.1)	3.2	K (°C)
pH	7.15	0.14	
$K_A 4.3$ (m value)	2.57	0.17	mol/m ³
$c(\text{Ca}^{2+})$	1.97	0.20	mol/m ³
$c(\text{Mg}^{2+})$	0.46	0.20	mol/m ³
$c(\text{Fe}^{2+})$	0.25	0.09	mmol/m ³
$c(\text{Mn}^{2+})$	0.42	0.27	mmol/m ³
$c(\text{NH}_4^+)$	1.11	0.56	mmol/m ³
$c(\text{Cl}^-)$	4.39	0.76	mol/m ³
$c(\text{SO}_4^{2-})$	0.81	0.07	mol/m ³
$c(\text{NO}_3^-)$	0.11	0.06	mol/m ³
$c(\text{NO}_2^-)$	0.43	0.43	mmol/m ³
$c(\text{PO}_4^{3-})$	0.32	0.21	mmol/m ³
$c(\text{SiO}_2)$	78.2	10	mmol/m ³
$c(\text{O}_2)$	8	4	mg/m ³

Table 5: Chemical composition and parameters of the original water [17]

Table 5: Continued

Measurable variable	Average	Standard deviation	Units
Conductivity	826	72	mS/m
Organic C	0.8	0.2	g/m ³
pH	8.03	0.08	
K _B 8.2 (p value)	0.04	–	mol/m ³
K _A 4.3 (m value)	3.11	0.21	mol/m ³
Conductivity	855	70	μS/cm

dissolved gases (except O₂ and CO₂) saturated with N₂

c(CO₂) = K_B8.2; c(HCO₃[–]) K_A4.3

K_B = base capacity

K_A = acid capacity

Table 5: Chemical composition and parameters of the original water [17]

The results of the study (Figure 3 below) showed that the corrosion increases as the O₂ content and flow rate increase, with an increased tendency towards local attack (wide pitting). The water adjusted to pH 8.0 by addition of sodium hydroxide solution had a favourable effect, although the local corrosive attacks were not suppressed completely.

[18] describes measurement methods used to evaluate surface layers and the formation of rusty water. By determination of the accumulation of iron on test zones, it is possible to evaluate the quality of the surface layer, while information on the formation of rusty water is not possible directly.

As an introduction to the studies described in [19], it is pointed out that the experiments reported in [13, 14] do not allow an unambiguous conclusion of the influence of neutral salts on the formation of rusty water. Experiments were therefore carried out in water which forms a good surface layer (Table 6) and has very low contents of substances such as organic carbon and phosphate, at a constant flow rate of 0.5 m/s in ND 20 steel pipes. Table 7 provides information on the neutral salt concentrations chosen. The results shown in Table 8 reveal the following trends in respect of the uptake of iron and the formation of rusty water:

- as the test duration increases up to 9 months, the material consumption rate and the uptake rate of iron decrease (Figures 4 and 5); overall, however, the probability of the formation of rusty water increases as the neutral salt content increases.
- non-uniform surface layers are formed at an increased neutral salt content, whereby an increased tendency towards local corrosive attacks is assumed, without measurement values being available.
- an increase in the nitrate content up to 250 mg/l has practically no influence on the corrosion behaviour.

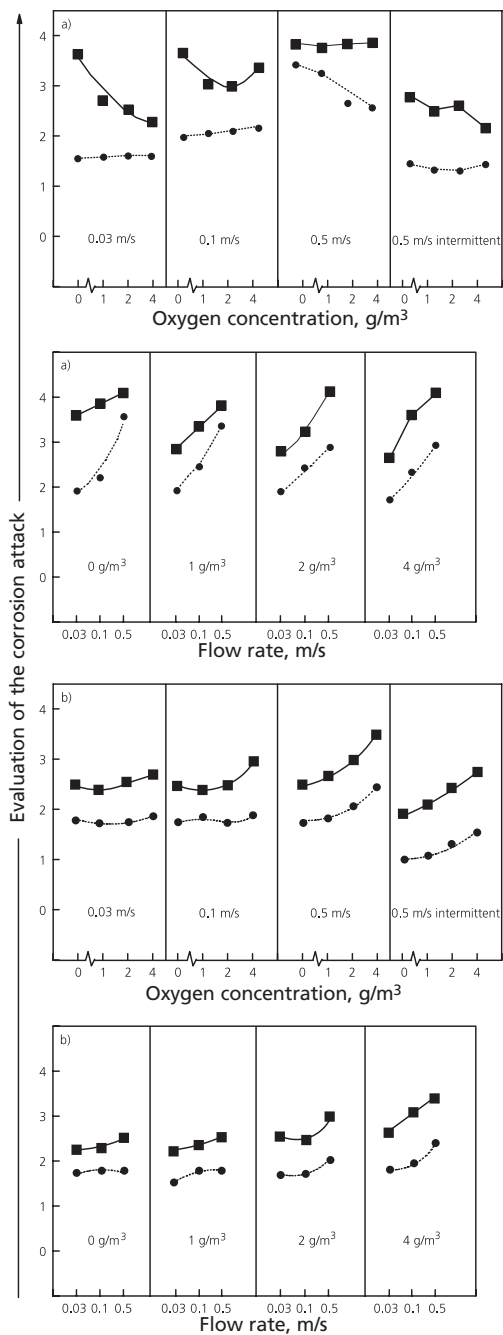


Figure 3: Influence of the oxygen concentration and the flow rate on the type of corrosion for a) galvanised steel and b) non-galvanised steel (mean values of time) as a function of the pH (number 1–4 see text)[17]

■ pH 7.2

● pH 8.0

Measurable variable	Measured value	Units
Temperature	283 (10)	K (°C)
pH	7.26	
Acid capacity up to pH 4.3	5.08	mol/m ³
Base capacity up to pH 8.2	0.75	mol/m ³
Buffer intensity	1.40	mol/m ³
Nitrate (NO ₃ ⁻)	1	mg/l
Chloride (Cl ⁻)	18	mg/l
Sulphate (SO ₄ ²⁻)	50	mg/l
Silicate (Si _{total})	5.90	mg/l
Nitrite (NO ₂ ⁻)	< 0.01	mg/l
Monophosphate (PO ₄ ³⁻)	< 0.01	mg/l
Calcium (Ca ²⁺)	96.40	mg/l
Magnesium (Mg ²⁺)	10.20	mg/l
Sodium (Na ⁺)	5.40	mg/l
Potassium (K ⁺)	1.90	mg/l

Table 6: Main parameters of the physico-chemical analysis of the original water from the Rheinwald waterworks [19]

Salt	Concentration			Arithmetic mean	Standard deviation	Number of measurements
	Reference	Maximum	Minimum			
	mg/l			mg/l	mg/l	
Sulphate	150	166	128	148	8.12	73
	250	271	235	248	9.44	65
	350	367	323	348	9.99	73
	500	540	465	499	24.78	11
Nitrate	20	30	13	21.5	4.14	66
	50	68	36	53	6.12	76
	100	125	84	106	8.20	76
	250	274	226	253	19.93	12

Salt	Concentration			Arithmetic mean	Standard deviation	Number of measurements
	Reference	Maximum	Minimum			
				mg/l	mg/l	
Chloride	50	57	40	46	3.14	67
	100	108	87	97	4.72	78
	250	272	229	250	8.16	78
	350	360	327	345	9.53	12

Table 7: Concentration of the different neutral salts during running time (previewed, maximum, minimum, mean and standard deviation) [19]

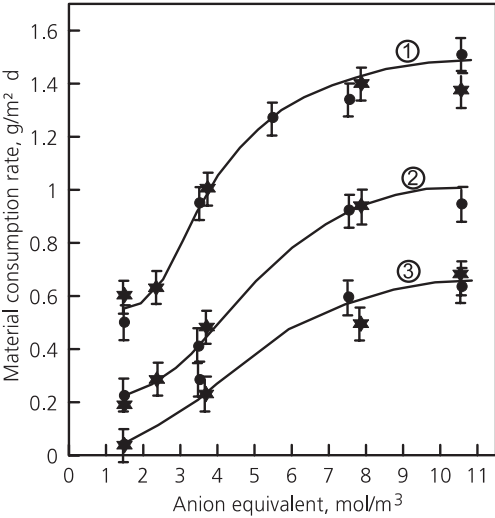


Figure 4: Corrosion rates of the test loops vs. chloride/sulphate concentration at different running times [19]

- ① 1–2 months
- ② 6 months
- ③ 9 months

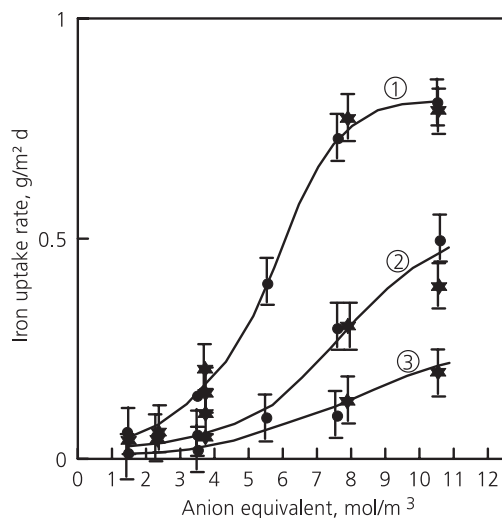


Figure 5: Iron uptake rates of the test loops vs. chloride/sulphate concentration at different running times [19]

① 1–2 months

② 6 months

③ 9 months

Tests were carried out on a rotating disk to study the influence of the chloride content on the corrosion of unalloyed steel in drinking water [20]. The killed steel RSt 37-2 (1.0038, cf UNS K02502) with a ground surface was used. Chloride was added to the initial water types listed in Table 9 in concentrations of 4.3, 7.1 and 11.3 mol/m³. The peripheral speeds of the disks were chosen so that they corresponded to flow rates of 0.04, 0.3 and 1.2 m/s – partly constant and partly intermittent.

Running time	Material consumption rate	Iron uptake rate	
Months	g/m ² d	g/m ² d	%
Low neutral salt content			
1	0.55	0.05	9
6	0.25	0.02	8
9	< 0.05	< 0.01	–
High neutral salt content			
1	1.40	0.78	57
6	0.95	0.45	47
9	0.60	0.23	38

Table 8: Comparison of the material consumption rates and iron uptake rates for low and high neutral salt contents as a function of the running time as well as the percentage iron uptake rate, referring to the material consumption rate [19]

The graph shown in Figure 6 shows the marked influence of the test duration on the material consumption rate per unit area. According to this graph, the chloride content even has an influence on general corrosion, but only in the initial phase at contents of 4.6 mol/m^3 . The evaluation of the pitting depth shows that it increases initially at low chloride concentrations, only to change into a more general attack at a chloride content of 4.6 mol/m^3 . When the surface layer was analysed, chloride was detected only at the steel/surface layer phase boundary and calcium only on the side of the surface layer adjacent to the water. Table 10 contains data on the composition of the surface layers after a test duration of 10,000 h.

A further 3 experiments carried out over a year on Berlin drinking water (Table 11) to which chloride was added up to 15.5 mol/m^3 are reported in [20]. The flow rate in 3/4" steel pipes DIN EN 10220 was intermittent, that is to say, the flow rate was 10 l/min in each case for 12 h and zero for 12 h. As can be seen from Figure 7, the material consumption rate per unit area also decreases here with the test duration, without any influence due to the chloride content. The long-term results summarised in Figure 8 show a corrosion rate of 30 to $60 \mu\text{m/y}$, from which it can be concluded that under the given conditions unalloyed steel is resistant to local corrosive attacks.

Measurable variable	Units	Annual average 1 st year		Annual average 1981 2 nd year		Annual average 1982 3 rd year	
		Bayer	BASF	Bayer	BASF	Bayer	BASF
pH		7.6	7.6	7.6	7.6	7.6	7.3
Conductivity	mS/cm	0.308	0.315	0.310	0.320	0.312	0.325
$\text{Ca}^{2+} + \text{Mg}^{2+}$	mol/m ³	3.26	1.42	2.98	1.40	2.52	1.46
$\text{K}_\text{A}4.3$	mol/m ³	3.57	3.81	3.36	3.77	2.97	3.79
$c(\text{Ca}^{2+})$	mol/m ³	2.56	1.17	2.32	1.17	1.94	1.20
$c(\text{Na}^+)$	mol/m ³	3.65	1.17	3.52	1.17	2.53	1.34
$c(\text{K}^+)$	mol/m ³	0.17	0.06	0.16	0.05	0.13	0.07
$c(\text{NH}_4^+)$	mol/m ³	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$c(\text{Fe}^{2+})$	mol/m ³	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.002
$c(\text{Mn}^{2+})$	mol/m ³	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
$c(\text{SO}_4^{2-})$	mol/m ³	1.08	0.02	0.98	0.02	0.79	0.03
$c(\text{Cl}^-)$	mol/m ³	4.23	0.31	3.95	0.31	3.30	0.31
$c(\text{NO}_3^-)$	mol/m ³	0.34	0.035	0.32	0.03	0.29	0.038
$c(\text{NO}_2^-)$	mol/m ³	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
$c(\text{PO}_4^{3-})$	mol/m ³	< 0.001	0.005	< 0.001	0.005	< 0.001	0.002
$c(\text{O}_2)$	mg/l	8.8	6.6	8.8	7.9	8.7	6.3
Number of measurements		53	53	52	52	52	52

Table 9: Results from test waters used for the study of the influence of chloride on the corrosion behaviour of RSt 37-2 (1.0038, cf UNS K02502) [20]

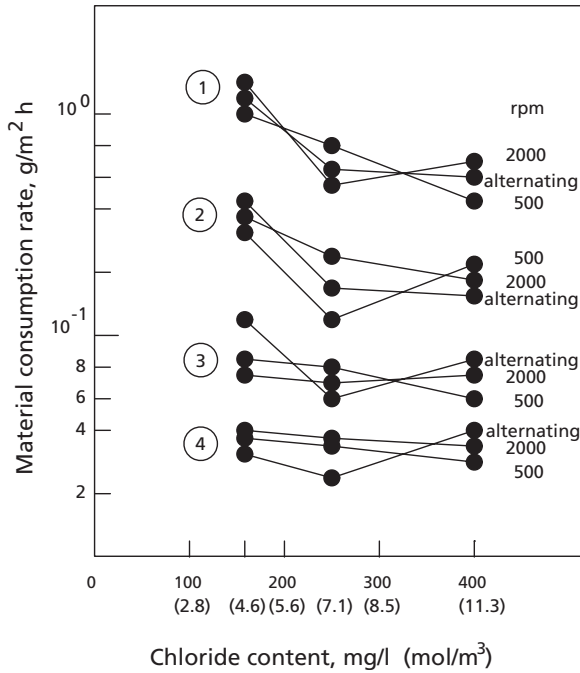


Figure 6: Material consumption rate per unit area on RSt 37-2 (1.0038, cf UNS K02502), based on the corroded surface, as a function of the chloride content at various rotational velocities and at room temperature (293–298 K (20–25 °C)) [20] after
 ① 100 h ② 800 h ③ 2,000 h ④ 10,000 h

The initially apparently contradictory results of the experiments in [19] and [20] must be seen from the point of view of the types of corrosion. [19] deals primarily with uniform general corrosion (removal of iron) and the formation of rusty water, while the conclusions in [20] primarily relate to wide or deep pitting corrosion.

To clarify whether the saturation index I_s , and the pH can be used for evaluating drinking water, experiments were carried out with scaled and pickled steel pipes in Witten water [21]. Sodium hydroxide solution was metered into the original water (Table 12) so that 4 types of water with the pH and I_s values shown in Table 13 could be analysed. The flow rates were a constant 0.5 and 1.0 m/s, and intermittently 0.5 m/s, as is usual in field experiments. On the basis of the analyses carried out on the surface layers over 900 days, one can conclude that the given experimental conditions, the flow rate, pH and I_s values and scaled and pickled surface states have no influence on the phenomenological pattern of the surface layers. This result is thought to be influenced considerably by the high content of phosphate and organic compounds.

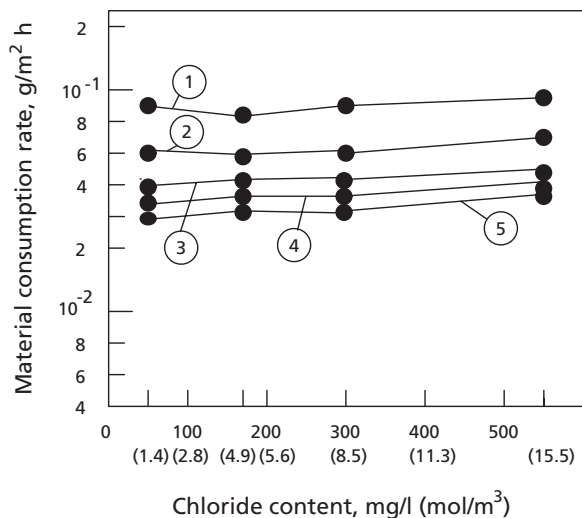


Figure 7: Material consumption rate per unit area on a pipe through which tap water flows (RSt 37-2 (1.0038)) in drinking water as a function of the chloride content and test duration: ① 0.5, ② 1.0, ③ 2.0, ④ 2.5 and ⑤ 3 years [20]

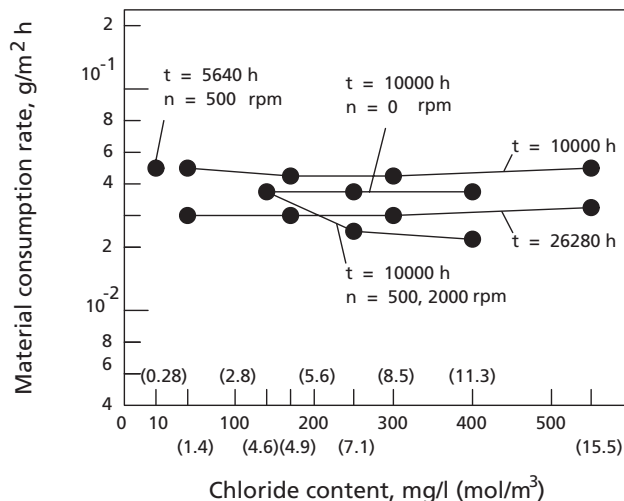


Figure 8: Material consumption rate per unit area on a disk and on a pipe through which tap water flows (RSt 37-2 (1.0038)) as a function of the chloride content. Long-term results [20]

t = test duration

n = rotational velocity

Measurable variable	Chloride ion concentration, mol/m ³	
	7.1	11.3
Measured values, %		
Cl ⁻	0.09	0.13
SO ₄ ²⁻	4.17	3.71
SiO ₂	0.87	1.22
P ₂ O ₅	0.14	0.34
Na ⁺	0.13	0.15
Ca ²⁺	16.30	13.70

Table 10: Analysis of the deposition layers on rotating disks made of RSt 37-2 (1.0038) after a test duration of 1000 h, n = 500 rpm [20]

One field experiment was based on the question of whether and to what extent various deacidification measures influence the corrosion behaviour of galvanised and black steel pipes [22]. The soft untreated water containing carbonic acid (Ebnet/Freiburg waterworks) was deacidified by metering in Mg(OH)₂ and Ca(OH)₂ and by filtration over limestone (for the water analyses, see Table 14). Here also, the corrosive attacks decreased over the test duration of three years, largely independently of the flow rate of 0.5 and 1.0 m/s. The highest material consumption rates occurred in the untreated water at 2 g/m² d for up to 600 days, and then remained constant at about 0.8 g/m² d. The initially high material consumption rates of 1.5 g/m² d in water deacidified by CaCO₃ filtration were reduced after 730 days to about 0.1 g/m² d, uniform, largely impervious surface layers being formed. In the pure water which had been deacidified by Ca(OH)₂, the material consumption rates were below 0.1 g/m² d. In respect of resistance, the deacidification methods investigated can be used in practice, depending on the possibility of monitoring.

Measurable variable	Annual average	Units
pH	7.6	
c(Ca ²⁺ + Mg ²⁺)	2.35	mol/m ³
K _A 4.3	3.89	mol/m ³
c(Ca ²⁺)	2.07	mol/m ³
c(Mg ²⁺)	0.28	mol/m ³
c(Na ⁺)	1.65	mol/m ³

K_A = acid capacity

Table 11: Water analysis of drinking water (Berlin) in studies on steel pipes according to [20]

Table 11: Continued

Measurable variable	Annual average	Units
$c(K^+)$	0.08	mol/m^3
$c(NH_4^+)$	0.004	mol/m^3
$c(Fe^{2+})$	< 0.001	mol/m^3
$c(Mn^{2+})$	< 0.001	mol/m^3
$c(SO_4^{2-})$	0.73	mol/m^3
$c(Cl^-)$	1.41	mol/m^3
$c(NO_3^-)$	0.01	mol/m^3
$c(NO_2^-)$	< 0.001	mol/m^3
$c(PO_4^{3-})$	0.001	mol/m^3
$c(SiO_2)$	0.25	mol/m^3
$c(O_2)$	7.1	mg/l
Number of measurements	92	

K_A = acid capacity

Table 11: Water analysis of drinking water (Berlin) in studies on steel pipes according to [20]

Measurable variable	Measured value	Units
pH	6.8	
m value	1.2	mol/m^3
Negative p value	0.35	mol/m^3
$c(Ca^{2+})$	1.2	mol/m^3
$c(Mg^{2+})$	0.25	mol/m^3
$c(NO_3^-)$	0.25	mol/m^3
$c(SO_4^{2-})$	0.6	mol/m^3
$c(Cl^-)$	0.8	mol/m^3
$c(Fe^{2+})$	< 0.1	mmol/m^3
$c(Mn^{2+})$	0.2	mmol/m^3
$c(PO_4^{3-})$	5	mmol/m^3

Table 12: Water analysis of drinking water (Witten) [21]

	Water sample 1	Water sample 2	Water sample 3	Water sample 4
pH	6.8	7.5	8.0	8.5
Saturation index	-1.2 to -1.5	-0.5 to -0.7	approx. ± 0	+0.5

Table 13: I_s and pH values of drinking water (Witten, see Table 12) after metering in different concentrations of NaOH [21]

Rusty water may form if different types of water are mixed. To clarify the corrosive attacks which occur here, unalloyed steel pipes were exposed for in each case about one year to water of constant quality at a flow rate of 0.5 m/s (constant and intermittent). The steel pipes were then installed in a different experimental plant with a different water quality under the same flow conditions. The consequences of changing the water shown in Table 15 were investigated. By way of example of this extensive series of investigations, Figures 9 and 10 show the material consumption rates per unit area and the iron uptake rates with respect to time. In general it can be said that the water to which the steel pipes are exposed after the change determines the material consumption and iron uptake rates. The time taken for the non-influenced state to be reestablished after changing the water can vary from a few weeks to months. Where constantly varying water qualities are distributed, the material consumption and iron uptake rates are higher than in the case of a single type of water. Intermittent flow rates additionally have an unfavourable effect here [23].

Measurable variable	Units	Untreated water	Measured value untreated water		Pure water
			+ $Mg(OH)_2$	+ $CaCO_3$	
pH		6.2	8.4	7.6	8.0
m value	mol/m ³	0.48	1.41	2.11	1.27
p value	mol/m ³	-0.93	–	-0.14	-0.05
Ca ²⁺	mol/m ³	0.30	0.23	1.13	0.7
Mg ²⁺	mol/m ³	0.10	0.53	0.33	0.15

Table 14: Partial analysis of the test waters used according to [22]

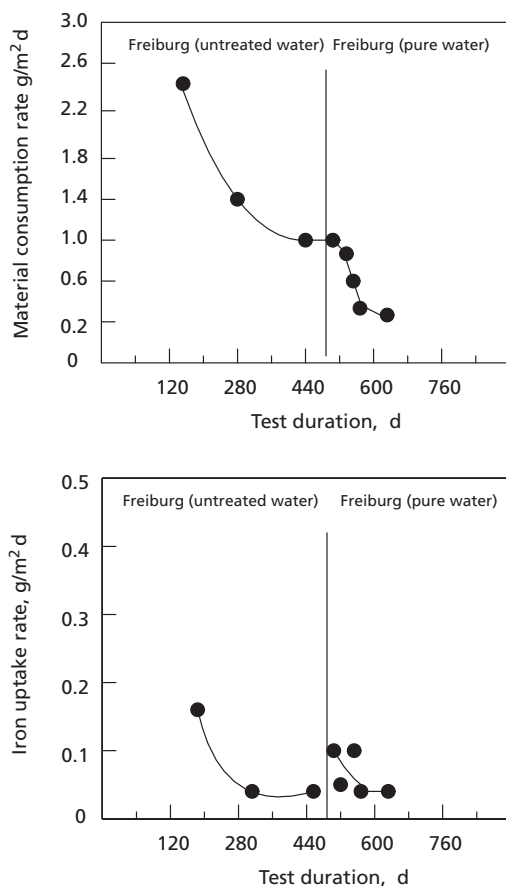


Figure 9: Material consumption rate and iron uptake rate on an unalloyed iron material before and after a change in the water quality. Change from non-deacidified (pH 6.2 – 6.5) to deacidified water (pH 8.0 – 8.2) [23]

Unalloyed cast iron

Pipes of unalloyed cast iron have been used for more than 100 years for long-distance and distribution lines. By the end of the fifties, grey cast iron was used exclusively for these pipes, and since that time has been replaced by ductile cast iron.

The inner surfaces of the pipes of both materials were, and today still are, provided with a coating or lining. The inner coating of grey cast iron pipes consisted of an approximately 60 to 120 μm thick layer of coal tar pitch produced by dipping [24]. These relatively thin layers are resistant in non-aggressive or only weakly aggressive drinking water, providing adequate protection from corrosive attack on the inner surfaces. In aggressive water – as described in [25] – rust nodules form which weaken or break through the pipe wall. Furthermore, encrustations develop, causing a reduction in pipe cross-section.

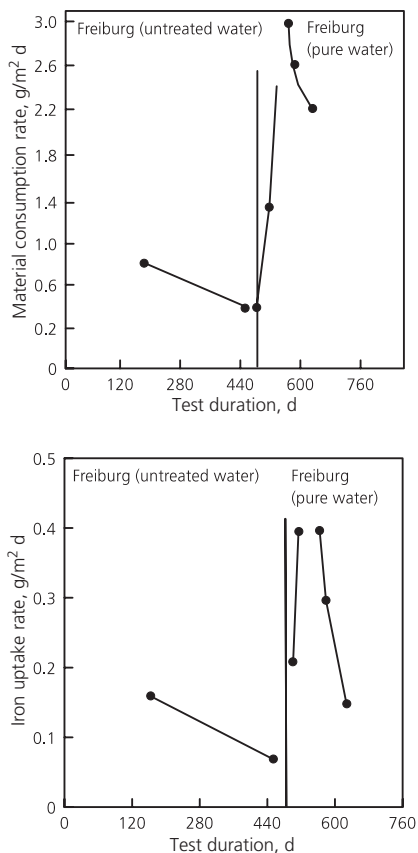


Figure 10: Material consumption rate and iron uptake rate on an unalloyed iron material before and after a change in the water quality. Change from deacidified (pH > 8) to non-deacidified water (pH < 6.5) [23]

Soft, acidic water (low pH)	↔ soft, alkaline water (high pH)
Soft, alkaline water (low mineral content)	↔ soft, alkaline water (high mineral content)
Soft, alkaline water (slightly buffered)	↔ hard equilibrium water (well buffered)
Surface water low in neutral salts (low temperature, negligible neutral salt content)	↔ riverine filtrate rich in neutral salts (high temperature, elevated neutral salt content)

Table 15: Water changes in a test series on steel pipes according to [23]

Because of the disadvantages described, the thin coating of tar pitch was replaced by a cement mortar lining [26]. Ductile cast iron pipes [27] with a cement mortar lining (CM lining) have since been used exclusively in Germany since the mid-seventies.

The resistance of the CM lining is of importance in respect of exposure to drinking water.

Structural steels with up to 12% chromium

These materials are of only limited resistance to drinking water. Ferritic CrNi steels with 12 % chromium – as described in the following section – may thus be susceptible to pitting, depending on the corrosion conditions.

Ferritic chromium steels with more than 12% chromium**Ferritic-austenitic steels with more than 12% chromium****Austenitic chromium-nickel steels****Austenitic chromium-nickel-molybdenum steels****Austenitic chromium-nickel steels with special alloying additions**

Amongst the stainless steels, ferritic Cr steels and the austenitic CrNi steels with and without added molybdenum must be considered as passivable materials for domestic installations. These materials are of particular interest for hot water pipes and hot water tanks, as well as for cold water pipes. The stainless steels suitable for domestic installations are summarised in Table 16.

General corrosion of all the materials is low, so that a very good resistance may be reported in this respect. Local corrosion attack in the form of pitting may occur on the materials under certain conditions. Since stainless steels which are susceptible to intergranular corrosion (IC) are more susceptible to pitting, only those materials which are IC-resistant due to the choice of an appropriate alloy composition are suitable. Pitting corrosion and the crevice corrosion associated closely with this depend, amongst other things, on the chloride concentration, on the structural conditions [28, 29] and on the flow conditions. The steel/water heat transfer can cause chlorides to concentrate in lime deposits and hence lead to increased pitting.

<i>DIN-Mat.No.</i>	<i>Designation</i>		
Ferritic steels			
1.4510	SAE 439	UNS S43035	X3CrTi17
Ferritic Mo-containing steels			
1.4521	SAE 444	UNS S44400	X2CrMoTi18-2
Austenitic steels			
1.4301	SAE 304	UNS S30400	X5CrNi18-10
1.4306	SAE 304 L	UNS S30403	X2CrNi19-11
1.4541	SAE 321	UNS S32100	X6CrNiTi18-10
Austenitic Mo-containing steels			
1.4401	SAE 316	UNS S31600	X5CrNiMo17-12-2
1.4404	SAE 316 L	UNS S31603	X2CrNiMo17-12-2
1.4436	SAE 316	UNS S31600	X3CrNiMo17-13-3
1.4435	SAE 316 L	UNS S31603	X2CrNiMo18-14-3
1.4571	SAE 316 Ti	UNS S31635	X6CrNiMoTi17-12-2
1.4439	SAE 317 LMN	UNS S31726	X2CrNiMoN17-13-5
1.4539	SAE 904 L	UNS N08904	X1NiCrMoCu25-20-5
Ferritic-austenitic steels			
1.4462		UNS S31803	X2CrNiMoN22-5-3

Table 16: Stainless steels suitable for domestic installations, water heating units and pipes [28]

In a detailed laboratory investigation [30], some possibly suitable stainless steels were investigated. From the results compiled in Table 17, the following conclusions can be drawn:

- Ferritic Cr steels with 18 % Cr are suitable as pipes for hot water up to 368 K (95 °C), especially if they are additionally alloyed with 2 % Mo. On the basis of this result, only steels with at least 16 % Cr were approved in DIN EN 12502-4 [31].
- Although the usual austenitic CrNi steel 1.4301 (SAE 304 UNS S30400) can be used for hot water pipes because of its good resistance, it cannot be used for heat exchanger pipes. The steel 1.4571 (SAE 316 Ti, UNS S31635) or materials with a higher molybdenum content must be used for these.

In the context of the studies in [30], the pitting or crevice corrosion potential of the steel 1.4301 in tap water which had, due to addition, a Cl^- content of 500 mg/l, was determined as $U_L = + 0.3 \text{ V}$ at 368 K (95 °C) by electrochemical analyses. The

rest potential in the nonexposed starting state was determined as $U_H = +0.52$ V to $+0.42$ V, that is to say the material ought to have suffered pitting, although this was not the case. In the finished state, the rest potential was $U_H = +0.2$ V, and hence the absence of pitting in the experiment was confirmed, U_L being greater than U_H .

When evaluating pitting data in the literature, the displacement of the potential in the negative direction caused by exposure of the material during the experiment must be taken into consideration.

The hard solder compounds also investigated in [30] showed a loss in adhesion between the solder and steel in the case of the ferritic Cr steels, that is to say knife-line corrosion occurred. It is possible to use a solder which contains 56 % Ag, 26 % Cu, 14 % In and 4 % Ni on austenitic CrNi steels. Solders containing Zn could not be used because of dezincification at the steel/solder phase boundary.

In another study on hard solder compounds, it was found that the silver hard solder L-Ag 40 Cd proved to be resistant in association with the steel 1.4301 in hot water containing up to 50 mg/l chloride [32].

Field experiments were carried out for up to 2 years to study the suitability of 1.4301 in domestic installations [33]. Table 18 shows the test site, the test duration and the operating conditions chosen. The associated water parameters are given in Table 19.

In each unit 8 m long, longitudinally welded pipes with pressed fittings were installed. These pipes were made of the steel 1.4301 (SAE 304 UNS S30400) and had the dimensions 22 mm $\times$ 0.7 mm and 15 mm $\times$ 0.7 mm. The results of these studies are summarised below:

- Neither local nor general corrosion occurred on the inner surfaces of the pipes. Where discolouration was found, this could be attributed to entrained constituents.
- In the Bremen unit, very firmly adhering encrustations occurred on pipes operated at a constantly high temperature of 363 K (90 °C). After removal of the encrustations, no corrosion was detectable on the steel surface. No encrustations occurred when the same unit was operated intermittently with hot water.
- In the case of all the pressed fittings, the surface underneath the butyl rubber sealing rings was still bright after 740 days.

Materials data general material designation	DIN– Mat. No.	SAE	Chemical composition, %						Test conditions		Material resistance											
			C Cr Ni Mo Ti N						Chlorides ²⁾	Flow ³⁾	Test duration	Pipe	Heat exchanger									
													C	Cr	Ni	Mo	Ti	N	d	348 K (75 °C)	368 K (95 °C)	348 K (75 °C)
Austenitic CrNi steels	1.4301	304	0.040	17.52	10.60	–	–	70	c	231	–	–	–	–	P, SCC							
																dc	–	–	–	P		
	500	c	–	–	–	–	P, SCC															
								dc	–	–	–	P, SCC										
1.4550	348 SAE 348	0.054	18.36	10.80	–	Nb (Cb) 0:39	70	c	176	n.a.	n.a.	–	–	–								
																dc	n.a.	n.a.	–			
500	c	–	–	–	–	n.a.	n.a.	–														
															dc	n.a.	n.a.	–				
Mo–containing, austenitic CrNi steel	1.4571	316 Ti	0.037	17.65	13.55	2.24	0.37	–	70	c	136	–	n.a.	–	n.a.							
																	dc	n.a.	n.a.	–	n.a.	
500	c	–	–	–	–	n.a.	n.a.	–														
															dc	n.a.	n.a.	–	n.a.			

P pitting, S weld seam corrosion, SCC stress corrosion cracking, () slight corrosion, n.a. no corrosive attack detectable

1) with 2 % Mo

2) tap water with and without a Cl[–] addition

3) continuous flow = c, 0.003 m/s and discontinuous = dc, 0.86 m/s

Table 17: Stainless steels usable in domestic installations and water heating systems [30]

Test site	Plant type ¹⁾	Pipe samples DIN–Mat.No. 1.4301	Test duration
		mm	d
Stuttgart	A 1		670
	A 2	15 × 0.7	391
	A 3		670
	A 1		740
Wiesbaden	A 2	15 × 0.7	616
	A 3		740
	A 1		678
Bremen	A 2	15 × 0.7	419
	A 3		666
	A 1	15 × 0.7	420
Hamburg ²⁾	A 2	–	–
	A 3	15 × 0.7	420
Berlin ³⁾			
– Kladow	cold	22 × 0.7	428
	warm		428
– Jungfernheide	cold	22 × 0.7	458
	warm		458

- 1) Temperature, K (°C) flow, l/h
A 1 plant – cold, continuous operation wetting temperature
278 – 285 (5 – 12) approx. 15
A 2 plant – hot, continuous operation approx. 363 (90) approx. 35
A 3 plant – hot, intermittent operation: approx. 363 (90) approx. 75
downtime 16 h
remaining period in rotation:
5 min flow,
25 min interruption

2) A 2 plant in Hamburg operating since 6.6.1974

3) industrial water pipes – both hot and cold (328 K (55 °C))

Table 18: Data from field tests [33]

Test site	pH	Conductivity	Free CO ₂	Total hardness	Carbonate hardness	SO ₄ ²⁻	Cl ⁻	O ₂
		μS/cm	mg/l	°dH	°dH	mg/l	mg/l	mg/l
Stuttgart	7.3	650	29	18.0	15.2	33	16	10.9
Wiesbaden	7.53	860	15.2	16.9	10.1	71	165	8.6
Bremen	8.34	1819	0.3	21.7	5.7	150.1	498	9.7
Hamburg	7.88	150	3.1	5.4	0.03	10	13	5.6
Berlin								
– Kladow	7.27/7.66	350/540	8.8/15.0	10.6/14.3	8.4/10.4	29/69	13/47	7.7/12.9
– Jungfernheide	7.23/7.80	738/945	16.4/19.6	19.1/21.9	10.4/12.9	132/157	63/124	4.8/10.3

Table 19: Test water parameters used in the investigation of the corrosion behaviour of 1.4301 (SAE 304, UNS S30400) in domestic installation units [33]

Experiments studying the corrosion behaviour of pipes and pipe connections made of the steel 1.4301 (SAE 304 UNS S30400) were carried out in cold drinking water in field tests lasting five years [34]. Table 20 contains data for pipes in various heat treatment states. The pipe connections were made of the same material as the pipes. Pressed fittings with a non-metallic seal and solder fittings were tested. The chemical composition of the solders used is shown in Table 21.

The results of these field tests can be summarised as follows:

- Outside the pipe connections, the pipes were completely corrosion-resistant, regardless of the heat treatment state investigated. According to [30], inter-crystalline corrosion should not exceed 10 mm when testing for resistance to this form of corrosion.
- After exposure for five years, crevice corrosion occurs below the non-metallic seal in pressed fittings at chloride contents of $> 1.3 \text{ mol/m}^3$ and $\text{pH} < 7$. This finding is of great importance, since no crevice corrosion was observed after 2 years in the experiments described in [32]. In [34], it is suggested that the crevice corrosion which occurred after 5 years was due to changes in the composition of the water, e.g. concentration of salts in the region of the pipe connections. On the basis of the results of these studies, pipes and pressed fittings of the corrosion-resistant steels 1.4401 (cf. SAE 316, UNS S31600) and 1.4571 (cf. SAE 316 Ti, UNS S31635) are proposed in [35] for use in drinking water installations.

Knife-line corrosion occurs at the solder joints at chloride contents of $> 1 \text{ mol/m}^3$. The solder L-Ag 40 Cd is more sensitive to corrosion than the other two solders.

The results reported for the investigations have, furthermore, led to on-site weld joints with hard and soft solders not being approved in the new DIN 1988-7 [36].

Mechanical joints (e.g. pressed fittings) on-site are possible, in which case the manufacturer's instructions must be strictly observed.

A summary of the studies on the use of stainless steels for water heaters and pipelines has been compiled by the CEOCOR [37]. Reference is made to the very small amounts of corrosion products released by the materials, which is of great importance in respect to drinking water hygiene.

If stainless steels are used for domestic installations, the release of chloride from sealing materials, amongst other things, must be monitored in order to guarantee the good resistance of the material. If the release of chloride ions is too high, there is the risk of increased concentration of chloride, with the possible consequence of pitting and/or crevice corrosion.

Gas bubbles must be avoided in the heated water, since the probability of pitting corrosion or crevice corrosion is greatly increased at the three-phase boundary of stainless steel/water/air as a result.

According to [31], 1.4571 (cf. SAE 316 Ti, UNS S31635) is suitable for water heaters. 1.4558 (X2NiCrAlTi32-20) is recommended for heating elements in water heaters.

In addition to the material properties described for stainless steels in drinking water, the possibility of external corrosion must be considered. [38] provides information on the aspects to be noted in this context.

<i>Chemical composition</i>								
C	Si	Mn	P	S	Cr	Ni	N	Fe
0.06	0.04	1.68	0.037	0.015	17.88	9.85	0.029	balance

heat treatment state

- solution annealed in pipe
- solution annealed, subsequent sensitisation by annealing for 10 min at 923 K (650 °C)/air
- solution annealed, subsequent sensitisation by annealing for 20 min at 923 K (650 °C)/air

Table 20: Chemical composition and heat treatment state of longitudinally welded ND 20 pipes (22 mm × 0.7 mm) consisting of 1.4301 (SAE 304, UNS S30400) [34]

<i>Solder no.</i>	<i>Chemical composition, %</i>						
	<i>Ag</i>	<i>Cu</i>	<i>Zn</i>	<i>Cd</i>	<i>In</i>	<i>Sn</i>	<i>Ni</i>
1	40	19	21	20	–	–	–
2	56	26	–	–	14	–	4
3	56	22	17	–	–	5	–

Table 21: Solder designations and chemical composition of solders used in the production of solder joints on pipes made of 1.4301 [34]

Zinc

Zinc is widely used as a coating on steel pipes in domestic installations. The requirements of zinc coatings applied by hot-dip galvanising are listed in DIN EN 10240 [39]. The maximum contents allowable (percent by weight) of accompanying elements in the zinc coating are listed in Table 22. These are of importance in respect to the release of toxic substances into drinking water. The weight of the coating per unit area must be at least 400 g/m^2 to achieve good corrosion protection and the coating should have a suitable layer structure characterised by a pure zinc phase and an alloy phase. Practical experience has shown that the probability of corrosion is very high, especially in respect to local attack, in the case of zinc coatings with a structure which does not comply with the standard. Steel pipes which have been blown out with air and not with superheated steam after hot-dip galvanising have a foam-like galvanised layer which tends to release white rust. The zinc coating is fissured in the region of the internal flashes of weld seams which have not been removed, and thus forms starting points for local corrosion [40]. According to DIN EN 12502-3 [41], zinc coatings which do not comply with the standard are classified into groups A, B and C.

<i>Accompanying elements</i>	<i>Content, %</i>
Aluminium	0.1
Antimony	0.01
Arsenic	0.02
Lead	0.8
Cadmium	0.01
Copper	0.1
Bismuth	0.01
Tin	0.1

Table 22: Maximum contents allowable of accompanying elements in the zinc coating according to DIN EN 10240 [39]

There is extensive literature on the corrosion behaviour of hot-dip galvanised steel pipes in cold water. In an experiment lasting 3 months on hot-dip galvanised ND 20 steel pipes in the types of water shown in Table 23 at a continuous flow rate of 0.12 m/s , it was found that the corrosion rate depends on the flow rate and the pH [42]. From theoretical considerations, this result is interpreted as follows: a virtually stationary state is established in the three-phase system of metal/surface coating/water, in which the transportation of Zn(OH)^+ ions from the surface of the coating into the water by diffusion is the rate-determining factor.

It has, furthermore, been demonstrated by electrochemical measurements that, in agreement with the investigations according to [43], it is not possible to calculate

the corrosion rate using the Stern-Geary equation with the aid of the polarisation resistance. To investigate the removal of Zn(OH)^+ , which determines the corrosion rate, small amounts of ZnCl_2 solution were added to tap water and the material consumption rate (zinc removal rate) was determined on rotating disks [44]. The result shown in Figure 11 confirms the opinion that the material consumption rate is determined by the content of Zn^{2+} ions in the water.

The degradation of zinc coatings in hot-dip galvanised 3/4" steel pipes at a constant flow rate of 1.4 m/min was monitored in tap water with the aid of metallographic microsection studies [43]. According to these, the pure zinc layer had the task of allowing transition to a pit-free, long-acting, protective layer.

As already indicated in [43], aging of the surface coatings occurs as the test duration increases, this being associated with a decrease in the corrosion rate which is not detected in short-term studies.

Measurable variable	Units	Water no.					
		5	6	7	8	9	10 ¹⁾
Temperature	K (°C)	282 (9)	287 (14)	283 (10)	285 (12)	286 (13)	289 (16)
pH		6.90	6.50	6.91	7.38	7.17	6.82
m value	mmol/l	1.6	2.4	6.0	3.4	4.4	1.6
p value	mmol/l	-0.48	-1.2	-1.0	-0.14	-0.48	-0.48
Total hardness	mmol/l	1.40	2.65	4.3	2.85	3.15	1.5
Calcium	mmol/l	1.20	2.05	4.0	2.55	2.6	1.1
Sulphate	mmol/l	0.55	1.25	1.45	1.15	3.35	1.15
Chloride	mmol/l	0.90	5.4	1.5	0.79	2.5	1.7
Nitrate	mmol/l	0.18	0.18	0.02	0.01	0.29	0.29
Oxygen	mg/l	4.8	6.2	10.8	8.5	3.0	3.9

1) The water contains 3.6 mg/l phosphate (P_2O_5), 10 % being polyphosphate

Table 23: Test water analyses used in the investigation of the corrosion behaviour of zinc-coated steel pipes in cold water [42]

By means of the long-term studies described in [45], it was possible to describe the nature, build-up and time course of the corrosion-protecting action of surface coatings in more detail. Long-term studies lasting 18 and 28 months were carried out on 1/2" steel pipes hot-dip galvanised to comply with the standard in Berlin tap water (Table 24) using the test parameters described in Table 25.

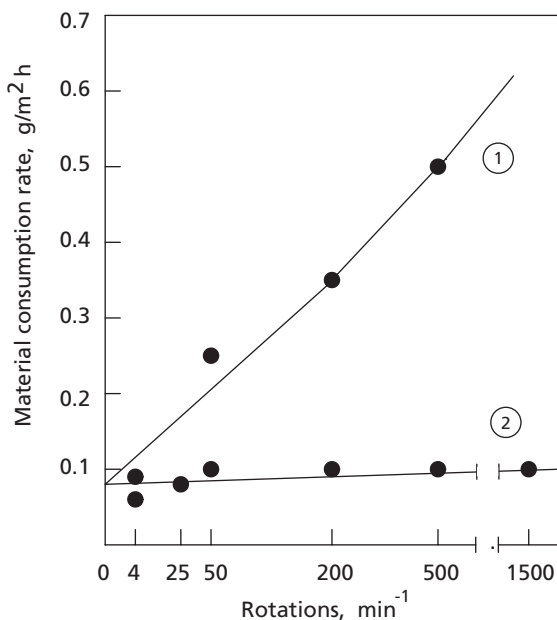


Figure 11: Material consumption rate of hot-dip galvanised disks as a function of the rotational velocity and the zinc content of the water (tap water, pH approx. 7.1) [44]

Zn²⁺ content <0.05 mg/l, pH 7.10-7.20

Zn²⁺ content 25-26 mg/l, pH 7.05-7.15

From the abundance of experimental results, the pH dependence of the corrosion behaviour of hot-dip galvanised steel pipes also found in all other studies will be discussed first using the example of the time-dependence of the material consumption per unit area shown in Figures 12 and 13. While the weight loss tends to rise significantly initially, but then to a lesser degree at pH 7 and 2 mg/l O₂, it increases linearly with respect to time at pH 6.9 and 0.5 mg/l O₂. The integral material consumption rate depends on the flow rate. However, this dependence becomes negligibly low over a prolonged test duration (see Figure 14). According to Figure 15, the pH dependence of the integral material consumption rate also decreases with respect to time, but is still distinctly pronounced after 18 months. It also decreases with time largely independently of the O₂ content (Figure 16). Metallographic studies have shown a virtually complete removal of the entire zinc layer after only 13 months in acidified water (pH 6.9). In the other types of water, the iron/zinc alloy phase was retained in a uniform layer even after 28 months. The Zn, Fe and Ca contents of the surface layers shown in Table 27 indicate that the primary layers firmly adhering on the metal side consist of zinc corrosion products. The loose secondary layers which form on the water side on or from the primary layers have zinc contents which decrease and iron and calcium contents which increase with respect to time.

<i>Measurable variable</i>	<i>Measured value</i>	<i>Units</i>
pH of sample (284.4–286 K (11.4 – 13 °C))	7.35 to 7.45	
Electrical conductivity at 293 K (20 °C)	53.2 to 55.0	mS/m
Acid capacity, pH 8.2	–0.36 to 0.21	mol/m ³
Acid capacity, pH 4.3	3.67 to 3.74	mol/m ³
Total alkaline earths	2.43 to 2.90	mol/m ³
Calcium (Ca ²⁺)	2.20 to 2.51	mol/m ³
Magnesium (Mg ²⁺)	0.23 to 0.39	mol/m ³
Chloride	1.03 to 1.20	mol/ m ³
Sulphate	0.94 to 0.97	mol/m ³
Nitrate	0.03 to 0.096	mol/m ³
Total silicon	approx. 350	mmol/m ³

Table 24: Data obtained from Berlin tap water during the test period [45]

<i>No.</i>	<i>x</i>	<i>y</i>	<i>z</i>
	<i>pH</i>	<i>Oxygen content</i>	<i>Flow rate</i>
		<i>mg/l</i>	<i>m/s</i>
1	7.9	8	0.3
2	7.4	2	0.1
3	6.9	0.5	0.03

Table 25: Test conditions [45]

Overall, it can be demonstrated from the experimental results that zinc layers are degraded too rapidly in acidic water with a low oxygen content, so that local corrosive attack with the consequence of premature rupture of the pipe wall occurs. In Berlin water, carbonation of the zinc hydroxide layer and incorporation of compounds of calcium, silicon and phosphate take place, surface layers which provide good protection being formed in the long term. The experiments with non-galvanised steel in Duisburg tap water already described [17] gave the results shown in Figure 3 with varying pH, O₂ content and flow rate.

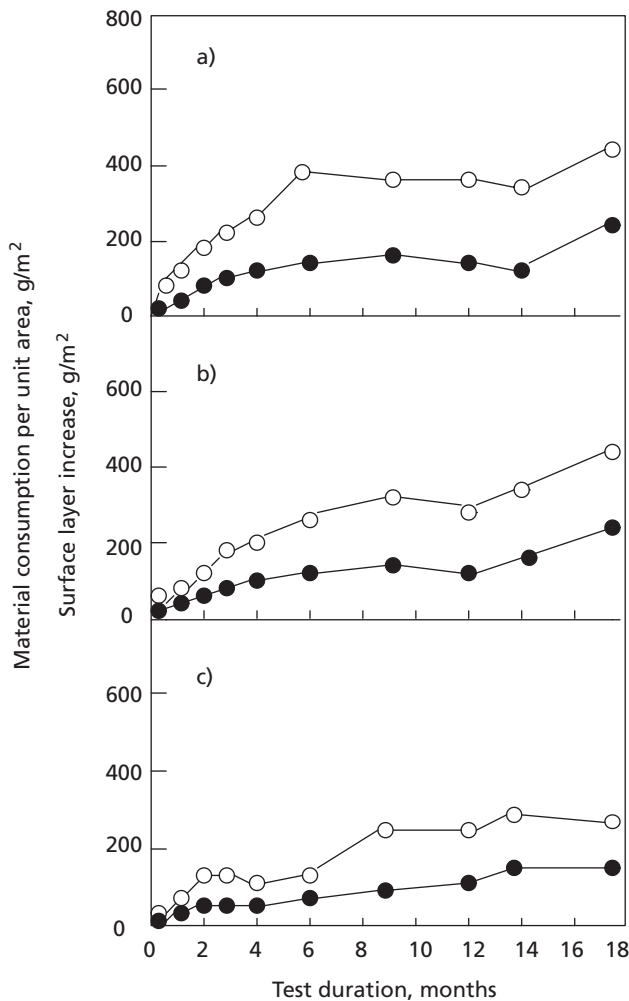


Figure 12: Material consumption per unit area (○) and surface layer increase (●) on zinc-coated steel pipes in Berlin tap water (pH 7.9, 2 mg/l oxygen) as a function of the test duration and the flow rate a) 0.3, b) 0.1 and c) 0.03 m/s [45]

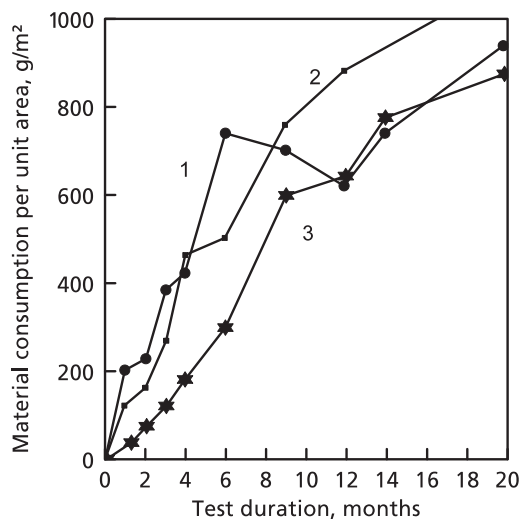


Figure 13: Material consumption per unit area as a function of the test duration with various flow rates, pH 6.9, oxygen content 0.5 mg/l [45]

① 0.3 m/s

② 0.1 m/s

③ 0.03 m/s

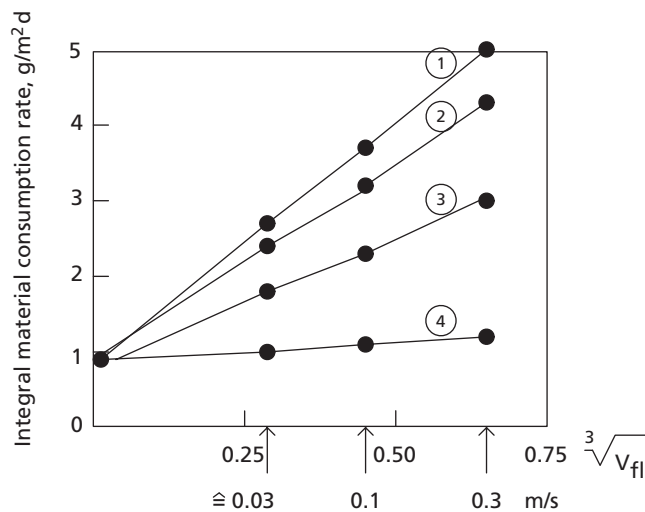


Figure 14: Integral material consumption rate as a function of $\sqrt[3]{V_{fl}}$ after different test durations, pH 7.4, oxygen content 2 mg/l at various flow rates [45]

① 0.5 months

② 2 months

③ 6 months

④ 18 months

Field tests on hot-dip galvanised steel pipes and pipe connections lasting five years are described in [46]. The data on the nature of the materials, the test duration and the operating conditions are summarised in Table 28.

The water parameters are the same as those already described in Table 26. The dependence of the homogeneity of surface layers on the water quality could be seen from metallographic studies. Water samples having relatively large neutral salt contents gave significantly less homogeneous surface layers in pipes through which the water flowed intermittently. The experimental results for smooth lengths of pipes have been assessed in [47], the evaluation being based on the material consumption per unit area $m_1(100 \text{ d})$, $m_1(1000 \text{ d extrapolated})$, $m_2(1000 \text{ d})$ and $= (m_1(1000 \text{ d}) - m_2(1000 \text{ d}))$. Hot-dip galvanised steel pipes can be classified into three groups according to Figure 17:

- Group 1: $m_1(100 \text{ d}) > 300 \text{ g/m}^2$ and $d) < 100 \text{ g/m}^2$. No protective surface layers are formed, e.g. water sample 05 according to Table 26, severe risk of corrosion.
- Group 2: $m_1(100 \text{ d}) > 100 \text{ g/m}^2$; $d)$ increases linearly with $m_1(100 \text{ d})$. As the removal of zinc increases, surface layers rich in iron oxide are formed initially, turning into protective layers of rust; e.g. water samples 01, 03, 04, 08, 10 and 11, local corrosive attack cannot be excluded in water which is often stationary [41].
- Group 3: $m_1(100 \text{ d}) \leq 100 \text{ g/m}^2$ and $d) < 100 \text{ g/m}^2$. After 5 years, metallic zinc is still present on the pipes, good corrosion resistance; e.g. water sample 02 (pH increased by NaOH metering to pH 8), no influence on the reduction in the humic acid content in water samples 06 and 07; water sample 09 has a high pH of 9.2.

Characteristics/ contents		Water samples										
		01	02	03	04	05	06	07	08	09	10	11
pH		7.2	8.0	6.9	6.9		7.8	7.0	9.2	7.2	7.4	
AC (pH 4.3)		4.5	2.5	2.0	6.4		1.7	5.2	0.6	5.6	3.7	
AC (pH 8.2)		0.76	0.06	0.57	1.5		0.05	0.95	0.05	0.82	0.27	
Con- ductivity (293 K (20 °C))	mS/m	97	43	39	99		60	127	19	58	69	
Ca ²⁺	mol/m ³	3.2	1.3		4.5		2.3	4.1	0.44	2.6	2.3	

3 → 2 NaOH dosing up to the saturation index SI = 0

5 → 4 polyphosphate dosing

6 → 7 reduction in the humic acid content

Table 26: Water analyses carried out on samples in the field tests (AC = Acid capacity) [48]

Table 26: Continued

Characteristics/ contents		Water samples										
		01	02	03	04	05	06	07	08	09	10	11
Mg ²⁺	mol/m ³	0.66	0.26		0.30		0.21	1.9	0.16	0.1	0.4	
Na ⁺	mol/m ³	27	1.8	1.2	1.2		1.2	3.5	0.35	1.2	1.7	
NO ₃ [−]	mol/m ³	0.36	0.21		0.06		< 0.03	0.18	0.08	0.02	0.04	
Cl [−]	mol/m ³	3.3	1.3		1.6		1.7	5.7	0.1	0.65	1.8	
SO ₄ ^{2−}	mol/m ³	1.1	0.5		1.4		1.6	2.2	0.34	0.25	0.7	
P _{total}	mmol/ m ³	5.0	4.0		36	3	< 0.7	0.8	0.4	16	0.5	
Organic C	g/m ³	0.6	1		2.0		7.1	4.0	2.1	1.5		2.5
O ₂	g/m ³	4	5		10		10	10	10	10	6	

3 → 2 NaOH dosing up to the saturation index SI = 0

5 → 4 polyphosphate dosing

6 → 7 reduction in the humic acid content

Table 26: Water analyses carried out on samples in the field tests (AC = Acid capacity) [48]

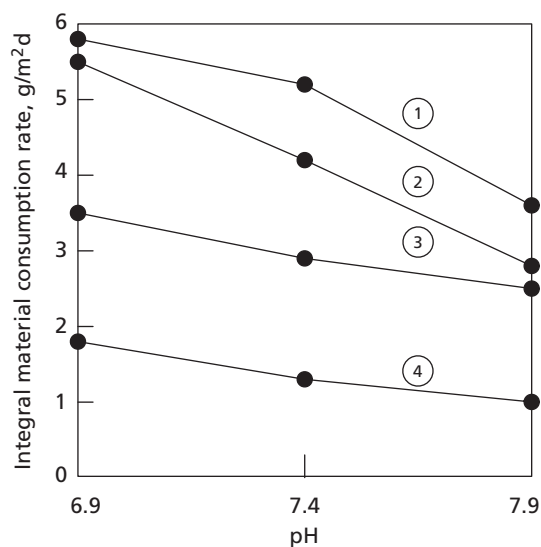


Figure 15: Integral material consumption rate as a function of the pH after various test durations, oxygen content 8 mg/l, flow rate 0.3 m/s [45]

① 0.5 months

② 2 months

③ 6 months

④ 18 months

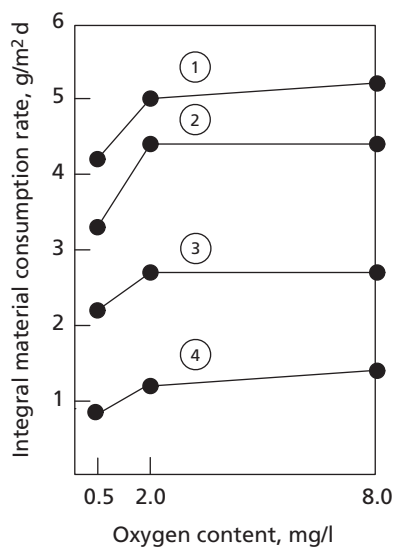


Figure 16: Integral material consumption rate as a function of the oxygen content after various test durations, pH 7.4, flow rate 0.3 m/s [45]

- ① 0.5 months
- ② 2 months
- ③ 6 months
- ④ 18 months

Unit	Layer	Zn content, %				Fe content, %				Ca content, %			
		4	9	13	28	4	9	13	28	4	9	13	28
122	primary layer	59	58	61	54	1	1	1.5	5	0.3	0.5	0.7	1.2
	secondary layer	36	19	25	8	2.5	7	9	17	9	20	13	21
222	primary layer	–	58	57	56	–	0.9	1	4	–	0.2	0.2	0.3
	total layer	59	–	–	–	1.5	–	–	–	0.2	–	–	–
	secondary layer	–	38	44	37	–	4.0	4	10	–	0.9	1.6	0.9
322	primary layer	54	70	60	–	1	5	6	–	0.1	0.2	0.3	–
	total layer	–	–	–	9	–	–	–	39	–	–	–	1.0
	secondary layer	43	38	39	–	3	9	7	–	0.7	1.1	1.0	–
332	total layer	(72)*	12	4.5	1.9	(11)*	25	37	41	(0.1)*	0.9	1.1	0.9

* metallic Fe/Zn particles

Table 27: Time dependence of Zn, Fe and Ca contents (%) in various surface layers [45]

Steel pipes:	Welded, stretch-reduced ND 20					
	Chemical composition, %					
	C	Si	Mn	P	S	Al
	0.1	0.03	0.50	0.03	0.02	0.01
Hot-dip galvanising:	a) According to DIN EN 10240, 586 g/m ² , 81 zinc layer					
	Chemical composition, %					
	Al	Pb	Cd	Cu	Sn	
	0.04	0.55	0.057	0.024	0.059	
	b) According to Group B, DIN EN 12502-3, 200 zinc-iron alloy phase					
	c) According to Group C, DIN EN 12502-3, blown out with pressurised air, 1130 g/m ² , 157					
Operating conditions:	a) Constant flow, 0.5 m/s					
	b) Intermittent operation					
	– downtime 12 h					
	– 12 h, 12'' per h flow					
Test duration:	4.5 to 5.5 years					

*test duration in d

Table 28: Test conditions [46]

Overall, a clear dependence of the corrosion rate on the carbonic acid concentration ($K_{B8.2}$) was found in these experiments:

- Group 1: $K_{B8.2} = 1.5$ without polyphosphate addition
- Group 2: $K_{B8.2} = 0.27$ to 1.5, water sample 04 demonstrates the favourable influence of the polyphosphate addition
- Group 3: $K_{B8.2} = 0.05$ to 0.06

It should also be noted that no influence of the neutral salt content was found in these experiments.

The marked influence of the CO_2 concentration can also be seen from experiments with galvanised steel pipes carried out under the experimental conditions described in [22]. The results of these experiments reveal, in addition to group 2 with $K_{B8.2} = 0.93$, the significant risk of corrosion in soft water containing carbonic acid ($K_{A4.3} = 0.48$). The water samples in group 3 ($K_{B8.2} = 0.05$ and 0.14) are formed by the deacidification measures described.

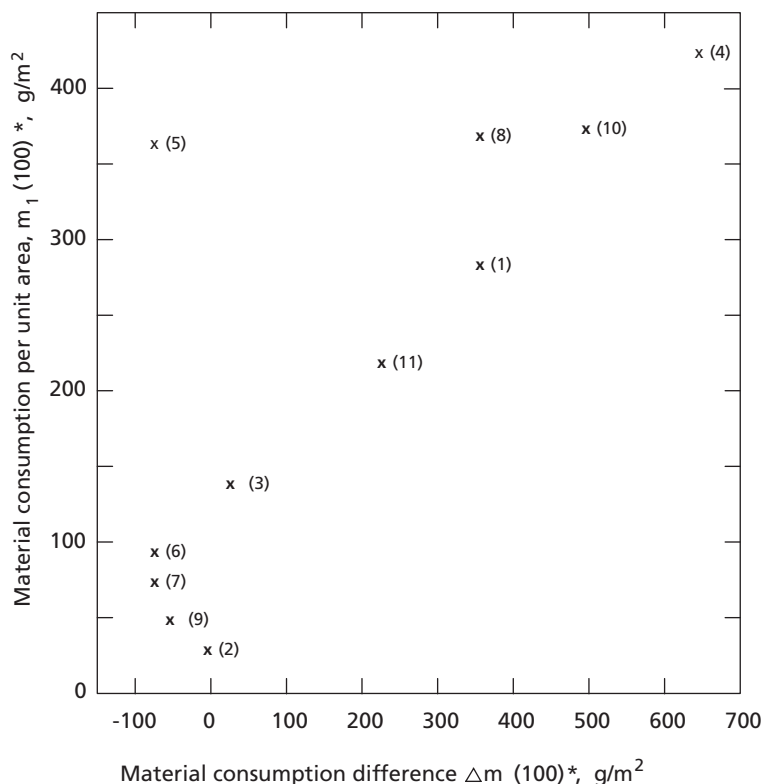


Figure 17: Relationship between the material consumption per unit area $m_1(100)^*$ and the material consumption difference = $(m_1(1000)^* - m_2(1000)^*)$ – the figures correspond to the water according to [47]

The evaluation [49] of the experiments [45] according to the data in [47] showed substantial agreement with the results of the experiments [47] for a test duration of 18 months.

Investigation of the long-term behaviour in the experiments described in [45] was continued on 9 specimens for up to 10 years [49, 50]. The oxygen content was kept constant at 6 to 8 g/m³ and the pH and flow rate were varied. The clear dependence of the material consumption per unit area at a flow rate of 0.3 m/s is shown in Figure 18.

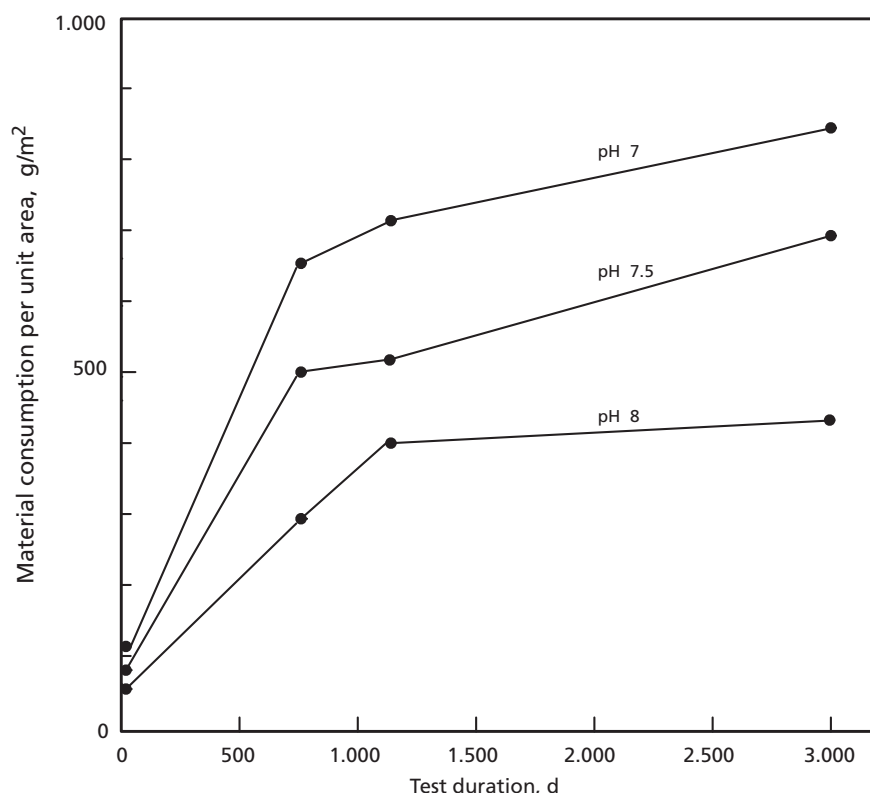


Figure 18: Relationship between the material consumption per unit area of hot-dip galvanised steel pipes in flowing water and the test duration (oxygen content 8 mg/l, flow rate 0.3 m/s) at various water pHs [49]

The influence of the pH and flow rate can be seen by comparing the residual zinc layers after 2.5 and 10 years with the aid of micrographs (see Figure 19). At pH 7.5 and 8.0 and flow rates of 0.1 and 0.3 m/s, residual zinc layers 25 to 40 μm thick are present even after 10 years, while after 10 years at pH 7.5 and a flow rate of 0.3 m/s, the residual zinc layer still present after 2.5 years has been removed completely. At a low pH (7.0) and a low flow rate (0.03 m/s), a zinc layer is no longer present after 2.5 years; but the corrosive attack on the steel progressed further for up to 10 years. Microprobe studies show the increasing incorporation on the water side of compounds due to the calcium, silicon (silicate) and phosphorus (phosphate) contents of the water. The finding that the surface layers provide a protective action under the experimental conditions described only as long as zinc is present is important. If zinc is no longer present, rust spots are formed and wide pitting corrosion occurs.

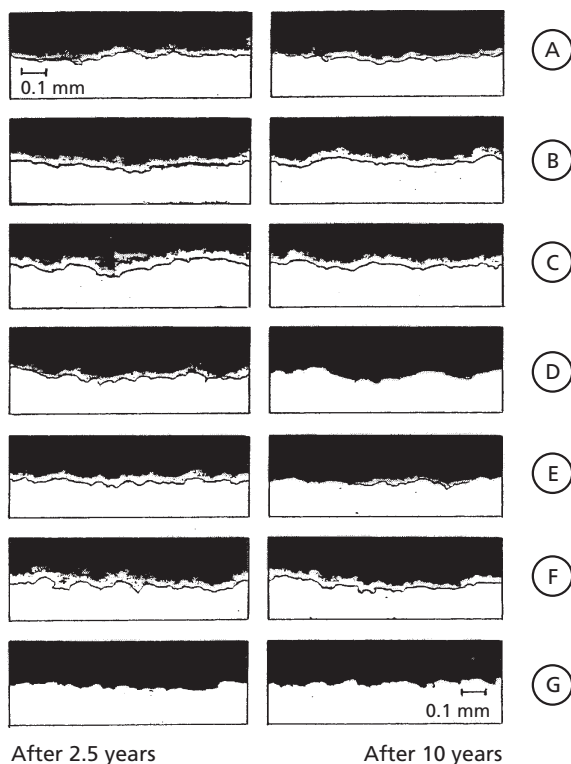


Figure 19: Comparison of the residual zinc layer on zinc-coated pipes after different service times in various waters [50]

- A) pH 8, oxygen content 6–8 g/m³, flow rate 0.3 m/s
- B) as A) but 0.1 m/s
- C) as A) but 0.03 m/s
- D) as A) but 0.1 m/s
- E) as D) but 0.1 m/s
- F) as D) but 0.03 m/s
- G) pH 7, oxygen content 6–8 g/m³, flow rate 0.3 m/s

The diagram in Figure 20 reflects the material consumption/time relationship with the original zinc layer. Curve ① applies to an increased pH and low flow rate; it indicates residual layers of zinc after 10 years. At a low pH and higher flow rate, the zinc layer has been removed after about 2 years and corrosive attack starts on the steel (Curve ②). While Curves ① and ② apply to an initial oxygen content of 6 to 8 mg/l, Curve ③ is typical of pH 7.0 and $c(\text{O}_2)$ of 0.5 mg/l. Mathematical analysis of the material consumption/time curves plotted showed a good fit on these curves when the logarithmic function

$$(m/g \times m^{-2}) = (a/g \times m^{-2}) \ln ((b/a^{-1})(t/a) + 1))$$

was taken as the basis. The exponential function chosen in previous publications

$$(m/g \times m^{-2}) = (a/g \times m^{-2} \times a^{-1})(t/a)^b$$

does not lead – as Figure 21 shows – to a description of the actual relationships. Some characteristic values of the logarithmic function are summarised in Table 29 [50].

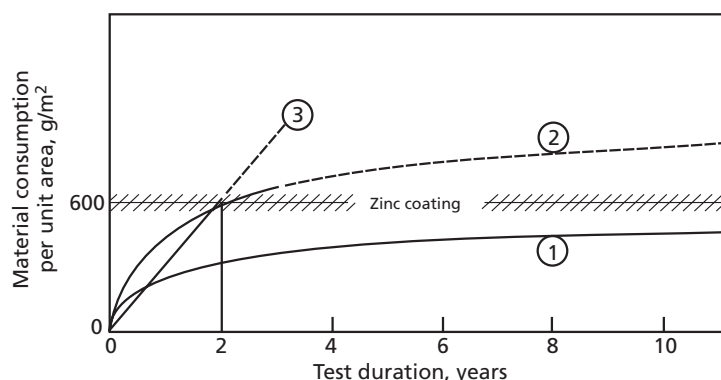


Figure 20: Typical material consumption per unit area curves for zinc in tap water in relation to the original zinc layer as a function of time [50]

- ① increased pH and low flow rate
- ② low pH and high flow rate
- ③ low pH and low oxygen content

Test conditions	$a/m^{-2} a^{-1}$	b/a^{-1}
pH 8.0 $O_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	103.7	0.0267
pH 7.5 $O_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	155.0	0.0303
pH 7.0 $O_2 = 6 - 8 \text{ mg/l}$ $v = 0.3 \text{ m/s}$	180.3	0.0382

Table 29: Characteristic values of the logarithmic function [50]

When evaluating the results of field and laboratory studies, it should be remembered that a higher water throughput has been used in these – in comparison with conditions in domestic installations. However, a higher water throughput causes higher corrosion rates in domestic installations than a lower throughput.

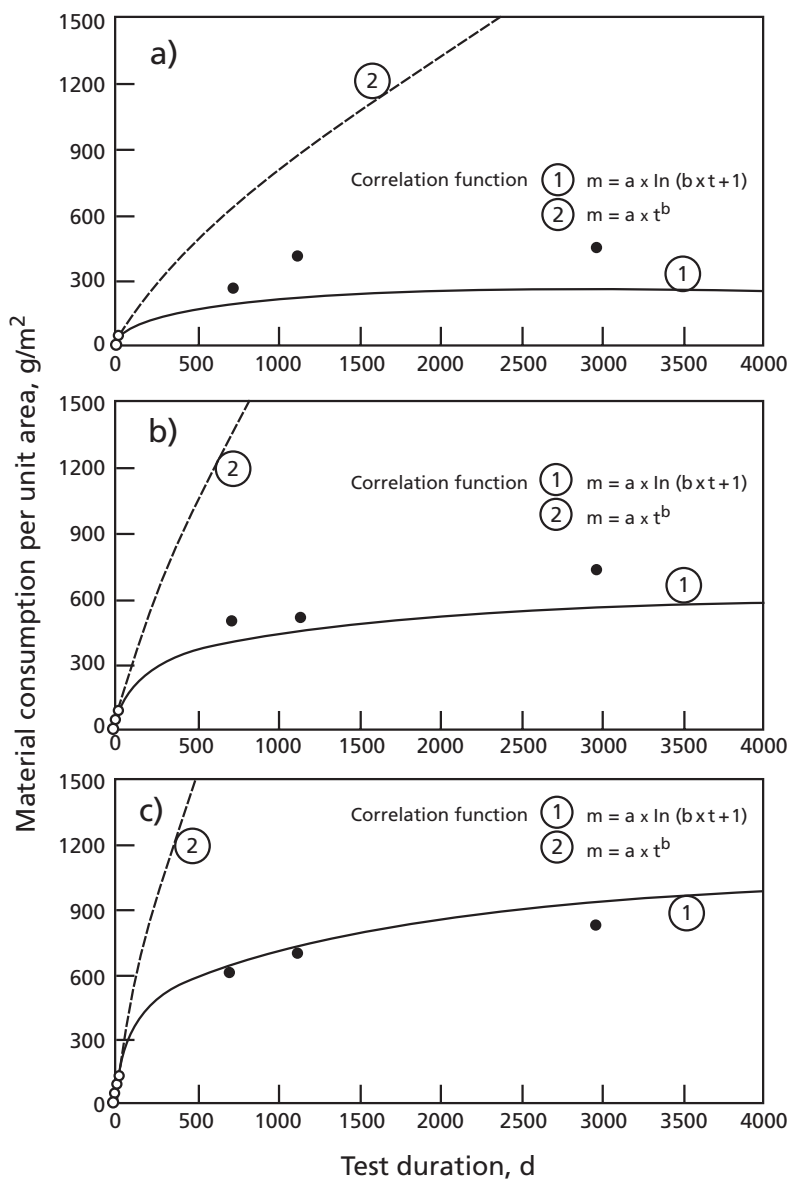


Figure 21: Correlation functions ① and ② at different tap water pHs (oxygen content 6–8 g/m^3 , flow rate 0.3 m/s) with regard only to short-term values ($t_{\text{max}} = 28$ d) [50]

- a) pH 8
- b) pH 7.5
- c) pH 7

Experiments were carried out for 2.5 years under the conditions listed in Table 30 to study the influence of the nitrate content in drinking water [51]. A good surface layer was formed in pipes with galvanising which complies with the standard according to DIN EN 10240, regardless of the nitrate content. Selective corrosion in the form of zinc tricklings was found in water with a high nitrate content of 1.26 mol/m^3 in pipes blown out with air, corresponding to group A, and in pipes with an intergrown FeZn alloy layer, group B, according to [41]. Severe corrosive attack occurred in pipes from group B in the same water.

The occurrence of white rust in pipes from group A was detected in a study lasting 9 years, while this was not the case in pipes galvanised according to the standard [52].

Steel pipes:	ND 20 according to DIN EN 10240
Hot-dip galvanising:	a) according to DIN EN 10240 b) according to Group B, DIN 12502-3 c) according to Group C, DIN 12502-3
Operating conditions:	a) constant flow 0.5 and 1.5 m/s b) intermittent flow 120 min/d throughput 0.25 m/s
Test duration:	2.5 years

Table 30: Test conditions according to [51]

In the experiments already described [14], the pH dependence found elsewhere, that is to say the decrease in removal of zinc as the pH rises, was also confirmed – as Figure 22 shows.

It can be seen from Figure 23 that under the given experimental conditions, the iron corrosion which starts after removal of the zinc layer results in the same iron contents in the surface layers as in the experiments with unalloyed steel pipes.

No clear adverse influence of ozone and chlorine treatment was found in experiments in water from Lake Constance (Table 31) over a test duration of five and a half years [53]. According to Figure 24, the material consumption rate of the zinc layer per unit area averaged for the period between 500 and 2000 days is about $0.1 \text{ g/m}^2 \text{ d}$.

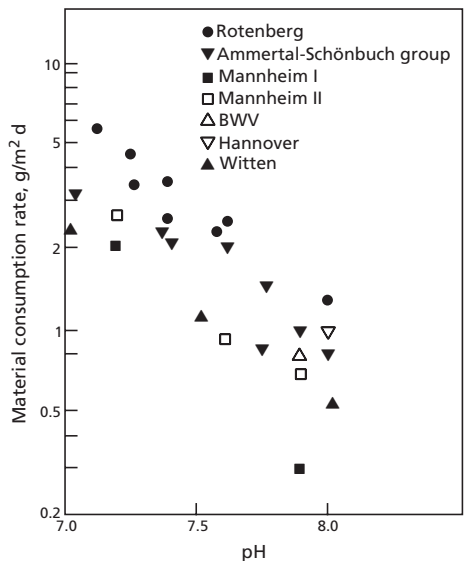


Figure 22: Influence of pH on the material consumption rate of zinc in 26 different water qualities (flow rate 0.5 m/s) [14]

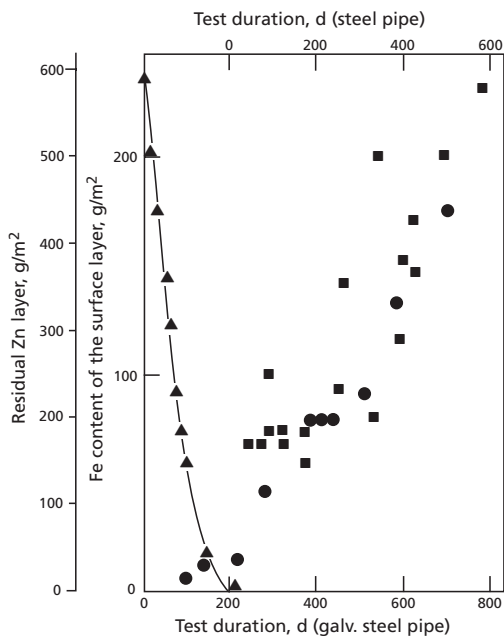


Figure 23: Comparison of the iron content in the surface layer of steel pipes after removal of the zinc layer (pH 7.2, flow rate 1.5 m/s) [14]
 ▲ residual zinc layer; ● iron content in the surface layer of the zinc-coated steel pipes; ■ iron content in the surface layer of the unalloyed steel pipes (2 test lines)

Measured value	Units
pH	7.8–8.0
m value	2.5 mol/m ³
Ca ²⁺	1.1 mol/m ³
Cl [−]	0.13 mol/m ³
SO ₄ ^{2−}	0.3 mol/m ³
PO ₄ ^{3−}	3–3.5 × 10 ^{−3} mol/m ³
org. C	1.1–1.3 mg/l

Table 31: Partial analysis of Lake Constance water – Sipplingen waterworks [53]

The reduction in corrosive attack by increasing the pH found in all the experiments is confirmed by studies in Switzerland [54]. By increasing the pH of Zürich lakewater by only 0.3 units (Table 32), a large reduction could be achieved in the material consumption per unit area (Figure 25). In Dübendorf groundwater (Table 32), the material consumption is higher – because of the noticeably lower pH of 7.1 compared with Zürich lakewater – and increases sharply with time (Figure 26).

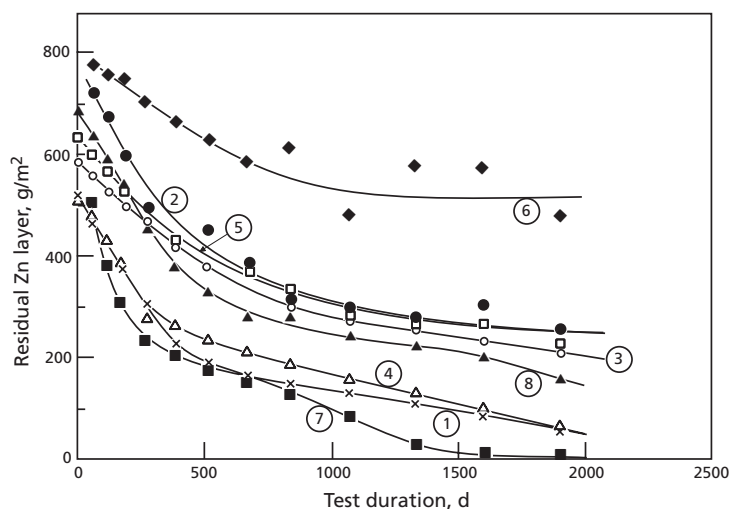


Figure 24: Material consumption rate per unit area of the residual zinc layer as a function of time during different water treatment steps using Lake Constance water and under various flow conditions [53]

- ① untreated water 1.5 m/s
- ② untreated water 0.5 m/s
- ③ untreated water 0.5 m/s intermittent
- ④ untreated water, ozonised 1.5 m/s
- ⑤ untreated water, ozonised 0.5 m/s
- ⑥ untreated water, ozonised 0.5 m/s intermittent
- ⑦ untreated water, ozonised and chlorinated 1.5 m/s
- ⑧ untreated water, ozonised and chlorinated 0.5 m/s

The corrosion behaviour of pipe connections in cold drinking water was also investigated in the field tests according to [46]. Table 33 provides information on the corrosive attack found with the aid of rating figures. Non-galvanised threads of malleable cast iron fittings are severely attacked in comparison with galvanised threads. Pronounced contact corrosion occurred on the non-ferrous metal fittings because of the relatively large non-ferrous metal cathodes. No noticeable contact corrosion was found on the hard solder connections because of the small area of the cathodes.

Measurable variables	Dübendorf groundwater pH 7.1		Zürich lakewater pH 8.0	
	mol/m ³	mg/l	mol/m ³	mg/l
Acid capacity (K _A 4.3)	5.7	–	2.62	–
Calcium (Ca ²⁺)	2.9	116	1.33	53
Sulphate (SO ₄ ²⁻ *)	0.92	44	0.313	15
Chloride (Cl ⁻)	0.76	27	0.127	4.5
Nitrate (NO ₃ ⁻)	0.32	20	0.054	3.3

*) value refers to half the molecular weight

Table 32: Water analyses according to [54]

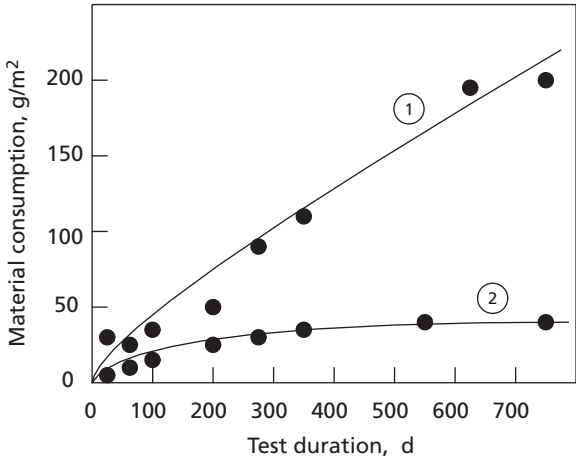


Figure 25: Internal corrosion on zinc-coated steel pipes. Influence of the pH [54]

① Zürich lakewater, untreated, pH 7.7

② Zürich lakewater, treated, pH 8.0

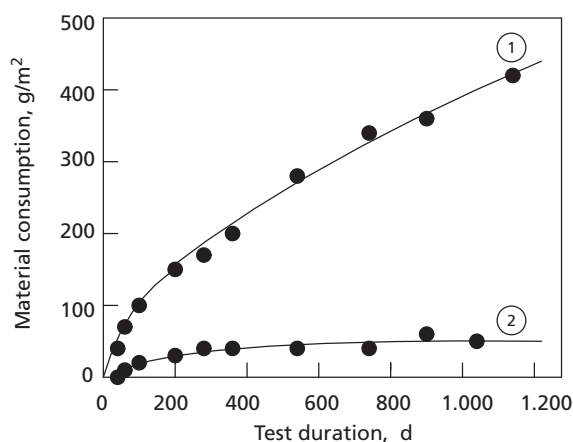


Figure 26: Internal corrosion on zinc-coated steel pipes. Influence of the water quality [54]

① Dübendorf groundwater

② Zürich lakewater

Water sample no.	Malleable cast iron fittings				Non-ferrous fittings		Hard solder connection	
	Non-galvanised threads		Galvanised threads		Inter-mittent	Flowing	Inter-mittent	Flowing
	Inter-mittent	Flowing	Inter-mittent	Flowing				
1	4	5	2	2	4	6	3	4
2	4	2	1	1	4	4	1	1
3	4	4	2	2	6	6	4	5
4	5	5	5	4	5	4	4	4
5	6	6	6	4	6	6	5	5
6	4	4	2	2	2	3	2	4
7	3	4	2	2	3	5	2	3
8	5	4	3	3	6	6	3	4
9	5	4	3	3	6	6	3	4
10	5	4	2	3	5	5	3	4
11	4	5	2	4	4	6	3	4

The figures have the following significance:

1 uniform surface layer, grey

2 uniform surface layer, brown

3 non-uniform surface layer, white/grey

4 non-uniform surface layer, brown

5 pronounced local corrosion, countless tiny rust spots

6 pronounced local corrosion, fewer but larger rust spots

Table 33: Evaluation of the corrosion on fittings in different waters [46]

The increased occurrence of corrosion damage to hot-dip galvanised steel pipes in heated drinking water (hot water) in mixed installations had already been attributed early on to the influence of copper ions.

Experiments were carried out in Berlin tap water (Table 34) with various pHs and copper ions of various origins to study the laws which apply [55].

Table 35 contains the test conditions. It can be seen from the corrosion results summarised in Table 36 that shallow pitting corrosion occurs already in water of pH 7.4 at a copper ion content of 0.1 mg/l. This form of corrosion also occurs in acidified water of pH 6.5 without copper ions; but is significantly increased by the latter, and is also found in the vertically arranged pipes. Copper ions only influence shallow pitting corrosion if the zinc layer has been removed locally and the steel surface is exposed. Typical points of local attack were found at the three-phase boundary of air/pipe surface/water. According to the experimental results, as long as no steel surfaces are exposed, copper which has been deposited, e.g. on new hot-dip galvanised surfaces, cannot induce local corrosion. However, if copper ions are constantly arriving at the inner surfaces of the pipes, pitting corrosion is induced.

<i>Measurable variables</i>	<i>Measured value</i>	<i>Units</i>
Sampling temperature	284.4 – 287.6 (11.4 – 14.6)	K (°C)
pH, electrometric	7.35 – 7.45	
Electrical conductivity at 293 K (20 °C)	530 – 610	
m value	3.53 – 3.74	mmol/l
p value	–0.22 to –0.3	mmol/l
Calcium (Ca ²⁺)	88.2 – 101	mg/l
Magnesium (Mg ²⁺)	5.73 – 9.47	mg/l
Sulphate (SO ₄ ²⁻)	68.3 – 115.5	mg/l
Chloride (Cl ⁻)	27.4 – 52.5	mg/l
Nitrate (NO ₃ ⁻)	< 2	mg/l
Iron (Fe ²⁺)	< 0.05	mg/l
Manganese (Mn ²⁺)	n.d.	
Copper (Cu ²⁺)	< 0.05	mg/l
Zinc (Zn ²⁺)	< 0.05	mg/l
Silicic acid as SiO ₂	15 – 20	mg/l
Phosphate	n.d.	

n.d. not detectable

Table 34: Fluctuation in measured values from Berlin tap water in a period of two years [55]

In [56], microprobe studies on the distribution of the elements in the surface layers of the pipes in the experiments [55] demonstrated areas of chloride and sulphate concentration at the metal/surface layer phase boundary. This gives the surface layers semi-conductor properties, leading to partial separation of regions at which anodic and cathodic part reactions proceed. As the concentration of copper ions increases, the cathodic part current is increased, so that pitting corrosion is intensified at the anodic regions.

Unit no.	Test conditions
Unit 1:	tap water, pH 7.35 to 7.45 (measured at sampling temperature)
Unit 2:	tap water, pH 7.35 to 7.45. In the flask 20 sheets of CuNi20Fe–F30 with a total surface area of 2000 cm ² were placed. Dimensions of a single sheet 50 × 100 × 1.5 mm
Unit 3:	tap water, pH 7.35 to 7.45. In the flask 20 sheets of SF–Cu (CW024A) with a total surface area of 2000 cm ² were placed. Dimensions of a single sheet 50 × 100 × 1 mm
Unit 4:	tap water, pH 7.35 to 7.45, ascending pipe at the front internally copper-plated
Unit 5:	tap water acidified with CO ₂ , pH 6.45 to 6.55
Unit 6:	tap water, pH 6.45 to 6.55, flask with 20 sheets of CuNi20Fe, total surface area = 2000 cm ²
Unit 7:	tap water, pH 6.45 to 6.55, flask with 20 sheets of SF–Cu, total surface area = 2000 cm ²
Unit 8:	tap water, pH 6.45 to 6.55, ascending pipe at the front internally copper-plated
Unit 9:	tap water, pH 6.45 to 6.55, copper concentration = 0.1 mg/l Cu ²⁺
Unit 10:	tap water, pH 6.45 to 6.55, copper concentration = 0.3 mg/l Cu ²⁺
Unit 11:	tap water, pH 7.35 to 7.45, copper concentration = 0.1 mg/l Cu ²⁺
Unit 12:	tap water, pH 7.35 to 7.45, copper concentration = 0.3 mg/l Cu ²⁺

Table 35: Test conditions used in the investigation of the corrosion resistance of hot-dip galvanised steel pipes in mixed installations [55]

Experiments in two different types of water (Table 37) at temperatures of 285 to 346 K (12 to 73 °C) under a constant water flow revealed, with the aid of rest potential measurements, the existence of a critical potential range for the occurrence of pitting [57]. By comparative studies on pure zinc and hot-dip galvanised steel pipes – as can be seen from Figures 27 and 28 – a potential shift in the noble direction was also found on pure zinc as the temperature increases, and not only on hot-dip galvanised steel pipes. The critical potential range for pitting corrosion on zinc, which depends on the water quality, lies coincidentally in the rest potential range of steel and is not to be attributed to a potential shift of zinc in the noble direction with respect to steel (potential reversal). A reduction in the potential shift in the noble direction and therefore the suppression of pitting corrosion was found, depending on the water quality, on addition of monomeric phosphates.

Unit	Operating conditions (see also Table 35)	Horizontal pipes		Vertical pipes	
		Test duration, months			
		4	9	13	13
1	tap water pH 7.4	–	–	–	–
2	pH 7.4 flowing over CuNi20Fe	–	–	–	–
3	pH 7.4 flowing over SF–Cu	–	+	+	–
4	pH 7.4 copper–plated ascending pipe	–	–	–	–
11	pH 7.4 0.1 mg/l Cu ²⁺	–	–	+	–
12	pH 7.4 0.3 mg/l Cu ²⁺	–	+	++	–
5	tap water + CO ₂ + air pH 6.5	–	+	+	+
			negligible	negligible	negligible
6	pH 6.5 flowing over CuNi20Fe	–	+	++	++
7	pH 6.5 flowing over SF–Cu	+	+	++	+
8	pH 6.5 copper–plated ascending pipe	–	+	+	+
			negligible	negligible	negligible
9	pH 6.5 0.1 mg/l Cu ²⁺	–	+	++	+
					negligible
10	pH 6.5 0.3 mg/l Cu ²⁺	–	+	++	+

– no shallow pitting corrosion

+ shallow pitting corrosion

++ extensive shallow pitting corrosion

Table 36: Corrosion behaviour of pipes under the test conditions mentioned in Table 35 [55]

Measurable variables	Dortmund	Ewersbach	Units
pH at 293 K (20 °C)	6.90	6.65	
Electrical conductivity at 293 K (20 °C)	29.0	16.0	mS/m
Base capacity up to pH 8.2 at 293 K (20 °C)	0.48	0.50	mol/m ³
Acid capacity up to pH 4.3 at 293 K (20 °C)	1.60	1.43	mol/m ³
Calcium (Ca ²⁺)	1.2	0.66	mol/m ³
Magnesium (Mg ²⁺)	0.20	0.36	mol/m ³
Sulphate (SO ₄ ²⁻)	0.55	0.22	mol/m ³
Chloride (Cl ⁻)	0.45	0.31	mol/m ³
Nitrate (NO ₃ ⁻)	0.18	0.056	mol/m ³
Oxygen (O ₂)	4.8	8.7	g/m ³

Table 37: Parameters used for test waters [57]

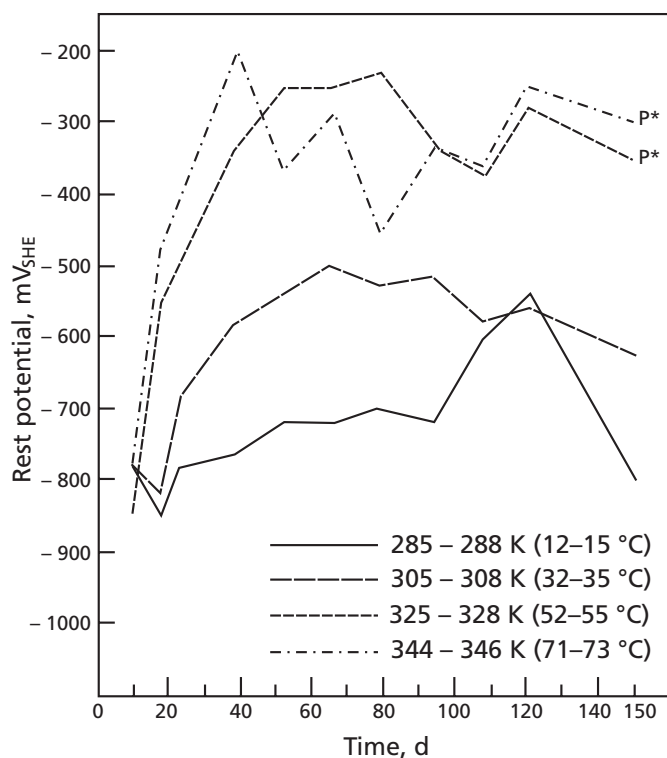


Figure 27: Rest potential/time curves for zinc in Ewersbach tap water as a function of water temperature [57]

* pitting corrosion

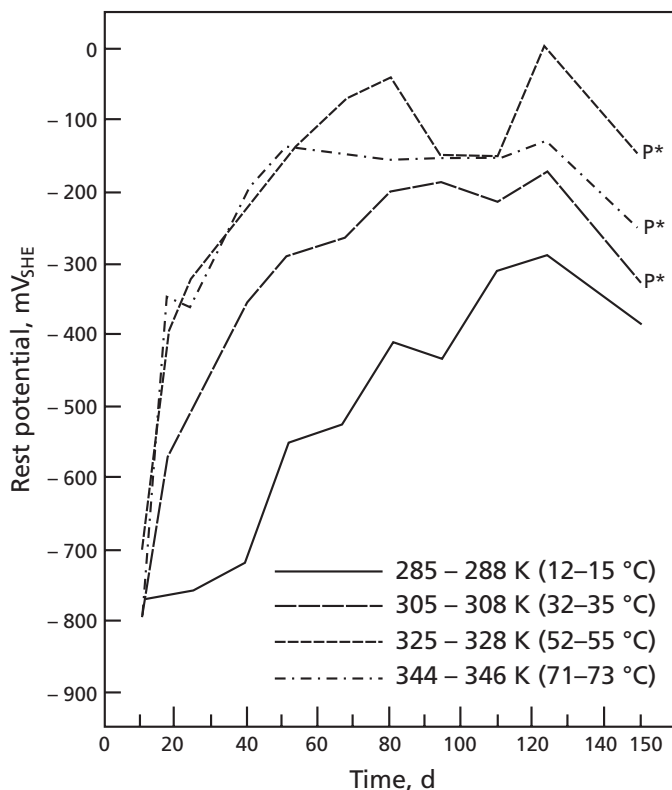


Figure 28: Rest potential/time curves for hot-dip galvanised steel in Ewersbach tap water as a function of the water temperature [57]

* pitting corrosion

Studies have been carried out in Berlin tap water (Table 38) under the experimental conditions shown in Table 39 to investigate the influence of phosphates and/or silicates on the pitting corrosion induced by copper ions [58]. X-ray scanning photographs have shown the formation of a primary layer of zinc reaction products and a secondary layer of inhibitors and calcium. The latter develops into corrosion-inhibiting protective layers in the course of time, the protective function of these being improved by inhibitors. The effectiveness of inhibition of general corrosion is given by the following sequence:

o-phosphate – silicate – silicate/phosphate – o/p-phosphate and p-phosphate. The mixture silicate/phosphate is the best as regards inhibition of local corrosive attack, while o-phosphate shows the lowest inhibition. All the other inhibitors can be classified in between. Although most of the inhibitors studied reduce the incidence of pits, the pit depth and therefore probability of damage are not substantially reduced. The inhibitor mixture silicate and phosphate prevents pitting on hot-dip galvanised steel pipes under the given experimental conditions, which can be applied to hot water circulation systems.

Measurable variables	Measured value	Units
Electrical conductivity at 293 K (20 °C)	50–62	mS/m
pH at 284 – 287 K (11 – 14 °C)	7.3–7.5	
Base capacity up to pH 8.2	0.33–0.44	mol/m ³
Acid capacity up to pH 4.3	3.9–4.0	mol/m ³
Total alkaline earths (hardness)	2.4–2.94	mol/m ³
Nitrate (NO ₃ ⁻)	0.05–0.1	mol/m ³
Chloride (Cl ⁻)	1.36–1.88	mol/m ³
Sulphate (SO ₄ ²⁻)	0.7–1.32	mol/m ³
Total phosphorus as P ₂ O ₃	< 0.2	mg/l
Total silicon as SiO ₂	18–22.2	mg/l

Table 38: Analysis of Berlin tap water in a period of two years [58]

Unit no.	Test conditions
0	tap water without additions
1	tap water flowing over copper sheet, no additions
2	tap water flowing over copper sheet + 5 mg/l P ₂ O ₅ as trisodium monophosphate ¹⁾
3	tap water flowing over copper sheet + 5 mg/l P ₂ O ₅ as trisodium monophosphate ²⁾
4	tap water flowing over copper sheet + 5 mg/l P ₂ O ₅ as sodium hexametaphosphate ³⁾
5	tap water flowing over copper sheet + 5 mg/l P ₂ O ₅ as combination of disodium monophosphate and sodium tripolyphosphate ⁴⁾
6	tap water flowing over copper sheet + 20 mg/l SiO ₂ as sodium waterglass 40/42° Bé ⁵⁾
7	tap water flowing over copper sheet + 20 mg/l SiO ₂ as sodium waterglass 58/60° Bé ⁶⁾
8	tap water flowing over copper sheet + (mg/l) 4 P ₂ O ₅ + 22 SiO ₂ as a combination of sodium waterglass and sodium tripolyphosphate ⁷⁾

All chemicals used are commercial products.

1) trisodium monophosphate, technically pure with a P₂O₅ content of 49.9 %

2) sodium tripolyphosphate, technically pure with 55.9 % P₂O₅

3) sodium hexametaphosphate (trade name) also Graham's salt, a long-chain polyphosphate with a chain length in the middle of 25 – 30 (10), P₂O₅ content 68.7 %

4) a mixture of 70 % sodium tripolyphosphate and 30 % disodium monophosphate, total P₂O₅ content = 62.5 %

5) sodium silicate with a molar ratio SiO₂: Na₂O = 3.42; D = 1.4 g/cm³, total solids content = 38.0 %

6) sodium silicate, molar ratio SiO₂: Na₂O = 2.09; D = 1.71 g/cm³, total solids content = 54.5 %

7) a mixture of 45.9 % SiO₂ as sodium silicate and 8.3 % P₂O₅ as sodium tripolyphosphate (Ferosil® 160)

Table 39: Test conditions used in the investigation of the effect of phosphates and silicates on copper ion-induced pitting corrosion on zinc-coated pipes [58]

Attempts were made under conditions close to those in practice to clarify whether modified zinc layers have a better corrosion resistance than standard galvanisation [59]. Inhibition by pure o-phosphate and a long-chain polyphosphate was also investigated. The electrolytic water treatment process proven in practice (called the electrolysis process for short) was included in the studies. The experimental conditions can be seen from Figure 29, and Table 40 contains the water analysis.

<i>Measurable variables</i>	<i>Measured value</i>	<i>Units</i>
pH	6.76	
Electrical conductivity at 293 K (20 °C)	37 ¹⁾	mS/m
Base capacity up to pH 8.2	0.43 ²⁾	mol/m ³
Acid capacity up to pH 4.3	1.75 (4.9° d)	mol/m ³
Calcium Ca ²⁺	1.45 (9.6° d)	mol/m ³
Magnesium Mg ²⁺	0.27 (9.6° d)	mol/m ³
Sodium Na ⁺	0.91 (21) ³⁾	mol/m ³
Sulphate SO ₄ ²⁻	0.55 (53) ³⁾	mol/m ³
Chloride Cl ⁻	1.16 (41) ³⁾	mol/m ³
Nitrate NO ₃ ⁻	0.35 (22) ³⁾	mol/m ³
Silicate SiO ₂	5.4	mg/l
Phosphate PO ₄ ³⁻	0.35	mg/l
Oxygen O ₂	7.4	g/m ³
KMnO ₄ consumption	5.4	mg/l

1) $\triangleq 370 \mu\text{S}/\text{cm}$

2) $\triangleq 19 \text{ mg}/\text{l CO}_2$

3) $\triangleq \text{mg}/\text{l}$

Table 40: Water analysis [59]

The best corrosion protection is achieved by the electrolysis process, as can be seen, for example, by comparing the material consumption per unit area on the five materials investigated in accordance with Figures 40 and 41. From the current density/potential curves plotted, it was found that the protective action by the electrolysis process is based on inhibition of the cathodic part reaction. This is evidently caused by incorporation of aluminium hydroxide into the surface layers which form. This has the effect of a significantly lower conductivity of the surface layer compared with the surface layers otherwise formed from zinc oxide. The studies also showed that the modified zinc layers tested, without the electrolysis method, show a distinctly poorer corrosion behaviour than standard galvanisation according to DIN EN 10240.

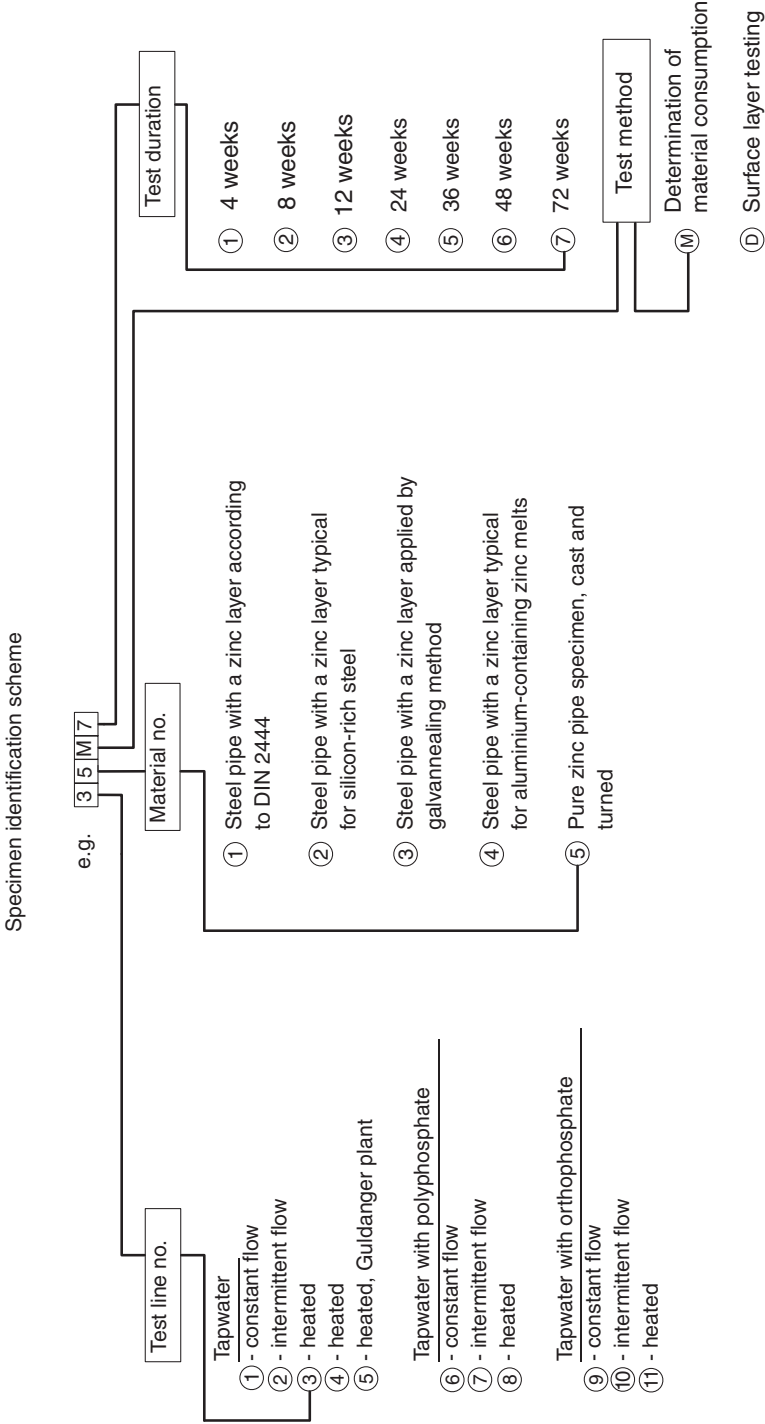


Figure 29: Specimen identification scheme and overview of the test conditions [59]

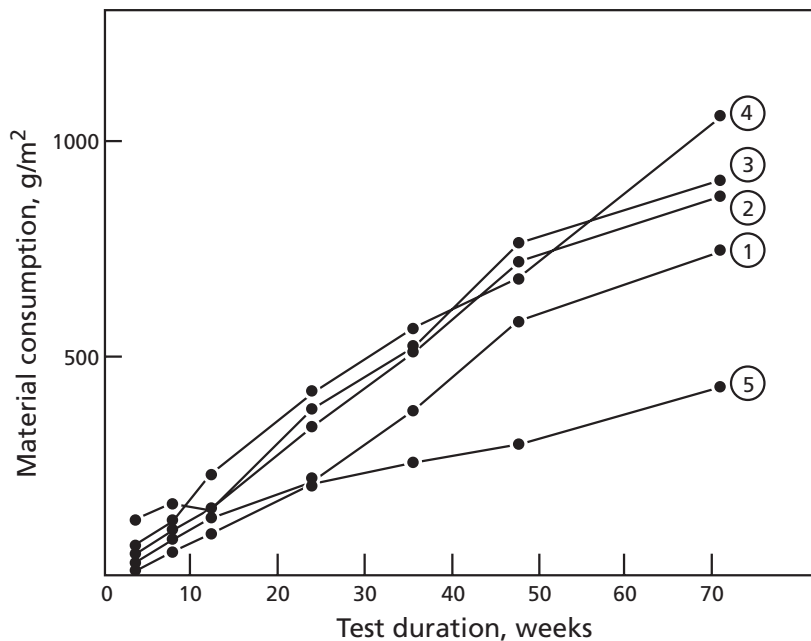


Figure 30: Material consumption in test line no. 4, see Figure 29 (Materials ①, ②, ③, ④ and ⑤ according to Figure 29) [59]

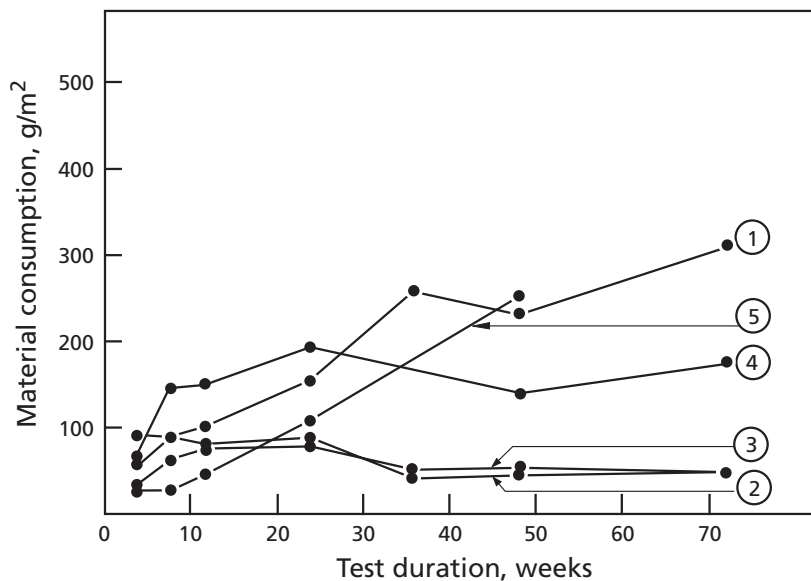


Figure 31: Material consumption in test line no. 5, see Figure 29 (Materials ①, ②, ③, ④ and ⑤ according to Figure 29) [59]

The advantageous formation of surface layers found in [59] due to the incorporation of Al_2O_3 is confirmed by the chemical composition of the protective layer shown in Table 41 [60]. On hot-dip galvanised steel pipes in particular, protective layers are formed similar to those found by investigating installed, hot-dip galvanised control lines for more than 10 years [61].

	Chemical composition, %					
	Fe_2O_3	Al_2O_3	CaO	ZnO	CO_2	SiO_2
Hot water outflow						
Scaling	52.3	17.6	4.8	0.68	4.65	2.0
Sand-blasted	54.0	21.5	2.3	1.04	2.86	2.2
Pickled	55.4	25.4	3.9	0.76	3.53	2.3
Zinc-coated	12.8	30.5	trace	43.0	6.52	3.4
Circulation						
Scaling	65.0	4.2	4.1	0.8	3.85	2.5
Sand-blasted	66.4	4.6	1.1	1.08	2.43	2.2
Pickled	67.4	3.9	3.1	0.72	2.89	2.4
Zinc-coated	23.2	20.1	trace	42.0	4.29	4.4

Table 41: Chemical composition of the protective layers [60]

Studies were carried out in cold and hot water in Denmark to investigate the influence of the quality of hot-dip galvanised steel pipes [62]. The water analysis is summarised in Table 42 and the test conditions in Table 43. The origin of the steel pipes investigated, the thickness of the zinc layer and data on the structure of the zinc layers are contained in Table 44. The result found was a tendency towards increased corrosion at low thicknesses in the absence of pure zinc. The most severe corrosion was observed on pipes from Hungary with the lowest coating thickness of 50 μm . Corrosive attack three times more severe than in cold water was found in circulating hot water or in hot water with intermittent operation.

The matter of reduction of nitrate to nitrite is discussed in respect of hygiene conditions when hot-dip galvanised steel pipes are used in domestic installations. The conditions which lead to nitrate reduction – especially in respect of the limit for nitrite of 0.1 mg/l stated in Table 1 – are discussed in [63–65]. The conditions can be described with the aid of Figure 32 as follows:

- The reduction to nitrite clearly depends on the flow conditions and the age of the hot-dip galvanised steel pipes installed.

- $c(\text{NO}_2^-) > 0.1 \text{ mg/l}$ occurs in stagnant water overnight (16 h) and over the weekend (64 h), compared with the daily average (daytime water).
- As the age of the installation increases, nitrite values lower than 0.1 mg/l are obtained even after prolonged stagnation times.

Measurable variables	Measured value	Units
pH	7.25	
Electrical conductivity	75	mS/m ³
$K_A 4.3$	5.4	mol/m ³
$c(\text{Ca}^{2+})$	3.2	mol/m ³
$c(\text{SO}_4^{2-})$	0.98	mol/m ³
$c(\text{Cl}^-)$	0.93	mol/m ³
$c(\text{NO}_3^-)$	0.10	mol/m ³
$c(\text{Na}^+)$	0.48	mol/m ³
$c(\text{Mn}^{2+})$	< 0.2	mmol/m ³
$c(\text{SiO}_2)$	0.33	mol/m ³
$c(\text{PO}_4^{3-})$	0.00	mol/m ³

Table 42: Water analysis according to [62]

	Temperature K (°C)	Operation
Cold water	298–301 (25–28)	$v = 1.2 \text{ m/s}$, constant
Hot water	338 (65)	$v = 0.3 \text{ m/s}$, circulation
Hot water	338 (65)	$v = 1.2 \text{ m/s}$, intermittent 25 l/3 h, tapping for 1 min

Table 43: Test conditions according to [62]

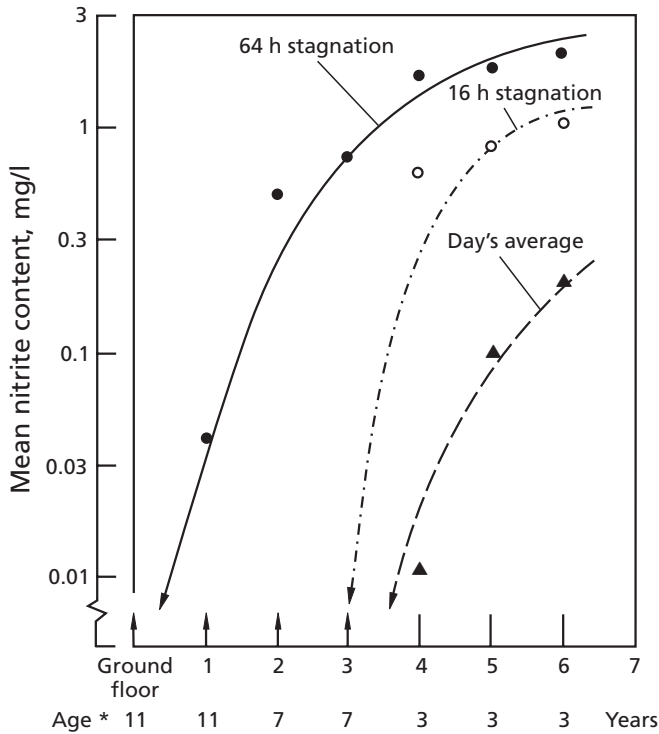


Figure 32: Mean nitrite content in daily water samples and stagnant samples overnight (16 h) and over the weekend (64 h) as a function of the test site (floor level) and service life of the installation [63, 64]

The oxygen content in drinking water is another parameter which influences nitrate reduction. As can be seen from Figure 33, nitrite formation decreases as the oxygen content increases. At oxygen contents of about 6 mg/l and a pH of about 7.5 usually present in drinking water, the nitrite content is less than 0.1 mg/l.

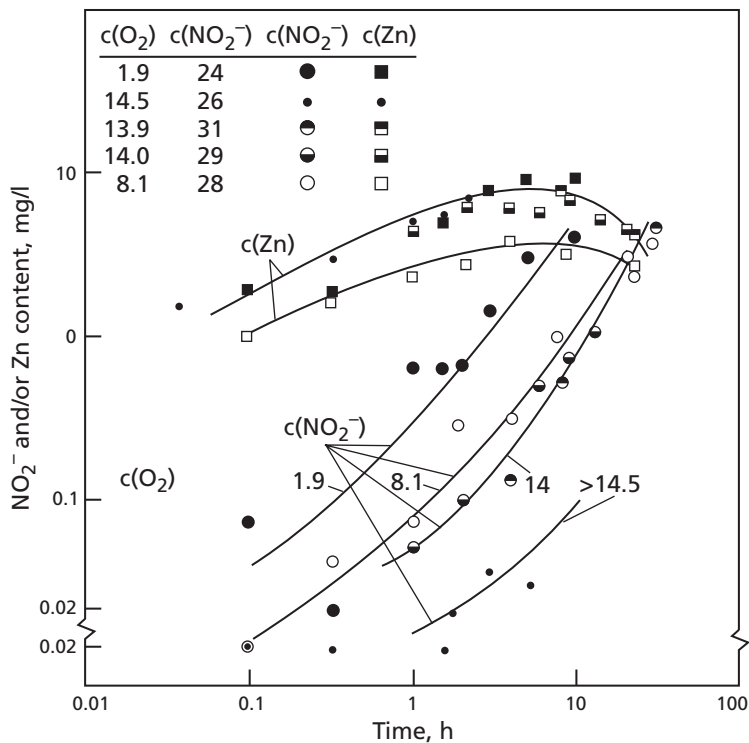


Figure 33: Effect of O₂ content on nitrite reduction [64]

Country of origin	Type	Inside coating analysis, %		Inside coating thickness, μm			Outside coating, μm	Comments on the structure and appearance of the zinc coating
		Pb	Cd	max.	min.	mean		
Germany Mannesmann	welded	1.14	0.097	110	70	90	75	smooth, regular, pure zinc all over
Germany Mannesmann	welded			250 120	70 60	150 85		fairly smooth, regular, pure zinc all over
Germany Mannesmann	welded	0.52	0.039	140 150	60 60	95 100	75	smooth, regular, pure zinc all over

Table 44: Examination of steel pipes in delivery state [62]

Table 44: Continued

Country of origin	Type	Inside coating analysis, %		Inside coating thickness, μm			Outside coating, μm	Comments on the structure and appearance of the zinc coating
		Pb	Cd	max.	min.	mean	mean	
Germany Mannesmann	seamless	0.95	0.114				80	slight roughnesses, otherwise regular, no metallographic examination
Germany Maximilians Hütte	seamless	0.50	0.021	90	60	75	85	smooth, regular, only iron-zinc alloy and no pure zinc layer since the steel is killed steel (Si: 0.37 %)
Hungary	seamless	0.64	0.055	60	50	50	95	smooth, longitudinal scratches produced by mechanical removal of excess zinc. Iron-zinc alloy only, no pure zinc layer since the steel is killed steel (Si: 0.31%)
Sweden	welded heavy seam	0.44	0.003	130	50	85	55	very irregular, zinc foam and heavy thickening at some places
Russia	welded			140	40	100		irregular, varying thickness of coating, layer of pure zinc all over
Russia	welded visible seam	0.80	0.002	210	60	125	60	highly varying thickening at some places, layer of pure zinc all over
		0.78	0.002	390	100	235		
Russia	welded visible seam	0.38	0.002	210	60	120	50	smooth, regular, at some places slight thickening, layer of pure zinc all over
		0.37	0.002					
Unknown	welded			630 280	80 140	260 170	165	very rough, large areas without pure zinc
Great Britain	welded	0.50	0.005	220 200	60 100	110 150	90	fairly regular, at some places slight thickening, layer of pure zinc all over

Table 44: Examination of steel pipes in delivery state [62]

Table 44: Continued

Country of origin	Type	Inside coating analysis, %		Inside coating thickness, μm			Outside coating, μm	Comments on the structure and appearance of the zinc coating
		Pb	Cd	max.	min.	mean	mean	
Austria	welded	0.83	0.001					slightly rough, small irregularities, no metallographic examination
India	welded	0.71	0.005	330	70	150	75	very irregular, formed zinc, heavy thickening
	heavy seam	0.71	0.006	480	30	220		
France/ Belgium Valex	welded			400	55	70–80	80	smooth, regular, thickening longitudinally, pure zinc all over
France/ Belgium Valex	welded, faintly visible seam			120	40	60	70	smooth, regular, thickening longitudinally, pure zinc all over

Table 44: Examination of steel pipes in delivery state [62]

Bibliography

- [1] Richtlinie des Rates über die Qualität von Wasser für den menschlichen Gebrauch (80/778/EGW)
Amtliches Blatt der Europäischen Gemeinschaft Nr. L 229
(Council guideline on the quality of water for human consumption (80/778/EGW)) from 15 July, 1980; Information from the European Commission No. L 229 from 30th August 1980, p. 11 (in German)
Bundesanzeiger Verlagsgesellschaft, D-Köln
- [2] Verordnung über Trinkwasser und über Wasser für Lebensmittelbetriebe (Trinkwasserverordnung-Trink V)
(Regulation on drinking water and water in the food industry
(Trinkwasserverordnung-Trink V)) from 22 May 1986 (in German)
BGBl No. 22, Part 1, p. 760
- [3] DIN EN ISO 8044 (02/2015)
Korrosion von Metallen und Legierungen – Grundbegriffe und Definitionen
(Corrosion of metals and alloys – basic terms and definitions) (in German)
Beuth Verlag GmbH, Berlin
- [4] DIN 2000 (10/2000)
Zentrale Trinkwasserversorgung – Leitsätze für Anforderungen an Trinkwasser, Planung, Bau, Betrieb und Instandhaltung der Versorgungsanlagen
(Central water supply, guiding principles on drinking water specifications, planning, construction and operation of plants) (in German)
Beuth Verlag GmbH, Berlin
- [5] Kruse, C.-L.
Korrosion und Korrosionsschäden, Grundbegriffe der Korrosionskunde in: Korrosion in Kalt- und Warmwassersystemen der Hausinstallation
(Corrosion and corrosion damage, basic terms in corrosion science – Corrosion in hot and cold water systems in domestic installations) (in German), p. 7
Deutsche Gesellschaft für Metallkunde, D-Oberursel, 1984
- [6] DIN 50929 (09/1985)
Korrosion der Metalle;
Korrosionswahrscheinlichkeit metallischer Werkstoffe bei äußerer Korrosionsbelastung; Teil 1: Allgemeines, Teil 2: Installationsteile innerhalb von Gebäuden, Teil 3: Rohrleitungen und Bauteile in Böden und Wässern
(The probability of corrosion on metallic materials under extreme corrosion exposure, Part 1: General Data, Part 2: Installed parts in buildings, Part 3: Pipelines and building components in the ground and water) (in German)
Beuth Verlag GmbH, Berlin
- [7] DIN VDE 0150 (04/1983) withdrawn
Schutz gegen Korrosion durch Streuströme aus Gleichstromanlagen [VDE-Bestimmung]
(Protection against corrosion due to stray currents of d. c. installation [VDE specification]) (in German)
Beuth Verlag GmbH, Berlin
- [8] DIN 50930-1 (09/1985)
Korrosionsverhalten von metallischen Werkstoffen gegenüber Wasser, Allgemeines (in German)
DIN EN 12502-1 (03/2005)
Protection of metallic materials against corrosion – Guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 1: General
Beuth Verlag GmbH, Berlin
- [9] DIN 2614 (02/1990)
Zementmörtelauskleidung für Gußrohre, Stahlrohre und Formstücke, Verfahren, Anforderungen, technische Lieferbedingungen (in German)
DIN EN 10298 (12/2005)
Steel tubes and fittings for onshore and offshore pipelines – Internal lining with cement mortar
Beuth Verlag GmbH, Berlin
- [10] Rahmel, A.; Schwenk, W.
Korrosion und Korrosionsschutz von Stählen (Corrosion and corrosion protection of steels) (in German), p. 112
Verlag Chemie, D-Weinheim, 1977

- [11] DIN 1988-7 (12/2004)
Technische Regel für Trinkwasser-Installationen (TRWI), Vermeidung von Korrosionsschäden und Steinbildung, Technische Regeln des DVGW
DIN 1988-200 (05/2012)
Codes of practice for drinking water installations – Part 200: Installation Type A (closed system) – Planning, components, apparatus, materials; DVGW code of practice (in German)
Beuth Verlag GmbH, Berlin
- [12] Kuron, D.; Horn, E.-M.; Gräfen, H.
Praktische elektrochemische Kontaktkorrosions-Tabellen von Konstruktionswerkstoffen des Chemie-Apparatebaues
(Tables of electrochemical contact corrosion on materials used in chemical apparatus construction) (in German)
Metalloberfläche 26 (1972) 11, p. 413
- [13] Schwenk, W.
Die Bedeutung der Ionen starker Säuren und Basen bei der Korrosion unlegierter Stähle mit und ohne Beschichtungen
(Importance of ions of strong acids and bases for the corrosion of coated and uncoated unalloyed steels) (in German)
Werkst. Korros. 30 (1979) 1, p. 34
- [14] Bächle, A.; Deschner, E.; Weiss, E.; Wagner, I.
Das Korrosionsverhalten von verzinkten und unlegierten Stahlrohren in Trinkwässern mit unterschiedlicher Härte und erhöhtem Neutralsalzgehalt
(Corrosion of galvanised and unalloyed steel tubes in drinking water of different hardness and increased neutral salt content) (in German)
Werkst. Korros. 32 (1981) 10, p. 435
- [15] Schulze, M.; Schwenk, W.
Über den Einfluß der Strömungsgeschwindigkeit und der NaCl-Konzentration auf die Sauerstoffkorrosion unlegierten Stahls in Wässern
(Influence of flow velocity and sodium chloride concentration on the oxygen corrosion of unalloyed steels in water) (in German)
Werkst. Korros. 31 (1980) 8, p. 611
- [16] DIN EN 12502-5 (03/2005)
Korrosionsschutz metallischer Werkstoffe – Hinweise zur Abschätzung der Korrosionswahrscheinlichkeit in Wasserverteilungs- und speichersystemen – Teil 5:
Einflussfaktoren für Gusseisen, unlegierte und niedriglegierte Stähle
(Protection of metallic materials against corrosion – guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 5. Influencing factors for cast iron, unalloyed and low alloyed steels) (in German)
Beuth Verlag GmbH, Berlin
- [17] Nissing, W.; Friehe, W.; Schwenk, W.
Über den Einfluß des Sauerstoffgehaltes, des pH-Wertes und der Strömungsgeschwindigkeit auf die Korrosion feuerverzinkter und unverzinkter unlegierter Stahlrohre in Trinkwasser
(Influence of oxygen content, pH and flow velocity under corrosion of hot-dip galvanised and bare piping of unalloyed steel in potable water) (in German)
Werkst. Korros. 33 (1982) 6, p. 346
- [18] Kuch, A.; Sontheimer, H.; Wagner, I.
Die Messung der Aufeisung im Trinkwasser – Ein neues Verfahren zur Beurteilung von Deckschichten in schwarzen Stahlrohren
(Measurement of iron-pickup by potable water – A new method for the assessment of surface layers in black steel piping) (in German)
Werkst. Korros. 34 (1983) 3, p. 107
- [19] Wagner, I.; Gerber, S.; Kuch, A.
Der Einfluß von Neutralsalzen auf das Korrosionsverhalten unlegierter Eisen-Werkstoffe in gut gepufferten Trinkwässern
(The influence of increased neutral salt content on the corrosion behaviour of non-alloyed steel in well buffered drinking waters) (in German)
Werkst. Korros. 36 (1985) p. 64

- [20] Kuron, D.; Gräfen, H.; Batroff, H. P.; Fäßler, K.; Münster, R.
Einfluß des Chloridgehaltes in Trinkwasser auf die Korrosion von unlegiertem Stahl
(Influence of chloride content in tap water on the corrosion of unalloyed steel) (in German)
Werkst. Korros. 36 (1985) 2, p. 68
- [21] Wagner, I.
Feldversuche Trinkwasser – Teilprogramm Wasser. Untersuchungen über das Korrosionsverhalten von metallischen Werkstoffen gegenüber Trinkwasser
Ergebnisse des Forschungs- und Entwicklungsprogramms “Korrosion und Korrosionsschutz”
(Field tests on drinking water – Subsection water. Investigation into the corrosion behaviour of metallic materials towards drinking water. Results from the research and development program “Corrosion and corrosion protection”) (in German), Information No.3 (1981–1983) p. 217
DECHEMA, D-Frankfurt, 1984
- [22] Beck, W.; Wagner, I.
Feldversuche Trinkwasser – Teilprogramm Wasser. Entsäuerung – Der Einfluß unterschiedlicher Entsäuerungsmaßnahmen auf das Korrosionsverhalten verzinkter und schwarzer Stahlrohre
(Field tests on drinking water – Subsection water. Deacidification – The effect of different deacidification measures on the corrosion behaviour of zinc-coated and black steel pipes) (in German)
Werkst. Korros. 35 (1984) 12, p. 572
- [23] Wagner, I.
Feldversuche Trinkwasser – Teilprogramm Wasser. Unterschiedliche Wässer – Der Einfluß wechselnder Wasserqualität auf das Korrosionsverhalten unlegierter Eisenwerkstoffe
(Field tests on drinking water – Subsection water: Different water qualities – The effect of changes in the water quality on the corrosion behaviour of non-alloyed iron materials) (in German)
Werkst. Korros. 35 (1984) 12, p. 569
- [24] Dieter, H. O.; Tiedge, C.
Über den Schutz von gußeisernen Rohren und Formstücken mit Steinkohlenteersonderpech
(Protection of cast iron pipes and molded parts with coal tar special pitch) (in German)
Straßenbau und Bautenschutz mit Steinkohlenteer 19 (1970) p. 27
- [25] Gras, W.-D.
Eigenschaften und Bewährung von Zementmörtelauskleidungen in gußeisernen Druckrohren
(Properties and reliability of cement mortar linings in cast iron pressure pipes) (in German)
fgr Information (1969) p. 16
- [26] Anonymous
Handbuch Gußrohr Technik, duktile Gußrohre und Formstücke
(Handbook of cast pipe technology, ductile cast pipes and molded parts) (in German)
Fachgemeinschaft Gußeiserne Rohre, D-Köln (1983) p. 23
- [27] Raffenberg, N.
Duktile Gußrohre für den Transport von Flüssigkeiten und Gasen
(Ductile cast pipes for the transport of liquids and gases) (in German)
Tech. Mitt. 64 (1971) 8, p. 325
- [28] Herbsleb, G.
Nichtrostende Stähle in Apparatebau und Haustechnik
(Stainless steels in plant engineering and building services)
IKZ-Haustechnik (1987) 13, p. 26
- [29] Herbsleb, G.
Rohrleitungen aus nichtrostenden Stählen in Wässern. Bedeutung der Verbindungstechnik und Oberflächenbehandlung für die Korrosionsbeständigkeit
(Stainless steel pipelines in water. Significance of the connecting technology and surface treatment for the corrosion resistance) (in German)
Bänder, Bleche, Rohre 40 (1989) 10, p. 554
- [30] Herbsleb, G.; Schwenk, W.
Korrosionsverhalten von Edelstahlrohren und Rohrverbindungen bei der Warmwasserverteilung in der Hausinstallation

- (Corrosion behaviour of alloy steel tubing and tube connections in warm water distribution systems in dwellings) (in German)
Werkst. Korros. 26 (1975) 2, p. 93
- [31] DIN EN 12502-4 (03/2005)
Korrosionsschutz metallischer Werkstoffe – Hinweise zur Abschätzung der Korrosionswahrscheinlichkeit in Wasserverteilungs- und speichersystemen – Teil 4: Einflussfaktoren für nichtrostende Stähle (Protection of metallic materials against corrosion – guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 4: Influencing factors for stainless steels) (in German)
Beuth Verlag GmbH, Berlin
- [32] Szederjei, E.; Bukowiecki, A.
Zur Frage einer Korrosionsgefährdung von hartgelöteten Edelstahl fittings, insbesondere durch die sogenannte “Messerschnittkorrosion” (The corrosion risk of hard-soldered high-grade steel fittings, particularly as a result of so-called knife-edge corrosion) (in German)
Werkst. Korros. 27 (1976) 6, p. 432
- [33] Herbsleb, G.; Schittko, H.
Standortauswahl von Pilotanlagen und Durchführung von Feldversuchen zur Erprobung von Edelstahlrohren bei der Kalt- und Warmwasserverteilung in der Hausinstallation (Selection of pilot plant location and execution of field trials to test high-grade steel pipes in hot and cold water distribution systems in domestic installations) (in German)
Gas- und Wasserfach, Wasser, Abwasser 117 (1976) 1, p. 19
- [34] Schwenk, W.
Feldversuche Trinkwasser – Werkstoffe, Teil 4: Nichtrostender Stahl (Field tests on drinking water – Materials, Part 4: Stainless steel) (in German)
Werkst. Korros. 35 (1984) 12, p. 581
- [35] DVGW Arbeitsblatt W 541, Entwurf Rohre aus nichtrostenden Stählen für die Trinkwasserinstallation (Stainless steel pipes for drinking water installations) (in German)
Wirtschafts- und Verlagsgesellschaft Gas- und Wasser mbH, D-Bonn, 1984
- [36] DIN 1988-7 (12/2004) withdrawn
Technische Regeln für Trinkwasser-Installationen (TRWI) – Teil 7: Vermeidung von Korrosionsschäden und Steinbildung; Technische Regel des DVGW (Codes of practice for drinking water installations (TRWI) – Part 7: Prevention of corrosion damage and calcareous deposit formation, DVGW code of practice) (in German)
Beuth Verlag GmbH, Berlin
- [37] Herbsleb, G.; Neussner, R.; Petermann, R.; Pitsch, T.; Romagnoli, M.; Scimar, R.; Szederjei, E.; TrabANELLI, G.; Tytgat, G.
Anwendung hochlegierter Stähle als Werkstoffe für Warmwasserbereiter und Wasserverteilungsanlagen. Bericht der Arbeitsgruppe 9 “Nichtrostender Stahl” des C.E.O.C.O.R. (Use of high-alloyed steels as materials for water heaters and water distribution plants. Report from working group 9 of the C.E.O.C.O.R. “Stainless Steel”) (in German)
Gas- u. Wasserfach, Wasser, Abwasser 119 (1978) 1, p. 31
- [38] Herbsleb, G.
Korrosionsbeständigkeit von Installationsteilen aus nichtrostenden austenitischen Chrom-Nickel-Stählen bei erhöhter Temperatur (Corrosion resistance of installation elements of stainless austenitic chromium-nickel steels at high temperatures) (in German)
Werkst. Korros. 37 (1986) 8, p. 354
- [39] DIN EN 10240 (02/1998)
Innere und/oder äußere Schutzüberzüge für Stahlrohre – Festlegung für durch Schmelztauchverzinken in automatisierten Anlagen hergestellte Überzüge (Internal and/or external protective coatings for steel tubes – specification for hot dip galvanised coatings applied in) (in German)
Beuth Verlag GmbH, Berlin

- [40] Schwenk, W.
Aus der Schadenforschung: Stahlrohre in der Kaltwasser-Installation
(From damage research: steel pipes in cold water installations) (in German)
Der Maschinenschaden 49 (1976) 6, p. 243
- [41] DIN EN 12502-3 (03/2005)
Korrosionsschutz metallischer Werkstoffe – Hinweise zur Abschätzung der Korrosionswahrscheinlichkeit in Wasserverteilungs- und speichersystemen – Teil 3: Einflussfaktoren für schmelztauchverzinkte Eisenwerkstoffe
(Protection of metallic materials against corrosion – guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 3: Influencing factors for hot dip galvanised ferrous materials) (in German)
Beuth Verlag GmbH, Berlin
- [42] Kruse, C.-L.
Untersuchungen zur Beurteilung der Korrosionsschutzwirkung von Deckschichten auf feuerverzinkten Stahlrohren
(Tests to assess the corrosion protection efficacy of surface layers on hot-dip galvanised steel pipes) (in German)
Werkst. Korros. 26 (1975) 6, p. 454
- [43] Friehe, W.; Schwenk, W.
Vorgänge bei der Schutzschichtbildung in verzinkten Stahlrohren
(Phenomena involved in the formation of protective layers in galvanised steel tubing) (in German)
Werkst. Korros. 26 (1975) 5, p. 342
- [44] Schwenk, W.
Beitrag über die Kinetik der Zinkauflösung in fließenden Leitungswässern
(Contribution to the kinetics of zinc dissolution in flowing tap water) (in German)
Werkst. Korros. 27 (1976) 3, p. 157
- [45] Rückert, J.
Einfluß des pH-Wertes, des Sauerstoffgehaltes und der Strömungsgeschwindigkeit von kaltem Trinkwasser auf das Korrosionsverhalten und die Schutzschichtbildung bei feuerverzinkten Stahlrohren
(Influence of pH-value, oxygen content and flow velocity of cold drinking water on corrosion behaviour and surface layer forming of galvanised steel tubes) (in German)
Werkst. Korros. 30 (1979) 1, p. 9
- [46] Kruse, C.-L.; Friehe, W.; Schwenk, W.
Felduntersuchungen mit feuerverzinkten Stahlrohren in Wässern
(Field tests on galvanised steel tubes in drinking waters) (in German)
Werkst. Korros. 37 (1986) 1, p. 12
- [47] Kruse, C.-L.; Friehe, W.; Schulze, M.; Schwenk, W.
Untersuchungen mit feuerverzinkten Stahlrohren – Auswertungen von Langzeit-Daten
(Field corrosion tests on hot dip galvanised steel pipes – Assessment of long term data) (in German)
Werkst. Korros. 38 (1987) 5, p. 229
- [48] Huppatz, W.
Feldversuche Trinkwasser – Werkstoffe, Teil 3: Aluminium
(Field trials on drinking water – materials, Part 3: Aluminium) (in German)
Werkst. Korros. 35 (1984) 12, p. 578
- [49] Rückert, J.; Schulze, M.; Schwenk, W.
Erörterungen zur Zeitabhängigkeit der Massenverluste von feuerverzinkten Stahlrohren in fließenden Wässern
(Discussion on the time dependence of corrosion rates in flowing waters of hot dip galvanised steel pipes) (in German)
Werkst. Korros. 38 (1987) 6, p. 307
- [50] Rückert, J.; Stürzbecher, D.
Langzeitverhalten feuerverzinkter Stahlrohre in Trinkwasser unterschiedlichen pH-Wertes und unterschiedlicher Strömungsgeschwindigkeit
(Long term performance of galvanised steel tubes in drinking water with different pH-value and flow velocity) (in German)
Werkst. Korros. 9 (1988) 1, p. 7
- [51] Wagner, I.; Dannöhl, R.
Der Einfluß unterschiedlicher Nitratgehalte auf das Korrosionsverhalten von verzinkten Stahlrohren

(The influence of different nitrate contents of drinking water on the corrosion behaviour of galvanised steel pipes) (in German)

Werkst. Korros. 36 (1985) 1, p. 1

[52] Th.; Clauß, W.; Friehe, W.; Künzler, R. Zinngeriesel? Eine Nachbetrachtung mit Ergebnissen aus einer Trinkwasser-Versuchsinstallation der Stadtwerke Biberach an der Riß

(A follow-up assessment with results from a drinking water test installation at Stadtwerke Biberach)

Neue Deliwa Zeitschriften 33 (1982), p. 90

[53] Maier, D.; Wagner, I.

Feldversuche Trinkwasser – Teilprogramm Wasser: Einfluß der Ozonung – Das Korrosionsverhalten verzinkter und schwarzer Stahlrohre in Wasser nach Ozonung und Chlorung (Field tests on drinking water – Subsection water: Effect of ozonisation – The corrosion behaviour of zinc-coated and black steel pipes in water after ozonisation and chlorination) (in German)

Werkst. Korros. 35 (1984) 12, p. 572

[54] Theiler, F.

Korrosionsverhalten von feuerverzinktem Stahl in Trinkwasser

(Corrosion behaviour of hot-dip galvanised steel in drinking water)

in: Kruse, C.-L.

„Korrosion in Kalt- und Warmwassersystemen der Hausinstallation“, p. 187

Deutsche Gesellschaft für Metallkunde, D-Oberursel, 1984

[55] Stichel, W.

Einfluß von Kupfer auf das Korrosionsverhalten verzinkter Rohre in warmen Brauchwässern

(Influence of copper on the corrosion behaviour of galvanised tubing in warm water systems) (in German)

Werkst. Korros. 26 (1975) 4, p. 258

[56] Meyer, D.; Stichel, W.

Elektronenstrahl-Mikroanalyse von Deckschichten verzinkter Warmwasserrohre

(Electron beam microanalysis of surface layers on galvanised hot-water steel tubes) (in German)

Werkst. Korros. 29 (1978) 12, p. 804

[57] Kruse, C.-L.

Über das Korrosionsverhalten von Zink und feuerverzinktem Stahl in erwärmtem Wasser

(Corrosion behaviour of zinc and hot dip galvanised steel in warm water)

(in German)

Werkst. Korros. 27 (1976) 12, p. 841

[58] Stichel, W.

Einfluß von Phosphaten und/oder Silikaten auf die durch Kupferionen ausgelöste Lochkorrosion in verzinkten Warmwasserrohren

(Influence of phosphates and/or silicates on copper ion induced pitting of galvanised hot water tubing) (in German)

Werkst. Korros. 32 (1981) 1, p. 19

[59] Kruse, C.-L.; Schmitt-Thomas, Kh. G.; Gräfen, H.

Korrosionsverhalten von feuerverzinktem Stahl in erwärmtem Wasser

(Corrosion behaviour of hot galvanised steel in warm water) (in German)

Werkst. Korros. 34 (1983) 11, p. 539

[60] v. Baeckmann, W.; Schwenk, W.

Handbuch des kathodischen Korrosionsschutzes (Handbook of cathodic corrosion protection) (in German), 2nd ed., p. 39 Verlag Chemie GmbH, D-Weinheim, 1980

[61] Burgmann, G.; Friehe, W.; Welbers, K.

Erfahrungen mit dem Guldager-Verfahren zum Korrosionsschutz von Warmwasserversorgungsanlagen (Experience with the Guldager method for corrosion protection of hot water supply plants) (in German)

Heizung-Lüftung-Haustechnik 23 (1972) p. 85

[62] Nielsen, K.; Yding, F.

Influence of pipe quality on corrosion of galvanised steel pipes for domestic water supply

Werkst. Korros. 34 (1983) 11, p. 547

- [63] Schwenk, W.; Friehe, W.
Beeinflussung der Wasserqualität beim
Transport in verzinkten Stahlrohren der
Hausinstallation
(Influencing of the water quality during
transport in zinc-coated steel pipes in
domestic installations) (in German)
DVGW-Schriftenreihe Wasser No. 31,
p. 343 (Eschborn, 1982)
Wirtschafts- u. Verlagsgesellschaft Gas-
und Wasser mbH, D-Bonn
- [64] Schwenk, W.
Nitratreduktionsvorgänge in
Trinkwasserinstallationen – ein reales
Problem oder nur Gesprächsthema?
(Nitrate reduction processes in drinking
water installations – a real problem or
just a topic of conversation?) (in German)
Sanitär-Installateur (1983) 5, p. 35
- [65] Künzler, R.; Schwenk, W.
Einflußgrößen der Nitratreduktion durch
feuerverzinkten und unverzinkten
unlegierten Stahl
(Influencing variables in the reduction of
nitrate by hot-dip galvanised and non-
galvanised, non-alloyed steel)
(in German)
Gas- u. Wasserfach, Wasser, Abwasser
124 (1983) 8, p. 378

Seawater

Author: P. Drodten / Editor: R. Bender

Introduction

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V 1 Marine atmosphere, splash, tidal and immersion zones

Over 70% of the surface of the earth is covered with seawater. This makes seawater the most widespread corrosive medium next to the atmosphere. Most metals, alloys and construction materials are corroded by seawater and marine atmospheres. The conditions of exposure are the main parameters determining the behaviour of the different materials. Exposure is classified roughly into four zones:

- marine atmosphere
- splash zone (SZ)
- tidal zone (TZ)
- immersion zone (IZ).

Atmospheric corrosion is not grouped with reactions in gases, but is rather an instance of electrolytic corrosion that occurs only when a film of liquid, moist deposits or corrosion products have formed on the metal surface. The rate of corrosion in seawater is determined mainly by the amount of oxygen that reaches the cathode, whereby the electrolyte resistance is of no consequence due to the large cross-section and good conductivity. In atmospheric corrosion, on the other hand, the relatively high level of electrical resistance of the thin film of moisture is a major determinant of the corrosion rate, since oxygen access is practically unhindered over the short diffusion pathways involved. Due to the good conductivity of the medium, the anode and cathode of a corrosion cell in seawater can be some distance apart. Such macroelements are frequently found on sheet piling or submerged surfaces of ships and can be made use of in applications of cathodic corrosion protection (CCP). In atmospheric corrosion, the elements act over very short distances only, rendering cathodic protection practically ineffective.

At an air temperature of 283 K (10 °C), an air pressure of 1,013 hPa and 60% relative humidity the water content is around 5.7 g/m³. At 303 K (30 °C) and relative humidity of 100%, the water content rises to 31.4 g/m³. The water film that condenses when the temperature drops or on relatively cold surfaces is always saturated with oxygen. Whereas corrosive action in a non-marine atmosphere is mainly determined by moisture content and potential industrial contaminations, the marine atmosphere is characterised by a raised content of salt particles carried on the wind from the sea spray. Since the salt particles deposited on the metal surface, or aerosols containing salt, also contain hygroscopic components, e.g. calcium and magnesium chlorides, liquid films form on the surface with very high salt content levels, even if the air is still above the dewpoint.

As the chloride content increases, not only does the electrical conductivity of the electrolyte solution, and thus the activity of the corroding elements, increase. The capacity of the solution to penetrate through protective layers and stabilise anodes locally increases as well. The chloride content drops rapidly as one moves away from the sea. How far away from the coast its influence is still felt depends to a large extent on wind force and wind direction as well as on wave height and cannot be stated in general terms. Normally, the influence of seawater salts can be ignored at a distance of about 1 km from the coast. Frequent and heavy rains can reduce corro-

sion since they dilute or wash off the salt concentrations. This is the reason why corrosion is more pronounced on the undersides of samples exposed at an angle and on the lee side of structural elements, since these surfaces remain moist longer and the washout effect is missing.

In the **splash zone (SZ)**, the materials are under the influence of high moisture levels and high salt content levels. Stress factors from solar exposure and UV light are also of consequence for organic materials or coatings. No fouling takes place in the splash zone.

In the **tidal zone (TZ)**, unrestricted oxygen access to the moist surfaces in the low water phase enhances corrosion. In this zone, fouling and wave movements can also have a considerable influence on corrosion processes.

In the **immersion zone (IZ)** as well, the water is practically saturated with oxygen. In addition to fouling, solute contaminants, suspended solids and water currents are additional factors to be reckoned with here.

As a result of these different stress factors, in particular the widely varying level of oxygen access, structural elements exposed in all of the zones, e.g. sheet pilings or ram mooring piles, macroelements may form resulting in increased corrosive activity on certain anodic segments and corresponding cathodic protection of others. Erosion levels measured on isolated samples mounted in the different zones are therefore of limited value only in evaluations of the behaviour of structural elements extending through most or all of the exposure zones.

V 2 Seawater corrosion parameters

Seawater is a complex aqueous salt solution and its principal influential factors on corrosion are summarised in Table 1.

Chemical factors	Physical factors	Biological factors
Solute salts	temperature	fouling
Solute gases • oxygen • carbon dioxide	movement • wave movement • current	animals • oxygen consumption • CO₂ production • sulphate-reducing
pH level	pressure	plants • oxygen production • CO₂ consumption
	solids	

Table 1: Main seawater corrosion parameters

V 2.1 Salt content

The salt content of seawater is defined as the total mass of salt in solution in 1 kg of seawater. Seawater in the open sea far from land in the major oceans has an average salt content within the range of 32–37.5 g/kg. This salt content shows considerable consistency in given regions and throughout the years. Nearer to the coast, in marginal seas and enclosed seas, the salt content level may deviate widely from this average (Table 2) [1]. Higher salt content levels result from higher evaporation rates, e.g. in the Persian Gulf and Red Sea; lower levels result when the influx of fresh water exceeds evaporation, e.g. in the Baltic Sea. The North Sea, with a salt content of about 35 g/kg, tends towards the levels in the Atlantic Ocean. Along the German North Sea coast, however, the salt content drops to about 32 g/kg.

<i>Oceanic region</i>	<i>Salt content, g/kg</i>
Baltic Sea	8
Black Sea	22
Atlantic Ocean	37
Mediterranean Sea	41
Caspian Sea	13
Dead Sea	260
Irish Sea	33
Red Sea	41
Persian Gulf	39–42

Table 2: Salt content of different oceanic regions [1]

Generalised conclusions can be based on salt content levels of approx. 35 g/kg and a chloride ion content of 19 g/kg. An assumed total salt content (or salinity) of 35 g/kg (3.5%) results in the seawater composition shown in Table 3 [2, 3].

<i>Component</i>	<i>Content level, g/kg</i>
Chloride	19.35
Sodium	10.78
Sulphate	2.71
Magnesium	1.29

Table 3: Average composition of seawater at a salt content level of 3.5% [2, 3]

Table 3: Continued

Component	Content level, g/kg
Calcium	0.41
Potassium	0.39
Hydrogen carbonate	0.14
Bromide	0.067
Strontium	0.008
Boron	0.004
Fluorine	0.001

Table 3: Average composition of seawater at a salt content level of 3.5% [2, 3]

Ignoring the components that are of practically no consequence in terms of corrosion, the salt content can be calculated based on the chloride ion content as per [4, 5]:

$$\text{Salt content in \%} = (1.81 \times \text{chloride ion content in \%}) + 0.003$$

At a chloride ion content of 1.9%, the resulting salt content is 3.44%.

The term “salinity” is generally used to express total salt content as “chlorinity” is used for chloride ion content.

The pH level of seawater is generally 7.7–8.2 [5].

The aggressiveness of seawater near the coast may be increased by uptake of gases such as carbon dioxide and sulphur dioxide from emissions and sewage. Raised amounts of hydrogen sulphide from rotting matter, as well as raised amounts of ammonium salts, sulphides and mordant residues from industrial sewage can also add to the aggressiveness of seawater [5].

So-called **synthetic seawater** is often used for laboratory corrosion experiments, the composition of which is either that listed in DIN 50905-4 [6] or ASTM Standard Specification D1141-90 [7]. These test solutions contain concentrations of the ions according to the relative amounts listed in Table 3. The pH level of these solutions is adjusted with sodium hydroxide solution to 7–8 (DIN) or 8.2 (ASTM). Experiments with such synthetic water solutions do not, however, take into account the influences of animals, plants and water movement so important to the effects of natural seawater and can therefore only provide comparative data on material behaviour.

In simplified test designs, NaCl solutions are also frequently used, e.g. with a sodium chloride concentration of $c_{\text{NaCl}} = 1 \text{ mol/l}$ or 0.5 mol/l , approximately equivalent to a 5% or 3% NaCl solution. Since these solutions contain no buffering substances, pH level changes, and therefore inconsistent test conditions must be expected in long-term experiments. Due to the lack of alkaline earth salts, these NaCl solutions also do not result in the deposits and covering layers that can exert a major influence on the corrosive action of natural or synthetic seawater. In electro-

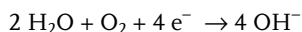
chemically controlled experiments in particular, calcium or magnesium salts are separated out with cathodic polarisation due to the raised pH levels. Therefore, the window of comparison for results of studies done in NaCl solutions with results from natural or synthetic seawater is narrow.

However, results of experiments with highly concentrated salt solutions can provide useful information concerning the behaviour of materials under the conditions involved in seawater desalination.

Brackish water has a lower salt content than seawater, varying with the tides and seasons between that of seawater and river water. The specific electrical resistance of such water can therefore be between 30 Ω cm and 1,000 Ω cm, with electrical conductivity levels between 33 mS/cm and 1 mS/cm. The pH level is between 6.5 and 8, the oxygen content, depending on aeration and temperature, is between 0 and 13 mg/l. The widely varying content levels of hydrogen carbonate, hydrogen sulphide, ammonium compounds and organic components all strongly influence the aggressiveness of brackish water [5].

V 2.3 Solute gases

The solute **oxygen content** is of primary importance as a component influencing the corrosion behaviour of most metals in seawater. The solute oxygen content can either increase or inhibit corrosion. In nearly neutral aqueous salt solutions, i.e. in seawater as well, the reduction of solute oxidants is the principal cathodic reaction step. The cathodic reaction step in corrosion of metals in seawater is the reduction of the oxygen dissolved in the water as per this formula



The equivalent anodic reaction step in metal corrosion is thus controlled by the amount of solute oxidant and its transport to the cathodic parts of the metal surface. In surfaces with no covering layers the corrosion rate is directly proportional to the oxygen concentration of the water and largely independent of the type and concentration of the solute salts [5, 8]. With increasing oxygen content levels and increasing water movement, most metals exposed to seawater in the active state show increased corrosion. The oxygen content of seawater is temperature-dependent and is approx. $c_{\text{O}_2} = 0.5\text{--}0.6$ mmol/l at temperatures around 283 K (10 °C).

In the case of some metals, e.g. stainless steels, the solute oxygen affects a potential shift to more positive levels and thus a passivation of the metal surface. When effectively adhering oxide covering layers form, corrosion may be appreciably reduced at higher seawater oxygen content levels, even on non-passive metals [5].

The content of solute oxygen depends mainly on temperature and salt content. The gases dissolved in seawater do not reach saturation levels by a long shot, not even in areas close to the surface. Table 4 lists the balanced saturation values for oxygen, nitrogen and carbon dioxide at a gas pressure of 101 kPa and at different temperatures and salt contents [9].

Chloride content g/kg	Temperature K (°C)	Oxygen ppm	Nitrogen ppm	Carbon dioxide ¹⁾ ppm
0	273 (0)	70.4	28.8	3,370
	285 (12)	52.5	22.7	2,198
	297 (24)	42.1	18.3	1,541
16	273 (0)	56.0	18.4	2,860
	285 (12)	42.9	14.2	1,888
	297 (24)	34.8	11.5	1,342
20	273 (0)	52.8	17.3	2,746
	285 (12)	40.4	13.4	1,814
	297 (24)	32.9	10.9	1,299

including H_2CO_3 , HCO_3^- and CO_3^{2-}

Table 4: Saturation values for different gases in salt solutions of varying concentration and temperature at a gas pressure of 101 kPa [9]

Table 5 shows the content levels of solute oxygen in seawater in balance with air at atmospheric pressure. Dependence on temperature and salt content are shown [3, 10].

Chloride content g/kg	0	5	10	15	20
Salt content g/kg	0	9.06	18.08	27.11	36.11
Temperature K (°C)	Oxygen content ppm				
273 (0)	14.62	13.70	12.78	11.80	11.00
278 (5)	12.79	12.02	11.24	10.49	9.74
283 (10)	11.32	10.66	10.01	9.37	8.72
288 (15)	10.16	9.67	9.02	8.46	7.92
293 (20)	9.19	8.70	8.21	7.77	7.23
298 (25)	8.39	7.93	7.48	7.04	6.57
303 (30)	7.67	7.25	6.80	6.41	5.37

Table 5: Oxygen content of seawater at different temperatures and salt content levels in balance with air at atmospheric pressure [10]

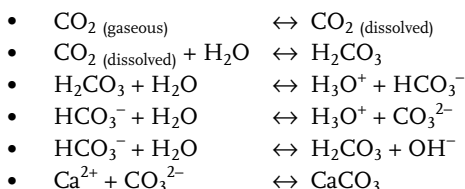
The oxygen content of seawater drops when temperature or salt content increases. In the Dead Sea, the oxygen content is therefore very low, approximately 1–1.5 ppm [11]. In the middle and northerly latitudes, oxygen content levels in the range of 8–12 ppm are measured depending on the temperature [10].

In [5], an oxygen content level of 8–10 mg/l is given for a temperature of 283 to 288 K (10 °C to 15 °C). In the open sea, the oxygen content level remains within the same order of magnitude up to a water depth of about 20 m. Measurements taken off the French coast show that oxygen content is not even appreciably reduced up to depths of 2,000 m [12]. The oxygen content is also dependent on the presence of oxygen-consuming or oxygen-producing substances, as well as on wave movement and related aeration processes in water layers near the surface. Oxygen content can drop to near-zero levels in highly polluted port and coastal waters.

Our knowledge of the content levels of solute oxygen is not only important for evaluation of corrosion conditions, but also in determining the necessary current density levels required for cathodic protection.

The **carbon dioxide content** of seawater is determined in waters close to the surface by exchange with atmospheric carbon dioxide. Plants consume CO₂ in the process of photosynthesis. The solute carbon dioxide influences the balance of carbonate/hydrogen carbonate and thus the formation of lime deposits and covering layers. This balance is the basis for the buffering properties of seawater and its relatively high pH level.

Possible balanced reactions in the CO₂/seawater system [13]:



V 3 Corrosion types

The corrosion behaviour of a material is not a material property such as ductility or strength, but must be considered as a complex characteristic of the corrosion system comprising material and medium, in which the ambient conditions such as, flow rate, etc. also play their respective roles. Corrosion in seawater and in marine atmospheres represents the reaction of the material with its environment. In the case of metallic materials, corrosion is caused by electrochemical exchange reactions involving the electrons and ions at the metal surface. For this reaction to take place, cathodic and anodic areas on the metal surface must be interconnected in the electrolyte solution so as to conduct electrons. Anode and cathode can be different materials in the structural element or different surface areas on a given material, e.g. resulting from structural inhomogeneity, surface films or covering layers.

The following corrosion types can occur on metallic materials in seawater:

- uniform surface corrosion
- shallow pit corrosion
- pitting corrosion
- crevice corrosion
- corrosion cracking

The occurrence of these corrosion types depends on the material, its chemical composition, its structural status, its surface, the construction and the operating conditions.

V 3.1 Uniform surface corrosion and shallow pit corrosion

These corrosion types occur in seawater on metals that are exposed in the active state such as unalloyed or low-alloyed steels. The main factor in the rate of corrosion of these non-passivable materials access to the surface by solute oxygen. In oxygen-free seawater, the reaction rate is practically zero.

Figure 1 shows the connection between mass loss in unalloyed steel samples (see Section “unalloyed and low-alloyed steels”) in NaCl solutions of differing concentration at 298 K (25 °C) and the proportion of solute oxygen [14]. The higher the salt concentration the lower the level of solubility for oxygen. Erosion is reduced accordingly. Test results after 1–2 days are shown.

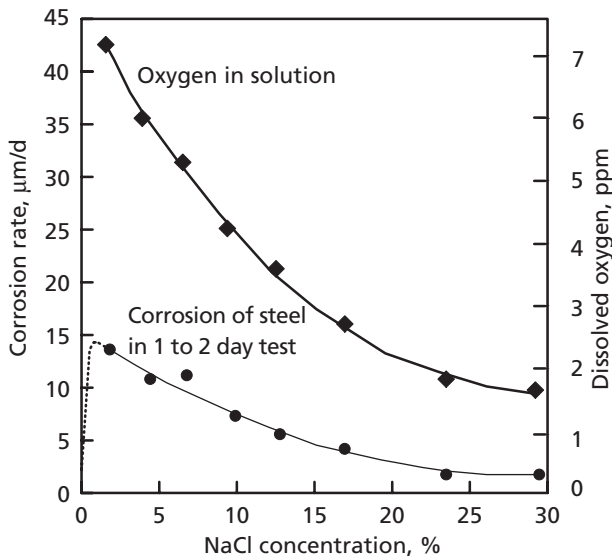


Figure 1: Dependence of corrosion rates of unalloyed steel in NaCl solutions on NaCl concentration and oxygen content at 298 K (25 °C) [14]

Evaluation of this seawater must consider its movement as well as its oxygen content, since both factors are of equal importance when it comes to transporting oxygen to the steel surface. This is why the corrosion rates in the tidal zone (TZ) are greater by a factor of 1.5 than in the immersion zone (IZ) [15].

Figure 2 provides a summary of exposure tests for seven different structural steel types at the Helgoland seawater test platform. The chemical composition of the structural steels are listed in Table 18 (see Section “unalloyed and low-alloyed steels”). The mean corrosion rates w and for the splash zone the initial rate of corrosion w_0 are entered next to the scatter band for surface loss of mass m_a [15, 16].

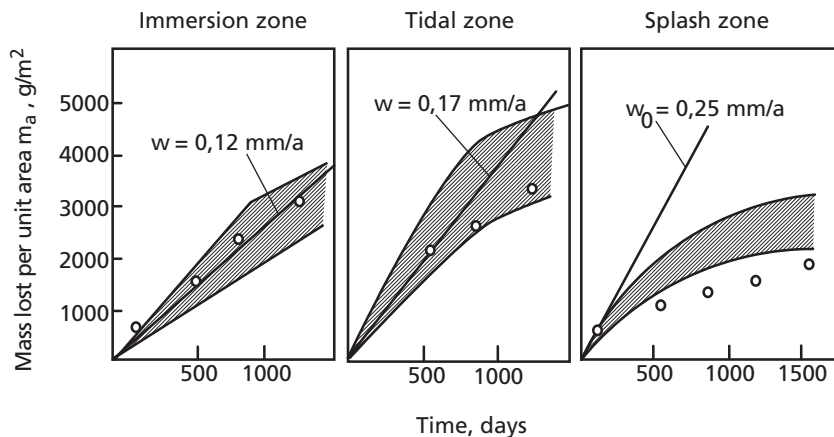


Figure 2: Corrosion of unalloyed and low-alloyed steels on Helgoland, materials see Table 18 [15, 16]

(○ weather-resistant WT steel (laboratory melt), cf. e.g. WTSt 37-3, DIN-Mat. No. 1.8961 or WTSt 52-3, DIN-Mat. No. 1.8963)

With increasing air contact, the corrosion rates increase and deviation of the measured values in the direction of smaller corrosion amounts begins at an earlier point. The rate of corrosion is raised by the increased air contact because more oxygen is available for the corrosion reaction. Since the oxidation process, however, continues to produce hardly soluble Fe(III) compounds, the formation of protective layers that make it more difficult for oxygen to reach the surface is also facilitated. Certain alloying elements have an enhancing effect as is demonstrated by a comparison of the measured values for a laboratory melt of a weather-resistant WT steel (points ○, cf. e.g. WTSt 37-3, DIN-Mat. No. 1.8961 or WTSt 52-3, DIN-Mat. No. 1.8963) in Figure 2 with the scatter range of the other steels. In the splash zone, the values for the WT steel are below the scatter band, in the tidal zone at the lower edge of the scatter band and in the immersion zone they fall within the scatter band, i.e. the protective effect is no longer present in the immersion zone.

Inhomogeneous covering layers that hinder oxygen access to varying degrees, are one of the causes of local shallow pit corrosion. Figure 3 shows that for the steels tested in Table 18 there is a close correlation between lower mass losses in the splash zone and increasing shallow pit depth in the immersion zone. Materials with alloying elements that favour formation of protective coatings in the presence of sufficient oxygen access, logically show the lowest mass losses in the splash zone (△, ○). In the immersion zone, these covering layers show incomplete development, so that instead of uniform surface corrosion in these steels shallow pit-like corrosion occurs [16].

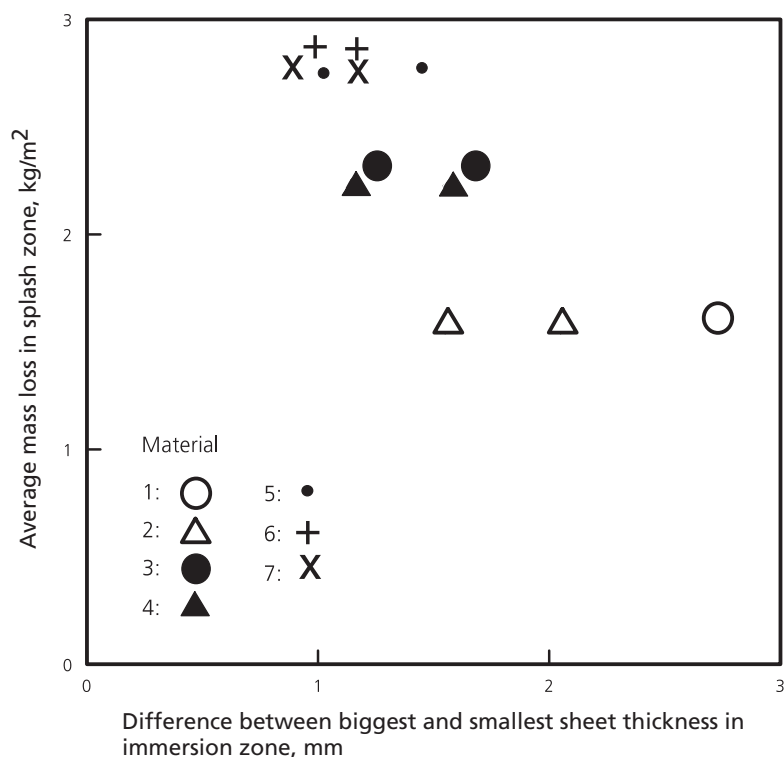
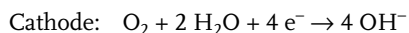
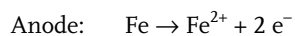


Figure 3: Connection between corrosion mass loss in the splash zone and locally varying corrosion depth in the immersion zone after 3.5 years, materials see Table 18 [15, 16]

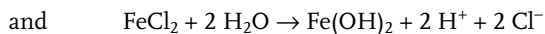
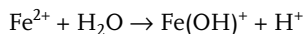
In cases involving inhomogeneous covering layers or damaged homogeneous covering layers, surfaces with different oxygen access levels are adjacent, resulting in the development of corroding elements. Such a corroding element is called an **aeration element** due to the different oxygen content levels at anode and cathode. Due to diffusion inhibition the areas under the covering layers are exposed to less oxygen and thus become anodes at which metal dissolution tends to occur. On the surfaces with more exposure to water containing oxygen, with the thinner covering layers or less damaged covering layers, the cathodic reaction of oxygen reduction tends to predominate.



The increase in pH level due to the OH^- ions thus formed results in the increasing passivation of these areas.



The following hydrolytic reactions



result, at the anode, in a lowering of the pH level and thus to increased corrosion.

Uniform surface corrosion, i.e. corrosion at a nearly uniform corrosion rate over the entire surface, is usually less problematic from an operational point of view. This factor can be taken into account in the structural element design in the form of an anticorrosive additive and can be controlled in many structural elements by means of regular wall thickness measurements, e.g. by ultrasonic means. Much more difficult problems result from local corrosion types such as pitting corrosion and stress corrosion cracking (SCC). The corrosion types are difficult to control and can rapidly lead to failure of structural elements after only a low level of mass loss. Damage from such corrosion types are rarely predictable and not only cause considerable losses in economic terms but also entail risks to safety and environmental protection. This applies in particular to system elements that must function under pressure.

V 3.2 Pitting corrosion and crevice corrosion

In general, susceptibility to local corrosion becomes greater as resistance to uniform surface corrosion increases. Uniform surface corrosion is practically negligible in metals that form a passivation layer or homogeneous protective layer in seawater, such as aluminium materials, stainless steels and copper materials. However, if the passivation or protective layer is not produced uniformly over the entire metal or if it is locally disrupted by certain components of the water or if the protective layer suffers local damage, these become anodic sites that are many times smaller than the surface areas of the intact passivation or protective surface. Since the ratio of these small, locally active sites to the large passivated areas is very unfavourable, the dissolution current density at the small anodic sites is very high in accordance with the area rule, so that, for example, pitting corrosion can achieve considerable penetration depths within a short period of time.

Chloride ions in aqueous solutions represent a specific corrosive agent for pitting corrosion on passive materials. In seawater as well, the chloride ions are responsible for pitting corrosion. The starting point for pitting corrosion is a locally increased adsorption of chloride ions to damaged or weak points in the passivation layer.

Such sites may be created on the metal surface by:

- inclusion of sulphides, oxides or nitrides
- dislocation
- broken slip lines.

Pitting corrosion of passive materials can result in corrosive damage within a short time despite the low mass losses at the small anodic sites. Hemispheric, crater or pinpoint corrosion sites may develop. There is then practically no surface corro-

sion besides the pitting corrosion. Determining the mass loss rates is therefore not a suitable means of assessing corrosion behaviour in seawater in these passive materials.

The general electrochemical corrosion behaviour and pitting corrosion behaviour of a stable passive or passivable metal can be assessed in terms of the **current-potential curve** (or current density-potential curve). Figure 4 schematically presents such a curve for a passive metal corroded in acids, e.g. chromium in sulphuric acid. Corrosion current I per unit of surface area (current density in A/cm^2) is plotted against the potential U .

As the potential increases, the material goes through the states “active,” “passive” and “transpassive.” At low potential levels, the corrosion current increases with the potential in the active range, as does metal dissolution according to Faraday’s law.

When the passivation potential U_{pas} is exceeded, the corrosion current value i_A drops to very low levels and metal dissolution practically ceases. In practical terms, the corrosion current then remains at a constant low level even as the potential continues to increase. The metal surface is protected by a very thin, invisible oxide layer (passivation layer).

Current density i

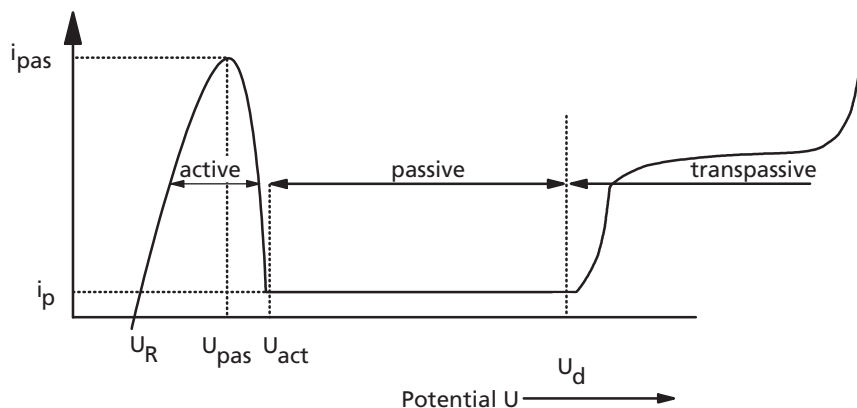


Figure 4: Anodic current-potential curve of a passivable metal (schematic)

- U_R = Rest potential
- U_{pas} = Passivation potential
- U_{act} = Activation potential
- U_d = Transpassive breakthrough potential
- i_{pas} = Passivation current density
- i_p = Dissolution current density in the passive state

For passivation, the passivation current density i_{pas} must be applied either by means of an anodic current (polarisation) or in the reaction with an oxidant at passivation potential U_{pas} . In the active and passive range, trivalent chromium (Cr^{3+}) is dissolved. Above the transpassive breakthrough potential U_d , i.e. after the transition to the transpassive range, the current density, and with it the rate of corrosion, rises once again, since at this high oxidation potential chromium then dissolves in hexavalent form (Cr^{6+}) as chromate.

In stable passive metals, for instance stainless steels, the weak oxidant water is sufficient to effect the transition to the passive range. The presence of oxygen in the water is not required for this purpose. The passivating oxide layer is quickly replaced following a mechanical rupture (repassivation). As a rule, the balance potential of the existing redox system, i.e. the redox potential of the corrosive agent, is established within a brief period. Stainless steels are therefore preferred for use in mediums the redox potential of which passivates them. In these mediums, the uniform surface corrosion levels are so small with free corrosion that the structural element can be expected to have a technically acceptable service life.

Generally speaking, the practical limit for corrosion resistance is considered to be a corrosion rate w of $w \leq 0.1 \text{ mm/a}$ ($\leq 4 \text{ mpy}$).

In steels, a relation holds between the three corrosion parameters

- corrosion current density: i in A/m^2
- mass loss rate per unit of surface area: v in $\text{g}/(\text{m}^2 \text{ h})$
- corrosion rate: w in mm/a (mpy)

as follows:

$$i = 1 \text{ A/m}^2 \triangleq v = 1 \text{ g}/(\text{m}^2 \text{ h}) \triangleq w = 1 \text{ mm/a} (39.37 \text{ mpy})$$

Besides a critical concentration of chloride ions, an additional precondition for development of pitting corrosion is exceeding a critical potential, the breakthrough potential for pitting corrosion (or: pitting potential) U_{pp} . In the current-potential curve, this value is characterised by a sharp increase in corrosion current. Therefore, pitting corrosion only results from corrosion stress due to a corrosive agent containing chloride if the corrosion potential of the steel assumes higher positive values than the pitting potential.

The resistance of a steel to pitting corrosion can be determined by comparing its current-potential curve in the relevant medium with the redox potential. This is explained in Figure 5.

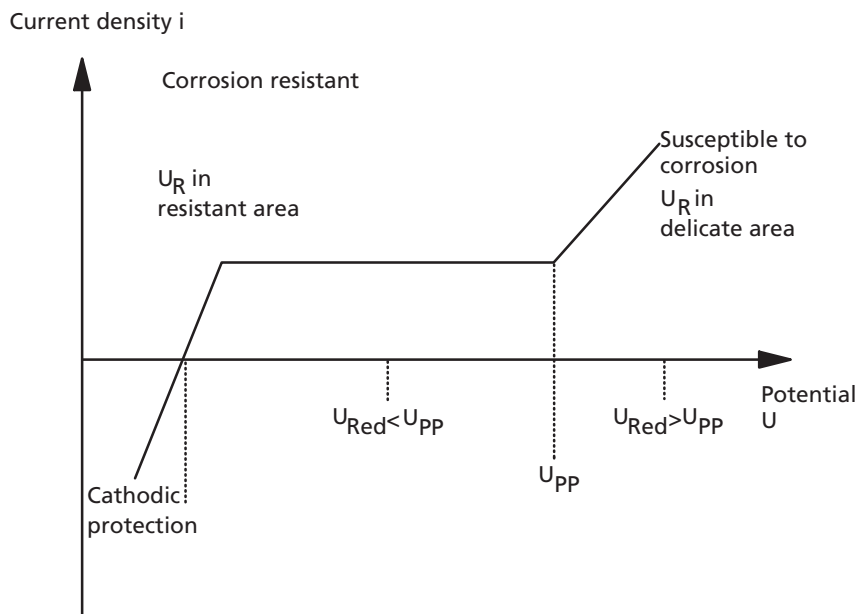


Figure 5: Schematic current-potential curve of stainless steels in neutral solution containing chloride

U_R = Rest potential

U_{Red} = Redox potential

U_{PP} = Breakthrough potential for pitting corrosion (pitting potential)

If the potential U_{PP} for stable pitting corrosion shows more positive values than the redox potential U_{Red} , no pitting corrosion can occur, since under long-term corrosion exposure the corrosion potential of the steel shifts in the direction of the redox potential, but cannot assume higher potential levels.

$$U_{red} < U_{PP} \rightarrow \text{resistant}$$

In the opposite case, the risk of pitting corrosion is always present.

$$U_{red} \geq U_{PP} \rightarrow \text{susceptible}$$

Higher redox potential U_{red} , i.e. higher content levels of oxidants, thus raise the risk of pitting corrosion because they shift the rest potential U_R of the steel in the direction of the pitting potential U_{PP} .

The pitting potential U_{PP} therefore represents in simple terms the susceptibility of a material to pitting corrosion. The resistance to pitting corrosion is greater the more positive the pitting potential. With increasing chromium or molybdenum content, the pitting potential of stainless steels is shifted to more positive values, i.e. resistance to pitting corrosion is increased, whereby the effect of molybdenum is about three times that of chromium.

The alloying elements nickel and manganese have no influence on the pitting potential. However, as the nickel content increases, the active dissolution rate in the

pit decreases. Existing pits grow more slowly and take longer to reach a critical size for the structural element. Nickel also facilitates the repassivation of existing pitting corrosion sites once the material has temporarily fallen into the critical potential range for pitting corrosion.

The resistance of the stainless steels to pitting corrosion is determined mainly by their content of the alloying elements chromium and molybdenum. The pitting resistance equivalent of a given steel can therefore be estimated based on its composition. The varying effectiveness of the alloying elements is taken into account by introducing the parameter **pitting resistance equivalent PRE** [17].

$$\text{PRE} = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo}$$

As the PRE increases, the pitting resistance of the steels increases. The chromium and molybdenum amounts in the form of carbides, nitrides or bound in intermetallic phases are without effect.

Figure 6 demonstrates the mainly linear dependence of pitting potential on the pitting resistance equivalent in a number of stainless steels.

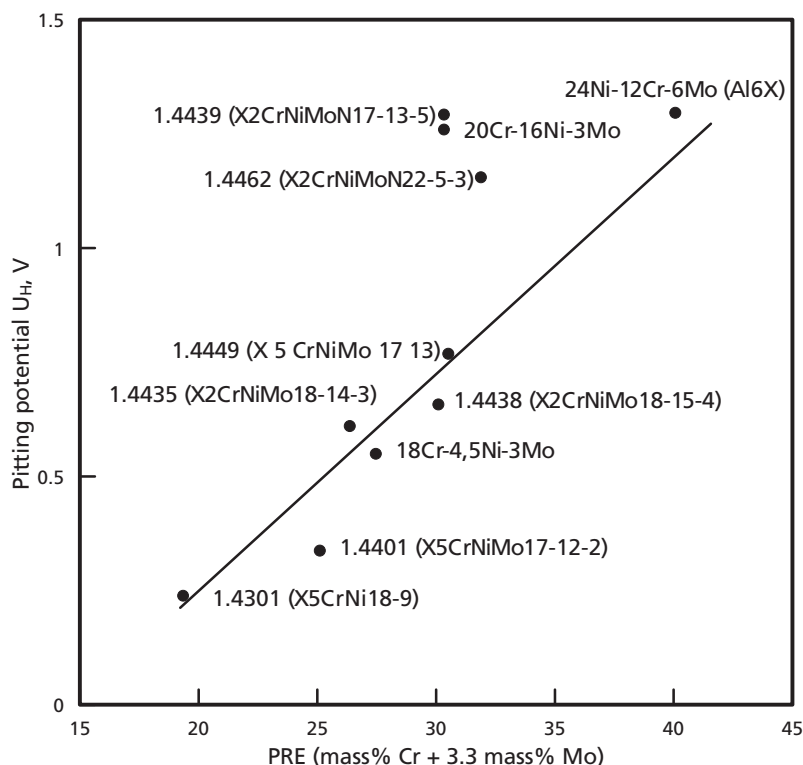


Figure 6: Dependence of pitting potential U_{pp} stainless steels in NaCl solution with $c(\text{NaCl}) = 1 \text{ mol/kg}$ at 293 K (20 °C) on the pitting resistance equivalent (PRE) [17]

Deviations from linearity in high-alloyed molybdenum steels are due to the favourable effect of nitrogen. For these steels, the nitrogen content can be taken into account in the pitting resistance equivalent. For austenitic stainless steels alloyed with at least 3% molybdenum:

$$\text{PRE} = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo} + 30 \times \text{mass\% N}$$

For austenitic-ferritic steels, for example DIN-Mat. No. 1.4462 (X2CrNiMoN22-5-3):

$$\text{PRE} = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo} + 16 \times \text{mass\% N}$$

The nitrogen component does increase resistance to pitting corrosion compared to steels containing the corresponding amounts of chromium and molybdenum, but it cannot compensate for lower chromium or molybdenum content levels [5].

The pitting resistance equivalent equations with nitrogen apply to welded connections only if the same high nitrogen content is assured in the welded connection. If this is not possible when using welding fillers of the same type, the reduced nitrogen content in the welded connection can be compensated by use of higher alloy content levels of chromium and molybdenum in the welding filler. At any rate, the significance of the pitting resistance equivalent, which actually only allows for an estimation of the pitting resistance equivalent, should not be given too much weight when selecting the material.

Figure 7 shows, based on a schematic current-potential curve, how the different alloying elements and the steel companion elements effect the corrosion behaviour of stainless steels.

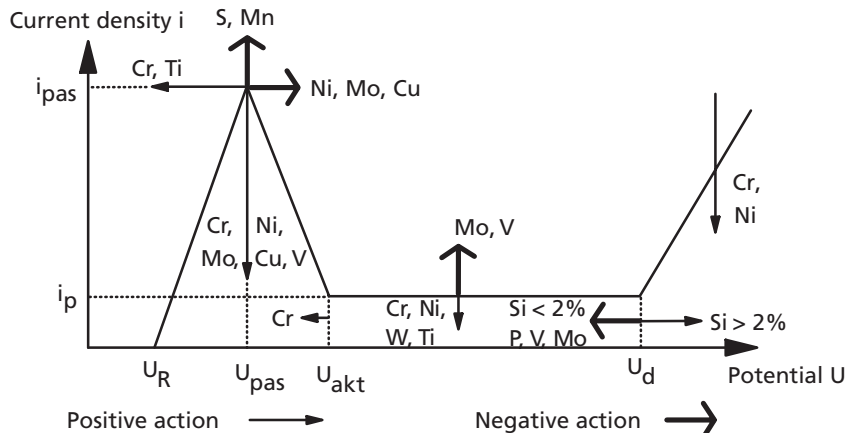


Figure 7: Influence of alloys and companion elements on corrosion of stainless steels [18]

- U_R = Rest potential
- U_{pas} = Passivation potential
- U_{akt} = Activation potential
- U_d = Transpassive breakthrough potential
- i_{pas} = Passivation current density
- i_p = Dissolution current density in the passive state

Besides the chemical composition, the other major factors in behaviour of stainless steels in terms of risk of pitting corrosion include:

- structure and purity of the steel
- processing
- surface status
- construction
- corrosive agent
- operating conditions.

Therefore it is not the average chemical composition of the steel that is responsible for its corrosion resistance, but rather the locally present chemical composition. All metallurgic processes that result in poorer homogeneity reduce corrosion resistance. This includes in particular the separation of carbides or intermetallic phases, withdrawing alloying elements from the matrix that can then not contribute to the “local pitting resistance equivalent”.

Molybdenum shows a strong tendency to precipitate. High-alloyed molybdenum steels therefore require particular care in production and processing to preserve the full effect of this alloying element.

Pitting usually starts at material inhomogeneity sites, e.g. sulphide inclusions in the surface. Not only the sulphur content of the steel plays a role here, but also the number and distribution of sulphides [19]. Since the sulphur contents of steels have dropped constantly in new steel production processes, modern steels are less susceptible to pitting corrosion than comparable qualities from earlier production.

The modern pan metallurgic processes not only reduce the amounts of sulphur in the steel, but also have favourable influences on the inclusion and distribution of sulphides. However, in many corrosive mediums the dissolution of the sulphide inclusions results in stable pitting corrosion only in steels with a low pitting resistance equivalent. In steels with a higher pitting resistance equivalent, the corrosion sites are repassivated.

In materials used and exposed in the active state, such as unalloyed and low-alloyed steels, conditions favour shallow pit and pitting corrosion if oxygen reduction is inhibited less than iron dissolution due to covering layers of all kinds and iron dissolution is unhindered at damaged sites on the covering layer. This is always the case in porous covering layers. Examples of such covering layers are mill scale with oil film or paint coatings and other unsuitable coatings.

Removal of mill scale is generally helpful in terms of corrosion protection. Whereas in seawater unprotected steel loses the mill scale relatively quickly due to rusting loss, the scale can adhere longer in brackish water and, if oil films are present, lead to pitting corrosion. In such cases, abrasive blasting can prevent the much less desirable pitting corrosion in favour of the less dangerous general corrosion.

Cathodic protection is generally a reliable protective measure against pitting corrosion.

Crevice corrosion in stainless steels is also only observed in corrosives containing chloride. As with pitting corrosion, crevice corrosion is initiated after a critical potential is exceeded. This threshold potential for crevice corrosion is always at a level further into the negative range than the pitting potential for the same material in the same solution. Crevice corrosion can therefore also occur in a material that is resistant to pitting corrosion in a given medium.

The reason for this is that oxygen access to the crevice is hindered and, the adsorption of chloride ions in the crevice and hindrance of liquid exchange. The result is a raised concentration of chloride ions in the electrolyte solution in the crevice compared to the rest of the electrolyte solution. The corrosion potential is exceeded in the crevice once the concentration of these ions is high enough.

In the ensuing crevice corrosion process, chloride-rich corrosion products with high iron and chromium contents are produced. The pH level of the electrolyte solution in the crevice is reduced by hydrolysis of these salts, accelerating the corrosion process. The probability of corrosion for a surface with crevices is thus greater than for a surface with no crevices. The level of the critical potential is determined mainly by the crevice geometry and the material involved [20, 21].

In unavoidable, construction-related crevices and in cases where deposits must be reckoned with, under which corrosion can also occur, a material with a higher pitting resistance equivalent must be selected than the pitting resistance equivalent alone would require.

With increasing chloride concentration and temperature and falling pH level, the threshold potential values for occurrence of pitting and crevice are shifted further into the negative range of potentials. Figure 8 illustrates the example of the connection between pitting potential and the chloride concentration for the steel 1.4439 (X2CrNiMoN17-13-5, cf. SAE 317 LMN) at two temperatures.

To ensure resistance to pitting corrosion or crevice corrosion, it is therefore also necessary to select a material with a higher pitting resistance equivalent in mediums with higher temperatures and/or with higher chloride ion content levels.

Table 6 shows examples of the pitting resistance equivalents required for steels to achieve sufficient levels of pitting resistance at various temperatures in seawater [23].

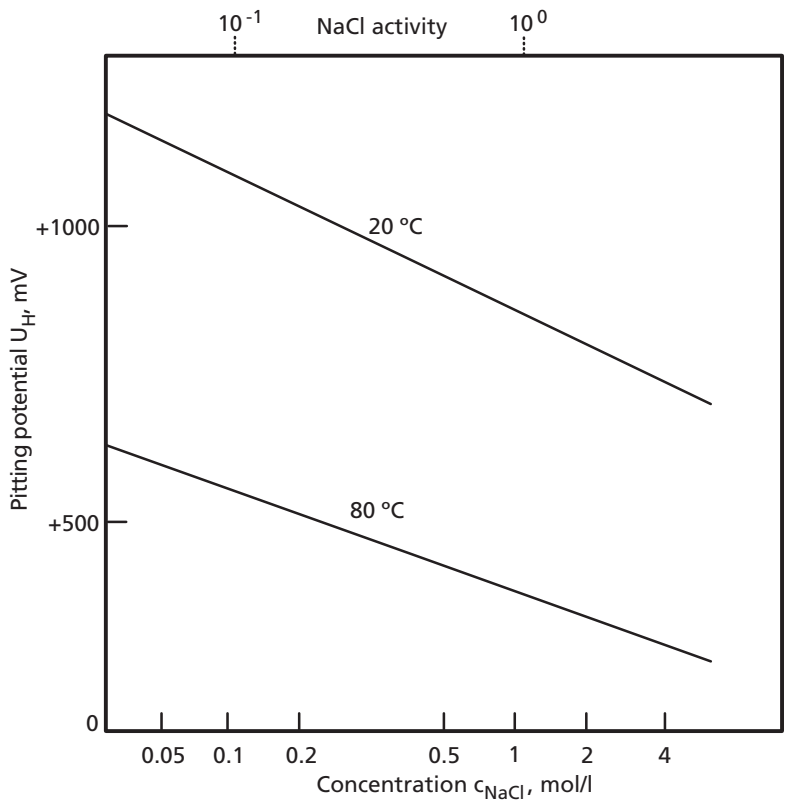


Figure 8: Dependence of pitting potential U_{pp} of the steel 1.4439 (X2CrNiMoN17-13-5, cf. SAE 317 LMN) on chloride ion concentration at 293 K and 353 K (20 °C and 80 °C) [22]

Pitting resistance equivalent	Threshold temperature for pitting resistance equivalent
35	313 K (40 °C)
30	298 K (25 °C)
25	283 K (10 °C)

Table 6: Threshold temperatures for pitting resistance equivalent in seawater at a given pitting resistance equivalent [23]

Figure 9 shows resistance to pitting corrosion of the high-alloyed steels and nickel alloys most frequently used in seawater [23]. The pitting resistance equivalent is listed for comparison [5].

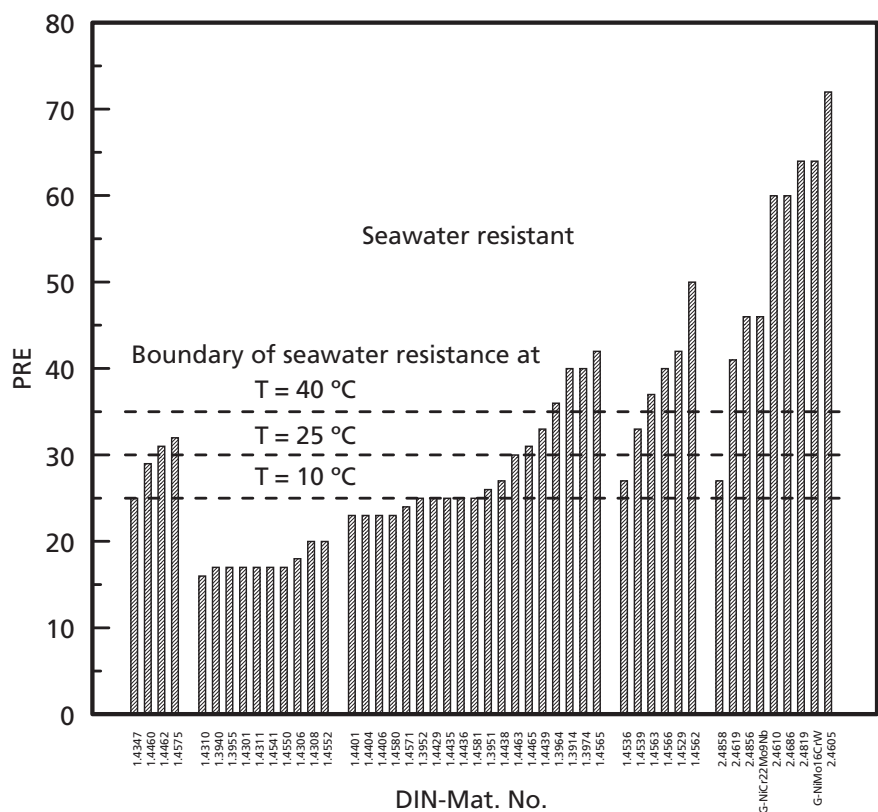


Figure 9: Resistance to pitting corrosion of high-alloyed steels and nickel alloys in seawater based on the pitting resistance equivalent (PRE) [5, 23]

Pitting and crevice corrosion can be avoided by means of cathodic corrosion protection (CCP). The effectiveness of cathodic protection for crevice corrosion is, however, limited by the crevice geometry.

Higher flow rates can have a positive effect on both pitting corrosion and crevice corrosion, since the enhanced substance exchange with external electrolyte solution reduces the accumulation of chloride ions, lowers the pH and reduces oxygen depletion in the pit or crevice. Washout of the pitting or crevice electrolyte solution makes stabilisation of the pitting or crevice corroding element more difficult. In favourable cases, corrosive processes that have already begun can be stopped and the corrosion sites repassivated.

V 3.3 Stress corrosion cracking

Stress corrosion cracking (SCC) can occur under the following conditions:

- Presence of a critical system “material/corrosive agent”, i.e. a specific corrosive agent acting upon a material susceptible to SCC.
- Material load resulting from static or dynamic tensile stresses (either constant over time, increasing over time or with low-frequency oscillation).
- These are critical conditions regarding the temperature and concentration of the medium and the potential.

Characteristic of this type of corrosion is low-deformation separation, in most cases without formation of visible corrosion products and without measurable mass losses. The necessary tensile stresses can result from either internal stresses in the structural element or from operational stress loads. A material resistant to stress corrosion cracking (SCC) when delivered can be sensitised for stress corrosion cracking by means of improper heat treatment, e.g. during welding or from deformation.

A special type of stress corrosion cracking may occur if atomic hydrogen, produced during corrosion reactions or pronounced cathodic polarisation at the steel surface, diffuses into the interior of the material. The diffusion of this hydrogen into the material enhances by promoters, e.g. hydrogen sulphide, in the corrosive agent. In materials with low levels of ductility and high strength, this hydrogen can then prevent reduction of internal stresses to the extent that cracking occurs (hydrogen-induced stress corrosion cracking, H-SCC).

Under critical conditions in high-strength steels (Table 23), hydrogen-induced stress corrosion cracking in seawater is conceivable. If at all, it would be expected in the increased hardness zones around the welding seam and under conditions of cathodic polarisation. Analyses of the welding seam areas in bending samples of high-strength steels with yield strengths of 355-890 N/mm² revealed no cracking after exposure periods of three years and cathodic polarisation of the samples by means of contact with zinc anodes. These tests support the conclusion that the risk of hydrogen diffusion into the materials is minimal, even in welded high-strength steels, and even with cathodic polarisation within the normal potential ranges used for cathodic corrosion protection (CCP) [24].

However, these findings apply only to the constant elongation stress mode and under the condition that no conditions enhancing hydrogen absorption apply, examples of which are:

- The presence of promoters, for instance in the form of sulphides from sulphate-reducing bacteria in anaerobic areas under fouling
- Low pH levels due to hydrolysis of corrosion products
- Gradual plastic-dynamic deformations.

In cases of plastic deformations within a critical rate range, however, even relatively soft structural steels in seawater may be at risk for hydrogen-induced stress corrosion cracking [25].

The austenitic chromium-nickel steels are highly resistant to this type of damage due to their high levels ductility, ready solubility for hydrogen in the austenitic matrix and low diffusion rates. Higher-strength ferritic and martensitic steels are more sensitive to this type of hydrogen-induced stress corrosion cracking. Alloying with nickel increases ductility to reduce the hydrogen diffusion risk. The sensitivity of nickel martensites is thus much lower than that of carbon-hardened chromium steels of comparable strength.

Cracks resulting from stress corrosion cracking (SCC) can occur in stainless steels in solutions containing chloride ions at temperatures above approx. 323 K (50 °C). The cracks are mainly transgranular and they occur when a critical threshold potential is exceeded. Figure 10 shows test results obtained in the boiling 42% magnesium chloride solution frequently used in laboratory tests [26].

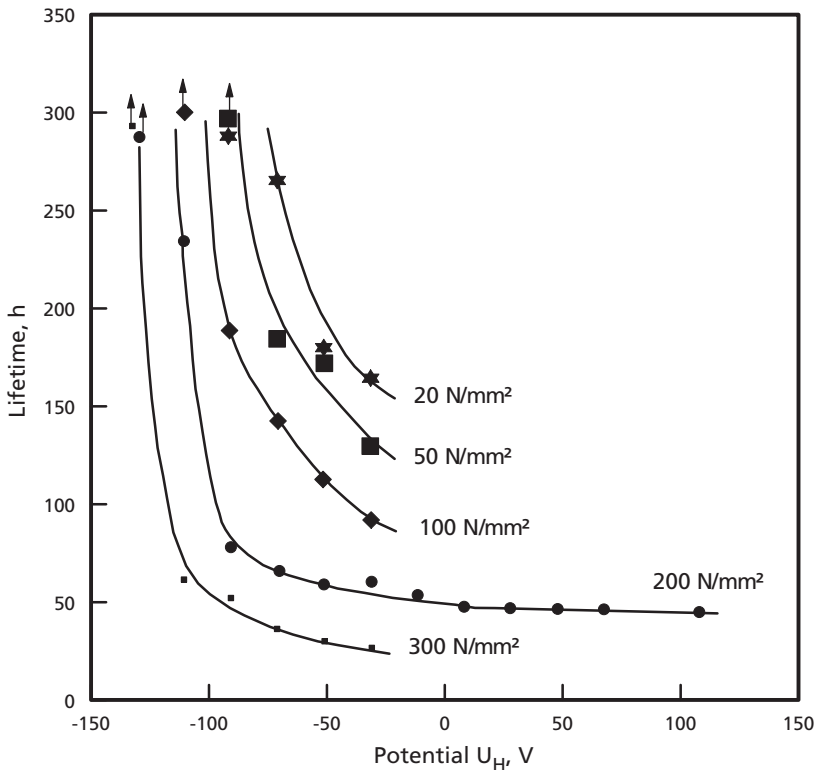


Figure 10: Influence of potential and tensile stress on the material life of tensile-test specimens made of 1.4301 steel (SAE 304, X5CrNi18-10) in boiling 42% MgCl_2 solution [26]

To reduce internal stresses in the material by means of stress-relief annealing, high temperatures exceeding 1173 K (900 °C) are required for stainless steels due to their high levels of thermal strength. Due to these high temperatures stress-relief

annealing of stainless steels is problematic, since warping is to be expected in thin-walled structural elements. The effectiveness of such annealing processes in avoiding stress corrosion cracking is also questionable, since the threshold stress levels that must be exceeded to initiate stress corrosion cracking are very low in many cases.

As shown in Figure 10, tensile stress levels of 20 N/mm^2 suffice to produce cracks resulting from stress corrosion cracking in austenitic 18/10-CrNi steels in aggressive chloride solutions at higher temperatures. This level is easily reached by both operational and internal stresses. The threshold tensile stress levels listed for stress corrosion cracking in stainless steels should therefore not be used as a basis for calculation in structural element designing.

Sufficient tensile stress levels to initiate stress corrosion cracking can also be created by coarse grinding of the surface in austenitic CrNi steels. Therefore, stressed surfaces ground in this manner must be etched off with strong mordant [27].

The extrapolation of the results obtained in boiling magnesium chloride solution to operational conditions is highly problematic. Concentrated acidic chloride solutions, such as MgCl_2 - or CaCl_2 solutions, can initiate stress corrosion cracking directly. In practically neutral aqueous chloride solutions, including seawater, prior pitting corrosion is generally a precondition for the initiation of corrosion cracks. The preconditions for corrosion cracks are created by accumulation of chloride ions and reduction of pH level due to hydrolysis of the corrosion products in the electrolyte solution present in the pit. The notch factor of the pitting also adds to local stress.

Stress corrosion cracking starting at pitting corrosion sites can therefore also occur in less aggressive mediums that do not cause stress corrosion cracking directly. In stainless steels, this means resistance to stress corrosion cracking is coupled to resistance to pitting corrosion.

The following steels can be used instead of stainless austenitic 18/10-CrNi steels if there is a risk of stress corrosion cracking:

- stainless ferritic chromium steels with 17-18% chromium with or without addition of molybdenum,
- ferritic-austenitic chromium-nickel steels (duplex steels) or
- austenitic chromium-nickel steels with increased nickel and/or molybdenum content.

As shown in Figure 11, nickel is the main alloying element used to increase the resistance of austenitic materials to stress corrosion cracking [28].

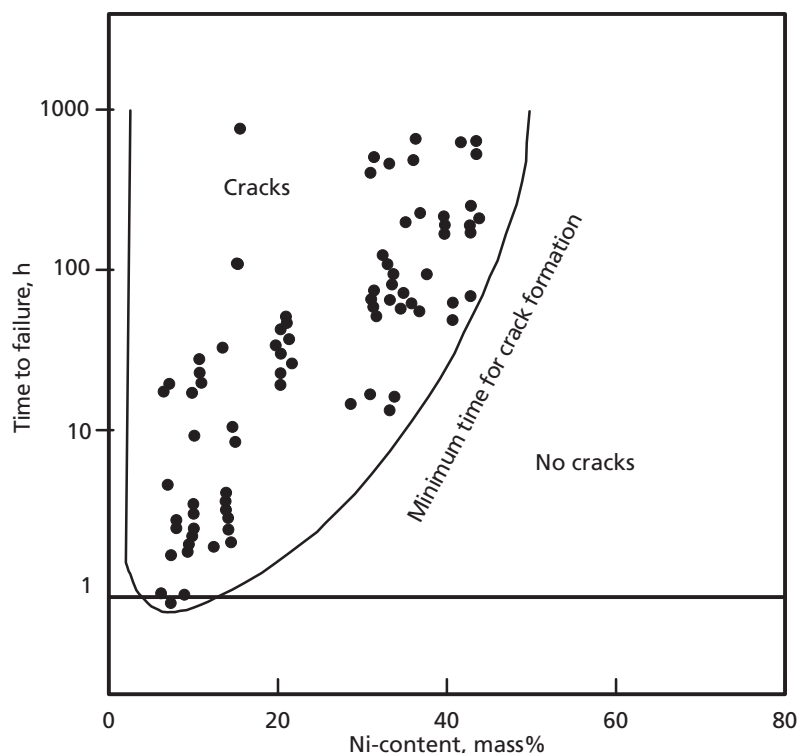


Figure 11: Influence of nickel content in steels with 18% chromium on stress corrosion cracking in boiling 42% MgCl_2 solution [28]

V 3.4 Corrosion fatigue

Corrosion fatigue (CF) can occur in all metallic materials when stress corrosion occurs concurrently with alternating mechanical stress. In contrast to stress corrosion cracking, which occurs only with specifically acting corrosive agents, CF can be produced in practically all corrosive mediums, that is in seawater as well. There are also no critical threshold conditions for the occurrence of CF as to the corrosion system or level of mechanical load required. It depends essentially on the material, material surface and mechanical stress parameters. A strong local corrosive effect results in increased susceptibility to corrosion fatigue due to the notching effect of corrosion troughs or pitting. Smooth samples can be protected by cathodic polarisation, but notched samples cannot. Therefore, cathodic corrosion protection (CCP) cannot prevent corrosion fatigue itself, although it can prevent development of critical shallow pits and thus indirectly prevent corrosion fatigue as well.

Compared to the Wöhler curve determined in exposure to air, the fatigue strength curve under CF conditions is steeper and the materials no longer reach a fatigue

limit. Instead of fatigue limit values, fatigue life values must be used for calculations under conditions of corrosion stress.

In view of the importance of this problem, especially in the field of offshore technology, a number of research projects have investigated it over the years. Special themes have also been covered, e.g.

- the influence of aftertreatment of welding seams,
- behaviour of UP-welded samples
- crack discovery and crack propagation measurement
- influence of frequency on behaviour of higher-strength steels.

Stainless steels are, generally speaking, passivated, but they can also be used in the active state if the attendant corrosion rates are sufficiently low. CF can occur in both states, although the appearance does differ:

- CF in the active state: numerous cracks
- CF in the passive state: few cracks or a single initial crack

In the passive state the corrosion fatigue usually originates at pitting corrosion sites. Resistance to corrosion fatigue therefore increases

- with increasing corrosion resistance and
- with increasing fatigue strength of the steel.

V 3.5 Contact corrosion

Contact corrosion can occur when two or more metals or metallic materials and electron-conducting solids with different free corrosion potentials U_R (rest potential) are interconnected so as to conduct electrons in the same electrolyte solution. The contact site not necessarily needs to be in the corrosive medium. The position of the materials in the practical **electrochemical series** for seawater decides which material will become the anode and which the cathode of the corroding element when they are paired. The corrosion potential of the cathode is lowered, that of the anode is raised.

Compared to the values for free corrosion, in contact corrosion the mass loss per unit area in the anodic material increases and is greatly reduced in the cathodic material, although it is not reduced to zero. The corrosion risk to the less noble material increases with the ratio of cathode surface area to anode surface area. The greater aggressiveness at the anode is particularly noticeable near the cathode.

The electrochemical series published in the literature must be differentiated as either the standard electrochemical series or the different practical electrochemical series, since the latter apply only to a certain given medium. The standard electrochemical series lists only the potentials of the pure elements in the list measured under standard conditions in a solution of their own salts against the normal hydrogen electrode.

The practical electrochemical series lists metallic and nonmetallic materials or chemical compounds, for example iron oxide, in the order of their free corrosion

potentials and apply only in the specific solution. The electrochemical series do not justify any conclusions concerning the corrosion behaviour of a single material. They serve only as an assessment of potential corrosion risk of the materials in electrical conducting contact. They also specify anode and cathode in particular material pairings, but provide no basis for a quantitative conclusion concerning the degree of corrosion.

The practical electrochemical series in Table 7 lists the relative free potentials of important metals and nonmetals in seawater at approx. 288 K (15 °C) [5].

Carbon, graphite	Positive
Iron(III)oxide (rust, scale)	
Stainless austenitic CrNiMo steels with more than 2.5% Mo, passive	
Titanium	
Ni80Cr13Fe6.5, passive	
Stainless austenitic CrNi steels, passive	
Stainless ferritic, or martensitic steels, passive	
Copper(I)oxide	
Silver, silver solders	
Nickel, passive	
Nickel-copper alloys	
Copper-aluminium alloys	
Copper-nickel alloys	
Copper-tin alloys (bronze)	
Copper-tin-zinc alloys (red brass)	
Copper-tin-zinc (lead) alloys	
Copper	
Copper-zinc alloys (brass)	
Tin	
Lead	
Ni80Cr13Fe6.5, active	
Nickel, active	
Stainless austenitic CrNi steels, active	
Stainless ferritic steels, active	
Lead-tin solders	
Hard chromium	
Cast iron	
Low alloyed steels	
Non alloyed steels	
Pure aluminium and zinc-free aluminium alloys	
Zinc containing aluminium alloys	
Zinc and zinc alloys	
Magnesium and magnesium alloys	Negative

Table 7: Practical electrochemical series in flowing seawater at 288 K (15 °C) [5]

Detailed information and tables on the compatibility of the most important metallic materials used in seawater are found in [29].

In systems that use seawater or brackish water as coolants, a hybrid design with different materials cannot always be avoided. To obtain data on the corrosion chemistry and chemical behaviour of material combinations in these mediums, an automated electrochemical measuring system was developed capable of measuring the free corrosion potentials of the individual materials, the mixed potentials of shorted material combinations and the flowing elemental current [30].

The result obtained in this way are summarised in **contact corrosion tables**, examples of which are contained in Table 9 a)–f). The elemental current densities in particular allow for a much more useful prediction of corrosion risks in hybrid constructions compared to the practical electrochemical series. The measurements were carried out on samples with an area ratio of 1:1 and a distance of 10 mm [30, 31]. The usefulness of the values is limited for other area ratios.

In these contact corrosion tables, the measured values are listed according to the scheme in Table 8.

Material combination	Copper				
Unalloyed steel	<table border="1"> <tr> <td>1</td><td>2</td></tr> <tr> <td>3</td><td>4</td></tr> </table>	1	2	3	4
1	2				
3	4				

Table 8: Scheme for contact corrosion tables

- 1: Free corrosion potential U_R of unalloyed steel: mV (U_H)
- 2: Free corrosion potential U_R of copper: mV (U_H)
- 3: Mixed potential U of unalloyed steel/copper: mV (U_H)
- 4: Corrosion current density i of the combination: $\mu\text{A}/\text{cm}^2$

Assuming that the corrosion current densities in most cases represent corrosion of the material with the lower potential, which can be assumed in most applications, the values listed under 4 can be converted into mass loss rates v using the following equation:

$$v = 0.373 \frac{Mi}{z} (\text{g}/(\text{m}^2\text{h}))$$

$$v = 8.95 \frac{Mi}{z} (\text{g}/(\text{m}^2\text{h}))$$

whereby:

- v Mass loss rate per unit area in $\text{g}/\text{m}^2 \text{ h}$ or $\text{g}/\text{m}^2 \text{ d}$
- M Atomic mass of metal in g/mol
- i Current density in mA/cm^2
- z Proton number of the metal

Temperature	Materials	Cast iron	17% Cr steel	18/9 CrNi steel
293 K (20 °C)	unalloyed steel	-515 -520 -520 4	+120 -520 -500 11	+130 -520 -515 7
313 K (40 °C)	unalloyed steel	-515 -535 -520 14	-235 -540 -525 13	+95 -540 -505 32

Table 9 a): Contact corrosion table in synthetic seawater

Temperature	Materials	Zn 99.99	Al 99.99	Pb 99.99
293 K (20 °C)	unalloyed steel	-790 -520 -780 16	-530 -525 -525 6	-255 -525 -500 19
313 K (40 °C)	unalloyed steel	-795 -540 -780 38	-880 -545 -550 9	-320 -540 -500 35

Table 9 b): Contact corrosion table in synthetic seawater zinc aluminium lead

Temperature	Materials	Copper	Brass	CuNi30Mn1Fe
293 K (20 °C)	unalloyed steel	+10 -52 -505 20	+30 -520 -500 22	+25 -520 -505 12
313 K (40 °C)	unalloyed steel	-30 -540 -505 28	+120 -535 -480 35	-25 -540 -495 24

Table 9 c): Contact corrosion table in synthetic seawater

<i>Temperature</i>	<i>Materials</i>	<i>Cast iron</i>	<i>17% Cr steel</i>	<i>18/9 CrNi steel</i>
293 K (20 °C)	unalloyed steel	-500 -500 2	+145 -520 -505 31	+135 -500 -475 28
313 K (40 °C)	unalloyed steel	-490 -460 -480 19	+180 -470 -460 24	+150 -470 -460 29

Table 9 d): Contact corrosion table in brackish water

<i>Temperature</i>	<i>Materials</i>	<i>Zn 99.99</i>	<i>Al 99.99</i>	<i>Pb 99.99</i>
293 K (20 °C)	unalloyed steel	-805 -515 -780 27	-450 -525 -520 5	-235 -515 -490 10
313 K (40 °C)	unalloyed steel	-770 -495 -750 28	-615 -480 -480 7	-270 -475 -470 14

Table 9 e): Contact corrosion table in brackish water

<i>Temperature</i>	<i>Materials</i>	<i>Copper</i>	<i>Brass</i>	<i>CuNi30Mn1Fe</i>
293 K (20 °C)	unalloyed steel	+45 -520 -520 9	+160 -520 -495 10	+160 -485 -480 9
313 K (40 °C)	unalloyed steel	-20 -500 -490 12	+190 -480 -475 13	+120 -490 -485 14
293 K (20 °C)	titanium	+51 +156 +61 0	+166 +145 +150 0	+152 +167 +162 0

Table 9 f): Contact corrosion table in brackish water

Table 10 summarises the potentials and the corrosion current density for the combination of an austenitic steel SAE 316 L (DIN-Mat. No. 1.4435, X2CrNiMo18-14-3) with other metals in the relatively low-salinity water of the Baltic Sea (3–5 g/kg chloride content) [32].

Time	Materials	Cast iron with lamellar graphite, GCL	Cast iron with spherical graphite, GCG	CuZn39Pb0.5, 2.0372 (Muntz metal)	Titanium	Nickel
10 d	1.4435 (SAE 316 L)	-523 +269 18.5	+513 -503 14.5	+133 +269 7.3	+297 +269 0	+27 +269 0.2
20 d	1.4435 (SAE 316 L)	-513 +269 29	+513 -493 12.5	+133 +279 5.5	+310 +279 0	+82 +279 0.1
30 d	1.4435 (SAE 316 L)	-503 +332 27	-493 -473 27	-88 +332 3.6	+292 +332 0	+122 +332 0
40 d	1.4435 (SAE 316 L)	-493 +337 39	-493 -473 27	-43 +337 3.6	+278 +337 0	+112 +337 0
50 d	1.4435 (SAE 316 L)	-493 +253 24.5	+483 -473 24	-18 +253 2.7	+287 +253 0	+107 +253 0
60 d	1.4435 (SAE 316 L)	-483 +277 24.5	+473 -453 23	-33 +277 1.1	+297 +277 0	+97 +277 0

Table 10 a): Contact corrosion table for steel DIN-Mat. No. 1.4435 (SAE 316 L, X2CrNiMo18-14-3) in contact with other metals [32]

Time	Materials	Hastelloy® C-276, DIN-Mat. No. 2.4811	CuNi10Fe1Mn, DIN-Mat. No. 2.0872	CuPb5Sn5Zn5, DIN-Mat. No. 2.1096	CuZn20Al2, DIN-Mat. No. 2.0460
10 d	1.4435 (SAE 316 L)	+207 +269 0 +225	+172 +269 0 +182	+185 +269 0.1 +191	+157 +269 0.1 +157
20 d	1.4435 (SAE 316 L)	+214 +279 0 +216	+157 +279 0.1 +157	+182 +279 0 +183	+172 +279 0.1 +172
30 d	1.4435 (SAE 316 L)	+223 +332 0 +300	+206 +332 0.1 +207	+192 +332 0 +192	+189 +332 0.1 +192
40 d	1.4435 (SAE 316 L)	+197 +337 0 +213	+203 +337 0 +207	+187 +337 0.1 +187	+182 +337 0.1 +182
50 d	1.4435 (SAE 316 L)	+194 +253 0 +227	+172 +253 0 +187	+185 +253 0 +187	+177 +253 0 +180
60 d	1.4435 (SAE 316 L)	+189 +277 0 +255	+194 +277 0 +197	+187 +277 0.1 +187	+184 +277 0.1 +187

Table 10 b): Contact corrosion table for steel DIN-Mat. No. 1.4435 (SAE 316 L, X2CrNiMo18-14-3) in contact with other metals [32]

[33] describes basic investigations of contact corrosion in combinations of different metals in synthetic seawater and in 3.5% NaCl solution. The following combinations were investigated:

- Carbon steel coupled with:
 - (0.19% C, 1.25% Mn, 0.29% Si, 0.01% S)
 - Stainless steel (SAE 316, DIN-Mat. No. 1.4435)
 - (17.1% Cr, 12.0% Ni, 2.3% Mo, 0.03% C, 0.03% S)

- Stainless steel (similar to 254 SMO, DIN-Mat. No. 1.4547)
(19.9% Cr, 18.1% Ni, 6.2% Mo, 0.01% C, 0.01% S)
- CuNi alloy
(14.7% Ni, 4.44% Mn, 1.12% Fe, 2.15% Al, 0.29% Cr, 0.27% Nb)

and

- 13% Cr steel coupled with:
(13.4% Cr, 0.50% Ni, 0.13% C, 0.42% Mn, 0.31% Si, < 0.05% Mo)
 - Stainless steel (similar to 904 S 13, 904 S 14)
(19.9% Cr, 23.9% Ni, 4.5% Mo, 1.2% Mn, 1.0% Cu, 0.37% Si, 0.06% S)
 - CuNi alloy
(14.7% Ni, 4.44% Mn, 1.12% Fe, 2.15% Al, 0.29% Cr, 0.27% Nb)
 - Nickel-based alloy (cf. DIN-Mat. No. 2.4856, Inconel® alloy 625)
(23.0% Cr, 8.2% Mo, 4.37% Fe, 3.75% Nb, 0.33% Si, 0.09% C, 0.16% Mn)
 - Nickel-based alloy
(19% Cr, 19% Fe, 3% Mo)

The tests were carried out at 291 and 331 K (18 °C and 58 °C). Samples with artificial crevices were tested in some instances. The results can be summarised as follows:

- Contact corrosion is a highly complex process and predictions are not feasible based on the electrode potential of the materials used. The potentials indicate only the driving force of the contact corrosion, whereas the resulting corrosion rate is determined by many other factors.
- The corrosion rate is often time-dependent. For example, it may drop to negligible values for less noble metals if a stable passivation layer is formed on the surface. Thus short-term results do not go far in defining conclusions concerning long term contact corrosion risks.
- The corrosion of carbon steel is more strongly influenced in contact with CuNi materials than in contact with high-alloyed stainless steels.
- In aerated solutions in motion, the contact corrosion rates are at first greater than under stagnant conditions. After longer terms of exposure, the corrosion rates are greater in NaCl solutions than in seawater.
- In seawater, fallen corrosion rates drop in time to lower values, since covering layers form on the cathodic components that hinder the cathodic chain of reactions. This results in the same corrosion rates on unalloyed steel, even under longer exposure, regardless of whether it is in contact with stainless steel or with CuNi materials. This process is for the most part independent of temperature.
- At natural ambient temperatures, calcium-rich deposits form (mainly CaCO_3) on the cathode, whereas at higher temperatures mainly magnesium compounds (Mg(OH)_2) are separated. These processes are also observed when cathodic protection is used.

Stainless steels can carry widely varying potentials depending on the prevalent seawater conditions. For high-alloyed steels (superaustenite with 6% Mo, e.g.

254 SMO, DIN-Mat. No. 1.4547 and super duplex steels, e.g. UNS S32750, DIN-Mat. No. 1.4410), Table 11 lists typical potential ranges [34].

Deaerated seawater	−155 to −225
Seawater with 0.2 mg/l O ₂	+145 to +45
Warm seawater	+345 to +445
Natural seawater	+495 to +595
Seawater with 0.5–1.0 mg/l Cl ₂	+795 to +895

Table 11: Potentials of high-alloyed stainless steels in seawater (U_H in mV) [34]

The potential values listed can change by a considerable margin if a biofilm with a high level of cathodic effectiveness forms on the metal surface at normal ambient temperature within 1–4 weeks. If chlorine is added to the seawater to prevent fouling, the reduction of the hypochlorite ions produced to chloride ions raises the potential by a considerable amount. Raising the temperature to about 25–30 °C above average seawater temperature, which would prevent formation of the biofilm, reduced the potential accordingly.

In compounds with other materials, the effect of high-alloyed stainless steels on corrosion in seawater is similar to a great extent. These steels can be connected to one another, and with other materials that are passive in seawater, without a risk of contact corrosion.

The extent to which the corrosion of unalloyed steels is increased by contact with high-alloyed steels depends to a large extent on the surface area ratios. Figure 12 shows the corrosion rate of an unalloyed steel determined in natural seawater in contact with a high-alloyed stainless steel at various different area ratios.

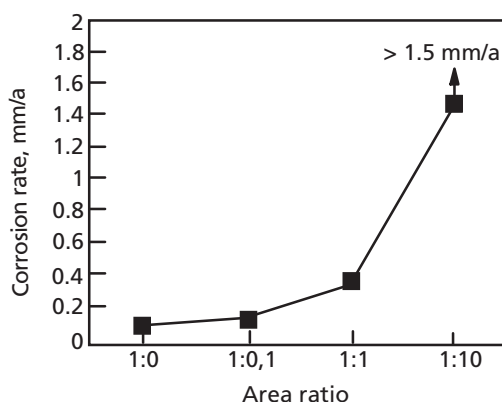


Figure 12: Corrosion rate of a carbon steel in contact with a high-alloyed steel in natural seawater as dependent on the area ratio: C steel/stainless steel [34]

If the area of the high-alloyed steel is small in relation to that of the C steel (0.1:1), the corrosion on the unalloyed steel will hardly be increased compared to free corrosion. At a ratio of 1:1 it is already increased by a factor of 5 and continues to increase at a fast rate as the area ratio becomes less and less favourable.

Figure 13 shows by the example of the connection of a pipe made of unalloyed steel with a pipe made of high-alloyed steel, that the effects of contact corrosion decline as the distance from the seam of the two metals increases. In the immediate seam area the corrosion rate for the unalloyed steel is approx. 1.5 mm/a (59 mpy), which figure is reduced to the normal value of approx. 0.15 mm/a (5.9 mpy) at a distance of about 1 m.

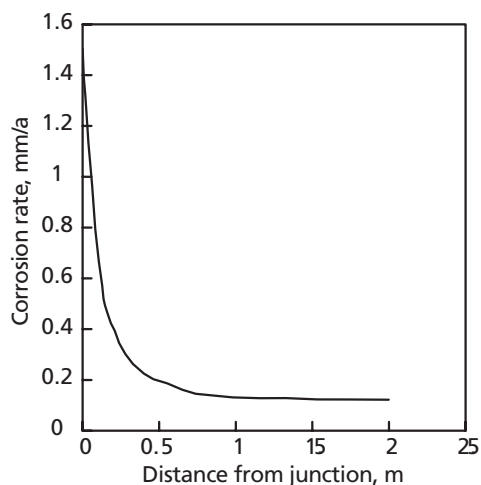


Figure 13: Corrosion rate of an unalloyed steel pipe in chlorinated seawater in contact with a high-alloyed steel pipe [34]

Contact corrosion can be avoided in composite pipelines made of unalloyed and high-alloyed steel by inserting isolation elements 2–2.5 m long (Figure 14). When made of high-alloyed steel are connected with pipes made of copper-nickel materials, isolation elements with a length equal to six times the pipe diameter are recommended [34].

In contact corrosion tests, the following materials,

- stainless steel X3CrNiMoN17-13-5 (SAE 317 LMN, DIN-Mat. No. 1.4439)
- CuNi10Fe1Mn (DIN-Mat. No. 2.0872)
- CuZn20Al2 (DIN-Mat. No. 2.0460)
- shipbuilding steel, grade A (see Table 15)
- EN AW-5083 (AlMg4.5Mn0.7, AA 5083)

were exposed for 2 years in the tidal zone and in the immersion zone on a natural seawater test platform in the North Sea (Helgoland), and in the immersion zone on a test raft in the Baltic Sea (Kiel), both isolated (Table 12) and each in contact with the others (Table 13) [35–37].

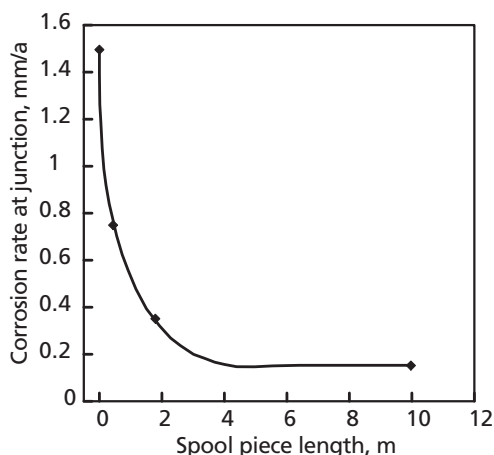


Figure 14: Corrosion rate at the conjunction of a unalloyed steel pipe in natural seawater with a high-alloyed steel pipe and with isolation elements of various lengths [34]

In the contact corrosion tests, samples with anode: cathode area ratios of 10:1, 4:1 and 1:1 were used. The dimensions of the cathodic sample were 20 cm × 40 cm. A further varied test parameter was the distance (0.2 cm, 15 cm, 100 cm) between anode and cathode. The following measured values were registered continuously:

- the free corrosion potential U_R of the samples in free corrosion
- in the contact corrosion tests
 - the corrosion potential of the anode U_a and the cathode U_k
 - the potential difference between anode and cathode and elemental current I_e

The mass loss rates per unit area of the individual materials depend to a great extent on the exposure locations (Table 12).

Material (DIN-Mat. No.)	Immersion zone		Comparison IZ	Tidal zone
	Baltic Sea	North Sea	North Sea/Baltic Sea	North Sea
	$g/m^2 h$	$g/m^2 h$	Factor	$g/m^2 h$
X3CrNiMoN17-13-5 (SAE 317 LMN, DIN-Mat. No. 1.4439)	0	0	1.0	0
CuNi10Fe1Mn (DIN-Mat. No. 2.0872)	6.4×10^{-3}	10×10^{-3}	1.3	2.8×10^{-3}

Table 12: Mass loss rates per unit area of tested materials [37]

Table 12: Continued

Material (DIN-Mat. No.)	Immersion zone		Comparison IZ North Sea/Baltic Sea	Tidal zone North Sea
	Baltic Sea	North Sea		
	$\text{g/m}^2 \text{ h}$	$\text{g/m}^2 \text{ h}$	Factor	$\text{g/m}^2 \text{ h}$
CuZn20Al2 (DIN-Mat. No. 2.0460)	10×10^{-3}	35×10^{-3}	1.6	2.2×10^{-3}
Shipbuilding steel (cf. Table 15)	100×10^{-3}	125×10^{-3}	3.3	212×10^{-3}
EN AW-5083 (AlMg4.5Mn0.7, AA 5083)	2.5×10^{-3}	1.9×10^{-3}	0.7	1.6×10^{-3}

Table 12: Mass loss rates per unit area of tested materials [37]

The comparison of measurement results in the immersion zone of the North and Baltic Seas shows different values in the North Sea compared to the Baltic Sea. The comparison of tidal and immersion zones in the North Sea shows higher corrosion rates in the immersion zone with the exception of shipbuilding steel. In the contact corrosion tests it was seen that in the North Sea the potentials of the materials in contact with one other material are changed more than in the Baltic Sea. The mass losses per unit area of anode materials were greater in the pairings exposed in the North Sea than with the same pairings in the Baltic Sea (Table 13) [37]. Table 13 lists the factors by which the rate of corrosion is greater in contact corrosion than in free corrosion.

Cathode	Baltic Sea/North Sea			
	Anode			
	CuNi10Fe1Mn (DIN-Mat. No. 2.0872)	CuZn20Al2 (DIN-Mat. No. 2.0460)	Shipbuilding steel (cf. Table 15)	EN AW-5083 (AlMg4.5Mn0.7, AA 5083)
X3CrNiMoN17-13-5 (SAE 317 LMN, DIN-Mat. No. 1.4439)	3/6	19/5	6.5/8.5	100/173
CuNi10Fe1Mn (DIN-Mat. No. 2.0872)		0.6/1.3	7.3/8.5	102/208
CuZn20Al2 (DIN-Mat. No. 2.0460)			6.7/7.8	105/224
Shipbuilding steel (cf. Table 15)				26/68

Table 13: Factors by which material losses in the anodic material in contact with the cathodic material is raised at an area ratio anode to cathode of 1:4 (anode/cathode distance 0.2 cm)

When the area ratio cathode to anode is changed, at the same distance between cathode and anode, the mass loss rate is also changed. The increased mass loss rate at the anode is, however, not directly proportional to the reduction of the anode surface area as would be expected according to the area rule. This is apparently due to the influence of fouling and the reaction products that are produced (Table 14). The distance between anode and cathode surfaces played only a secondary role in the results obtained.

Materials in contact	North Sea			Baltic Sea		
	Area ratio anode : cathode					
	1 : 1	4 : 1	10 : 1	1 : 1	4 : 1	10 : 1
X3CrNiMoN17-13-5 ¹⁾ : Shipbuilding steel ²⁾	1	1.7	8.2	1	1.8	6.8
X3CrNiMoN17-13-5 ¹⁾ : AlMg4.5Mn ³⁾	1	2.4	11.9	1	2.0	17.5
CuNi10Fe1Mn ⁴⁾ : Shipbuilding steel ²⁾	1	1.5	4.4	1	3.4	6.4
CuNi10Fe1Mn ⁴⁾ : EN AW-5083 ³⁾	1	2.2	8.6	1	4.6	8.2

¹⁾ SAE 317 LMN, DIN-Mat. No. 1.4439

²⁾ cf. Table 15

³⁾ AlMg4.5Mn0.7, DIN-Mat. No. 3.3547

⁴⁾ DIN-Mat. No. 2.0872

Table 14: Factors by which the mass loss rates are raised when the area ratios from anode to cathode are raised (distance 2 cm) [37]

V 3.6 Current-induced corrosion types

Rapidly flowing liquids can mechanically wear away or corrode materials surfaces (erosion). This corrosion type is exacerbated by gas bubbles and solid particles in the liquid current (abrasion) and is usually characterised by furrow-like, smooth indentations following the direction of flow of the medium. If this surface corrosion damages or destroys protective covering layers or passivation layers, an aggressive medium can then raise levels of corrosion at these sites. This combination of mechanical surface erosion and corrosion, known as **erosion corrosion**, involves alternating destruction and repair processes in which the rate of repair of the protective layer is the decisive factor in material resistance. Erosion corrosion is only local in areas where the current is interrupted.

Damage from erosion corrosion is frequently observed on pump impellers, deflection vanes and pipe bends.

Cavitation can also lead to local destruction of protective layers. In rapidly flowing liquid and on solid surfaces that oscillate in the liquids, gas or steam bubbles are produced at sites at which the pressure in the liquid is briefly lowered to vapor pressure due to flow in excess of the critical flow rate threshold. When the pressure is raised again, these bubbles collapse suddenly (implosion) and a jet of liquid hits the material surface at a high rate of speed. This sudden stress load pattern is continuously exposing or creating active surfaces on which increased corrosion (**cavitation corrosion**) takes place in an aggressive medium.

Particularly susceptible to damage from cavitation corrosion are, for example, ships' propellers, condenser pipes, pump impellers, widened segments in pipelines or flow channels.

Unalloyed and low-alloyed steels/cast steel

The unalloyed and low-alloy cast iron and steel types represent the bulk of materials used in seawater due to their good mechanical properties, the good processing qualities, availability and prices. On the other hand, these materials must always be protected against corrosion by means of coatings or cathodic protection, usually in combination with a coating. Only in special cases can the expected service life of the vessel be achieved by selecting a greater hull thickness as required for strength.

The different qualities of unalloyed and low-alloyed steels differ mainly in their mechanical and engineering properties. The engineering properties and the application properties of steels are determined to a great extent by their chemical composition and structure. These properties can be controlled within a wide range by means of the production processes melting, forming and heat treatment so as to adapt them to the requirements of specific applications, of course resulting in certain differences in alloy composition. These steels do not, however, contain alloying elements in amounts that would result in the formation of a protective passivation layer in response to water exposure as is the case in high-chromium steels with Cr content levels exceeding 13%.

Table 15 lists the relevant steels in their most important groups together with the basic analytical values. The normal strength steels for shipbuilding contain solely the alloying elements carbon and manganese for strength as well as perhaps silicon or aluminium to steady the melt during casting. The tensile strength is approx. 450 N/mm². Several different steel grades are differentiated according to the required viscosity properties. Because of the requirement for ready weldability, the C content is limited to a maximum of 0.23% or the C equivalent $(C+Mn/6)$ to a maximum of 0.40%. The properties and compositions of these steels are set out, for instance, in the standards DIN EN 10025-1 to -2 [38], DIN EN 10083-1 to -3 [39], DIN EN 10025-1 to-3 and -4 [40], DIN EN 10293 [41] and DIN EN 10213-1, DIN EN 10213-3, DIN EN 10293 [42].

Steel	C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Nb
Normal strength shipbuilding steels												
Steel grade A	< 0.21	< 0.5	2.5×%C	< 0.040	< 0.040							
Steel grade B	< 0.21	< 0.35	> 0.80	< 0.040	< 0.040							
Steel grade D	< 0.21	0.10–0.35	> 0.60	< 0.040	< 0.040					> 0.015		
Steel grade E	< 0.18	0.10–0.35	> 0.70	< 0.04	< 0.04					> 0.015		
Higher strength shipbuilding steels												
A(H), D(H), E(H) 32, 36, 40 ¹⁾	< 0.18	< 0.50	0.90–1.60	< 0.035	< 0.030	< 0.20	< 0.08	< 0.40	0.03–0.10	> 0.015	< 0.35	0.02–0.05
F(H) 32, 36, 40 ¹⁾	< 0.16	< 0.50	0.90–1.60	< 0.025	< 0.025	< 0.20	< 0.08	< 0.80	0.03–0.10	> 0.015	< 0.35	0.02–0.05
F(H) 42, 46, 50, 62, 69 ¹⁾	< 0.18	< 0.55	< 1.60	< 0.025	< 0.025				0.03–0.10	> 0.015		
D(H), E(H) 42, 46, 50, 62, 69 ¹⁾	< 0.20	< 0.55	< 1.70	< 0.035	< 0.030				0.03–0.10	> 0.015		0.02–0.05
Normalised fine-grained structural steels												
S275N (e.g. 1.0490)	< 0.18	< 0.40	0.40–1.30	< 0.040	< 0.040							
S355N (e.g. 1.0545)	< 0.18	0.10–0.50	0.90–1.60	< 0.040	< 0.040							
S500N (e.g. 1.8907)	< 0.21	0.10–0.50	1.00–1.70	< 0.035	< 0.035			0.40–0.70	0.10–0.20			
Weathering (patinable) structural steels												
S235J2W ²⁾ (e.g. 1.8961)	< 0.13	0.10–0.40	0.20–0.50	< 0.045	< 0.035	0.50–0.80		< 0.40			0.30–0.50	
S355J2G1W ³⁾ (e.g. 1.8963)	< 0.15	0.10–0.40	0.20–0.50	< 0.045	< 0.035	0.50–0.80		< 0.40	0.02–0.10		0.30–0.50	

< maximum value, > minimum value

1) Strength classes, 2) WTSt 37-3, 3) WTSt 52-3

Table 15: Analytical values for unalloyed and low-alloyed steels frequently used in shipbuilding and marine engineering (mass%, balance: iron and trace elements)

High-strength shipbuilding steels are melted with much higher Mn contents and reduced C contents due to increased strength and viscosity requirements. Only three examples are listed here for fine-grained structural steels. Up to the strength class S355N, these steels also contain only C and Mn as alloying elements as well as Al and/or vanadium or niobium as a grain refining agent. In the higher-strength qualities, nickel is added as an additional alloying element.

More recently, sheetmetals made of thermomechanically rolled fine-grained structural steel with a minimum yield strength of 355 N/mm², and up to thicknesses of 70 mm, have been approved for welded shipbuilding constructions by the classification bodies for grades A, D and E. Due to its chemical composition, this steel has a low carbon equivalent and therefore very good weldability. The chemical composition and main mechanical properties of this steel are shown in Table 16 [43].

	C	Si	Mn	P	S	Nb	Ni
XAMAR 36 A							
XAMAR 36 D	≤ 0.13	0.10–0.50	0.90–1.60	≤ 0.020	≤ 0.015	≤ 0.05	≤ 0.35
XAMAR 36 E							

	Minimum yield point R_{eH} N/mm ²	Tensile strength R_m N/mm ²	Minimum elongation at break A_5 %
XAMAR 36 A			
XAMAR 36 D	355	460–620	22
XAMAR 36 E			

Test temperature K (°C)	Minimum notched bar impact work A_v J			
	longitudinal	transverse	longitudinal	transverse
Plate thickness, mm	≤ 50		> 50, ≤ 70	
XAMAR 36 A	0			
XAMAR 36 D	253 (–20)	34	24	41
XAMAR 36 E	233 (–40)			27

Table 16: Chemical composition (mass%) and mechanical properties of the high-strength thermomechanically rolled shipbuilding steel XAMAR 36

In weather-resistant structural steels (e.g. DIN-Mat. No. 1.8961, S235J2W, 1.8963, S355J2G1W) the improved corrosion resistance in the atmosphere is achieved by means of addition of chromium and copper.

In offshore applications, high-strength steels are also used for which the requirement for best weldability and excellent viscosity, including thickness deformation capacity, is preeminent.

Since in unalloyed and low-alloyed steels, with few exceptions, the same alloying elements are always used within relatively narrow limits, these steels show about the same electrochemical behaviour, and an influence of the alloying elements within these orders of magnitude, or of the steelmaking process itself, on corrosion in seawater can be expected for the splash zone at most, but not under water.

The values for the free corrosion potential are $U_H = -0.3$ V to -0.5 V and depend on the nature of the surface at the onset of the seawater stress load. Descaled surfaces have lower potentials than those with adhering scale or rust. Parts with different surface states therefore also show varying potentials, which may result in locally exacerbated corrosion. Therefore, the precondition for a mostly uniform surface corrosion is an evenly descaled and cleaned surface. With advancing corrosion, the initial surface influence on the free corrosion potential is reduced and the potentials are shifted in the positive direction. With increasing flow rate, the potentials also increase in the positive direction.

The rate of general corrosion in these materials is mainly determined by oxygen access and therefore depends on the movement of seawater, which maintains oxygen transport to the surface, and the formation of covering layers on the surface, which hinder oxygen access. Table 17 lists the erosion levels for uniform surface corrosion determined in various long-term studies in the North Sea.

<i>Corrosion rate, mm/a (mpy)</i>		
<i>Immersion zone</i>	<i>Tidal zone</i>	<i>Splash zone</i>
0.14–0.08 (5.51–3.15)	0.21–0.13 (8.27–5.12)	0.10–0.07 (3.94–2.76)

Table 17: Uniform surface corrosion in unalloyed and low-alloyed steels in the North Sea

The corrosion rates during the first two years are higher, whereupon in subsequent years they move towards the lower values as the covering layers and fouling increasingly hinder oxygen access. This was confirmed in corrosion tests over a period of several years off Helgoland, in which tests seven steels (Table 18) different in both alloy content and steelmaking process, i.e. steelmaking process and deoxidation, were tested in the immersion zone (IZ), tidal zone (TZ) and splash zone (SZ) [15].

<i>Symbol</i>	<i>C</i>	<i>Si</i>	<i>Mn</i>	<i>P</i>	<i>S</i>	<i>N</i>	<i>Al</i>	<i>Cr</i>	<i>Cu</i>	<i>Ni</i>	<i>Melting¹⁾</i>	<i>Deoxidation method</i>
○	0.09	0.46	0.49	0.093	0.035	0.006	0.031	0.65	0.42	0.48	SM	Si and Al killed
△	0.12	0.25	0.54	0.035	0.036	0.006	0.005	0.04	0.13	0.05	–	Si killed
●	0.05	0.00	0.48	0.026	0.018	0.005	0.004	0.03	0.06	0.04	LD	rimmed
▲	0.12	0.17	0.45	0.030	0.039	0.004	0.031	0.05	0.14	0.05	SM	Si and Al killed
•	0.07	0.00	0.37	0.025	0.036	0.003	0.004	0.04	0.15	0.06	SM	rimmed
+	0.13	0.00	0.39	0.039	0.090	0.005	0.004	0.08	0.23	0.08	SM	rimmed
×	0.07	0.21	0.33	0.013	0.022	0.004	0.050	0.02	0.11	0.05	SM	Si and Al killed

1) SM: Siemens-Martin process, LD: Linz-Donawitz process

Table 18: Mass% of steels tested in the North Sea water off Helgoland [15]

The corrosion mass loss of the steels in Table 18 after exposure in the North Sea water off Helgoland in the splash, tidal, and immersion zones is shown in Figure 2. The scatter bands of the seven steels are shown. As was expected, the weather-resistant steel (○) with raised levels of copper, nickel, chromium and phosphorus, which favours the formation of denser rust layer, shows the lowest rust levels in the splash zone. A steel (△) with raised silicon and manganese contents shows nearly equivalent behaviour. The corrosion rates of both steels are at the lower limit of the scatter band. In the tidal and immersion zone, on the other hand, all steels fill out the scatter band uniformly. The resulting corrosion rates are listed in Table 19.

<i>Exposure zone</i>	<i>Mass loss rate per unit area kg/m² a</i>	<i>Corrosion rate mm/a (mpy)</i>
TZ	1.35	0.17 (6.69)
IZ	0.90	0.12 (4.72)

Table 19: Measurement parameters for rates of corrosion of unalloyed and low-alloyed steels in the North Sea from Table 18 and Figure 2

No dependence of the corrosion rates on the steel composition was found. The mean corrosion rates are higher in the tidal zone than in the immersion zone by a factor of 1.5.

Corrosion rates of this order of magnitude were determined in unalloyed steels in other tests as well. Exposure tests over a period of 4 years in Monaco revealed, for example, corrosion rates between 0.090 mm/a and 0.122 mm/a (3.54 and 4.8 mpy) [44]. In Bremerhaven, similar values of 0.100 mm/a–0.140 mm/a (3.94–5.51 mpy) were recorded. In general, corrosion rates in the range of 0.070 mm/a–0.100 mm/a (2.76–3.94 mpy) are reported for harbour waters with varying tidal levels. On sheet piles in the US after 35 years of exposure, values of 0.110 mm/a (4.33 mpy), and at another location corrosion rates of 0.060 mm/a–0.130 mm/a (2.36–5.12 mpy) were measured [45]. On this basis, under normal conditions, corrosion rate of 0.125 mm/a (4.92 mpy) can be taken as a guideline value for unalloyed steels in the immersion zone. The higher corrosion rates sometimes observed are due to accelerating effects such as the formation of elements or to anaerobic conditions, e.g. in harbour waters. High flow rates result in clear increases in corrosion, since they not only help maintain the oxygen transport to the surface, but also make the formation of covering layers difficult or impossible or remove covering layers that had already formed. At flow rates of 10 m/s, corrosion rates of 1 mm/a (39.4 mpy) are reached.

Cast steel

The behaviour of unalloyed and low-alloyed cast steel in seawater is for the most part comparable to that of rolled material. The free corrosion potentials for cast steel are within the same order of magnitude as for unalloyed steels. The corrosion rates in Table 17 also apply to steel castings. In long-term exposure, after 2 years, a corro-

sion rate of 0.07 mm/a (2.76 mpy) was measured. If the casting crust is left on the material, the pitting corrosion at defective sites may be more pronounced, whereby pitting corrosion factors, i.e. ratios of maximum pit depth/mean corrosion were measured as follows 11 after 1 year, 5 after 8 years and 3.3 after 16 years [46].

Influence of the alloying elements

In principle, an improvement of rust corrosion rates in low-alloyed steels is possible as well in the tidal and immersion zone, but expectations should not be too high. The significant improvements frequently cited in the literature and patent registrations are usually based on tests in the laboratory and cannot be confirmed in practical applications or only in reduced form. It must also be noted that in the low-alloyed steels shallow pit corrosion or pitting corrosion is frequently observed in addition to uniform surface corrosion. Examples can be cited in which certain alloying elements reduce the uniform surface corrosion, only to cause increased pitting at the same time.

Influence of chromium and combinations of chromium with other elements

Numerous tests – including natural seawater exposure tests – have demonstrated that a small chromium addition reduces the corrosion rates considerably without rendering steels more susceptible to pitting corrosion. In the upper part of Figure 15, the influence of chromium on seawater corrosion of a structural steel is presented [47]. Accordingly, only 0.5% and 1% Cr have a significant effect and reduce mass losses by 35%/65% compared to chromium-free steel. Improvements from higher chromium contents above this level are then relatively small.

In chromium-free steels, higher aluminium contents of 2.5–5% Al do improve general corrosion resistance, but they also increase the tendency to shallow pit or pitting corrosion [48]. In chromiferous steels, however, even small levels of aluminium reduce the corrosion rates. The lower section of Figure 15 shows that by means of addition of 0.2% aluminium the already low corrosion rate of a 2% Cr steel can be further reduced by a significant amount. The favourable influence of a combination of chromium and aluminium was also confirmed by long-term exposures in the North Sea at water depths of 45 m and 90 m [49]. These results show that the addition of as little as 1% Cr and 0.5% Al can reduce the corrosion rate in comparison to standard commercial steels by a factor of 2 to 4. Molybdenum had little effect on general corrosion. A molybdenum content of 0.5% results in only slight improvement, whereas a content level of 1.5% Mo appears to have a negative effect.

Other tests on steels with 0–4% Cr and 0–1% Al or Mo also showed that a steel with 2% Cr and 1% Al represents the best compromise in resistance to uniform and local corrosion. Chromium contents above 2% continue to reduce the corrosion rates, but also increase the tendency to pitting corrosion [50].

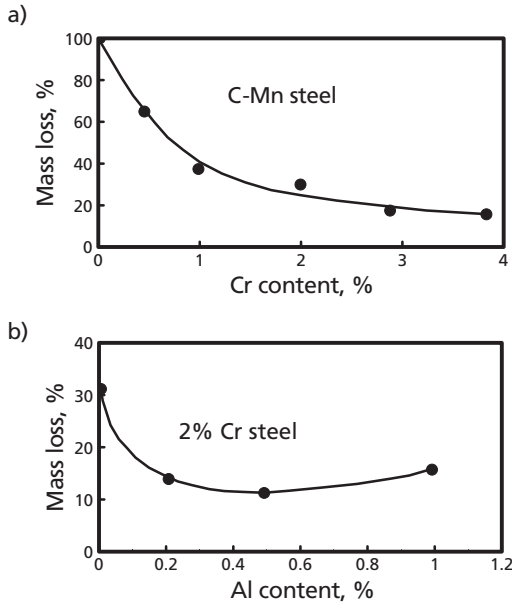


Figure 15: a) Influence of chromium on corrosion of unalloyed and low-alloyed C-Mn steel
b) Influence of aluminium on corrosion of 2% Cr steel [47]

Extensive exposure tests in the North Sea on the influence of the elements copper, chromium, aluminium, nickel and silicon on corrosion in seawater showed that the corrosion in the immersion zone in seawater is significantly reduced by suitable combinations of the alloying elements Cr + Al, Cr + Al + Cu and Cr + Si. At longer exposure times, the corrosion rates can be reduced to as little as 20% of the rates for unalloyed steel. In the tidal zone (TZ), however, only the combination Cr + Si results in an improvement, albeit of only 20% after four years. In the splash zone (SZ) improvements by a factor of 2 can be achieved [50].

Whereas for unalloyed steels mean corrosion rates of 0.12 mm/a (4.72 mpy) in the immersion zone and 0.17 mm/a (6.69 mpy) in the tidal zone were recorded, the values for these low-alloyed steels were approx. 0.05 mm/a (2 mpy) for the immersion zone and 0.19 mm/a (7.5 mpy) for the tidal zone. The improvement in corrosion behaviour observed in the deep sea tests with 1% Cr + 0.5% Al by a factor of 2 can thus only be confirmed for the immersion zone. As was expected, the corrosion is most pronounced, and least dependent on the chemical composition of the steel, in the tidal zone.

For the “seawater corrosion resistant steels” sold commercially under various different designations, the reported improvements in corrosion behaviour by a factor of 2 or 3 also apply only to the immersion or non-immersion zone. In the tidal zone, the corrosion rates practically fall into the general scatter band of the low-alloyed steels [47, 51]. Therefore, these steels also require corrosion protection in the tidal zone.

Influence of sulphur

It is known that, among the unavoidable impurities in steel, the sulphides are highly active in causing the development of local corrosion in neutral waters containing chloride. On the other hand, the pitting potentials of manganese-rich sulphides measured are only to be considered apparent pitting potentials for short-term tests lasting for a few minutes only in synthetic seawater. In longer test periods, the initial selective corrosion observed caused by dissolution of the sulphides undergoes a transition to uniform surface corrosion. It is therefore in any case incorrect to draw conclusions concerning the long-term behaviour of the material in seawater from the initial appearance of the corrosion in the environment of sulphide inclusions.

The results of two-year exposure tests off Helgoland involving steels that differed as to steelmaking process, steading process, sulphur content and sulphur distribution showed that higher sulphur proportions up to approx. 0.2% in the steel noticeably increase corrosion mass loss only in the splash zone [52]. Table 20 lists the chemical compositions of the tested steels and Figure 16 shows the corrosion rates observed after 2 years of exposure.

Sample no.	C	Si	Mn	P	S	Al	Cr	Cu	Pb	Ca
1	0.10	0.46	1.46	0.012	0.005	0.037	0.04	0.08		
2	0.16	0.33	0.49	0.008	0.005	0.003	0.02	0.01		
3	0.16	0.39	0.52	0.007	0.17	0.005	0.03	0.01		
4	0.15	0.32	0.54	0.008	0.004	0.008	0.03	0.0		0.003
5	0.15	0.34	0.48	0.007	0.17	0.008	0.02	0.01		0.003
6	0.08	0.02	1.13	0.057	0.24	0.004	0.04	0.09	0.25	
7	0.07	0.05	0.40	0.018	0.019	0.004	0.02	0.06		

No. 1 = S355N (DIN-Mat. No. 1.0545)

No. 2-No. 5 = test melting charges

No. 6 = SAE 1109 (10S20, DIN-Mat. No. 1.0721)

No. 7 = HI, ship's boiler plate, grade 1 (DIN-Mat. No. 1.3052)

Table 20: Chemical composition of the tested steels (mass%) [52]

In contrast to the thin, firmly adhering rust on the low-sulphur steel samples, the rust that forms on the sulphur-rich samples is loose and full of thick blisters. Apparently there is an increased formation of sulphate esters on these samples, whereby the sulphur is from the steel, not from the SO_2 in the air as is the case with the sulphate esters observed in atmospheres containing SO_2 .

In the tidal zone, the effect of the higher sulphur content is correspondingly reduced, since here the rich oxygen supply required to oxidise the sulphur is only available at low tide and the influence of fouling and cover layer formation increases with exposure duration. No influence of sulphur on corrosion rates is observed in the immersion zone.

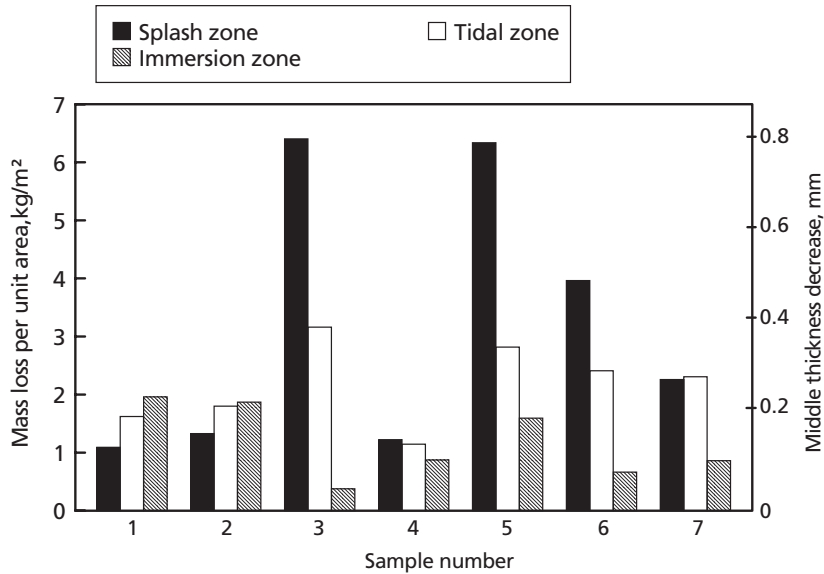


Figure 16: Mass loss per unit area in steels from Table 20 after 2 years of exposure in seawater [52]

– Influence of sample dimensions and location –

The different levels of oxygen access in the different water zones may, in extensive structures, for example sheet pilings or mooring posts, lead to the formation of aeration elements. Measurements have shown that the cathodic areas are usually on or just above the waterline [53]. The result is then increased corrosion in the tidal zone, which may be much larger than would be expected based on the different rusting rates in samples exposed separately in the tidal and immersion zones.

Much more complex and difficult than the usually relatively small samples with approx. 0.02 m² surface are long samples with exposure extending from the splash zone (SZ) through the tidal zone (TZ) and into the immersion zone (IZ) or even into the silt zone/sea floor. Since the large-area aeration elements may form on such samples as described above, it can be expected that the results of corrosion tests in such long samples will differ clearly from those obtained with small individual samples.

The results of comparative tests on both sample types for 4 years in the brackish water of Wilhelmshaven listed in Table 21 show that particularly pronounced differences occur in the tidal zone just above MTHW (mean tidal high water) and just below MTLW (mean tidal low water), whereas in the immersion zone, and above MTHW in the splash zone, the corrosion rates are the same, as was expected [54].

Location	Corrosion rates after 24 months, mm/a (mpy)		Corrosion rates after 48 months, mm/a	
	Multi-zone samples 8 × 150 × 10,000 mm	Short samples 8 × 150 × 1,000 mm	Multi-zone samples 8 × 150 × 10,000 mm	Short samples 8 × 150 × 1,000 mm
SZ	0.01 (0.39)	0.03 (1.18)	0.01 (0.39)	0.01 (0.39)
	0.01 (0.39)	0.05 (1.97)	0.02 (0.79)	0.08 (3.15)
MTHW	0	0.18 (7.09)	0	0.18 (7.09)
	0	0.19 (7.48)	0	0.14 (5.51)
	0	0.13 (5.12)	0	0.09 (3.54)
MTLW	0.08 (3.15)	0.05 (1.97)	0.07 (2.76)	0.07 (2.76)
	0.13 (5.12)	0.10 (3.94)	0.17 (6.69)	0.09 (3.54)
	0.09 (3.54)	0.09 (3.54)	0.10 (3.94)	0.08 (3.15)
IZ	0.09 (3.54)	0.08 (3.15)	0.08 (3.15)	0.07 (2.76)
	0.10 (3.94)	0.09 (3.54)	0.07 (2.76)	0.07 (2.76)

SZ: Splash zone

MTHW: Mean tidal high water (mean flood tide)

MTLW: Mean tide low water (mean ebb tide)

IZ: Immersion zone

Table 21: Influence of sample location and dimensions on corrosion of steel (0.07% C, 0.26% Si, 1.13% Mn, 0.020% P, 0.021% S, 0.061% Al, 0.006% N) in brackish water [54]

These results confirm the experience obtained with steel sheet pilings in the seawater of Kure Beach in which the corrosion profile shown schematically here in Figure 17 was found after 5 years [55].

On these sheet pilings, increased corrosion was also observed just below the low tide line that did not occur in tests of the individual samples.

Of practical significance is the fact that with short samples, corresponding to steel structural elements, located only at certain levels, in some cases show much greater loss of thickness than the multi-zone structural elements. These influences in many cases go beyond the influence of different steel types used. It is therefore important when designing structures that will be exposed in several different seawater zones, for example harbour pilings, to apply the rust corrosion rates obtained from test results with long samples.

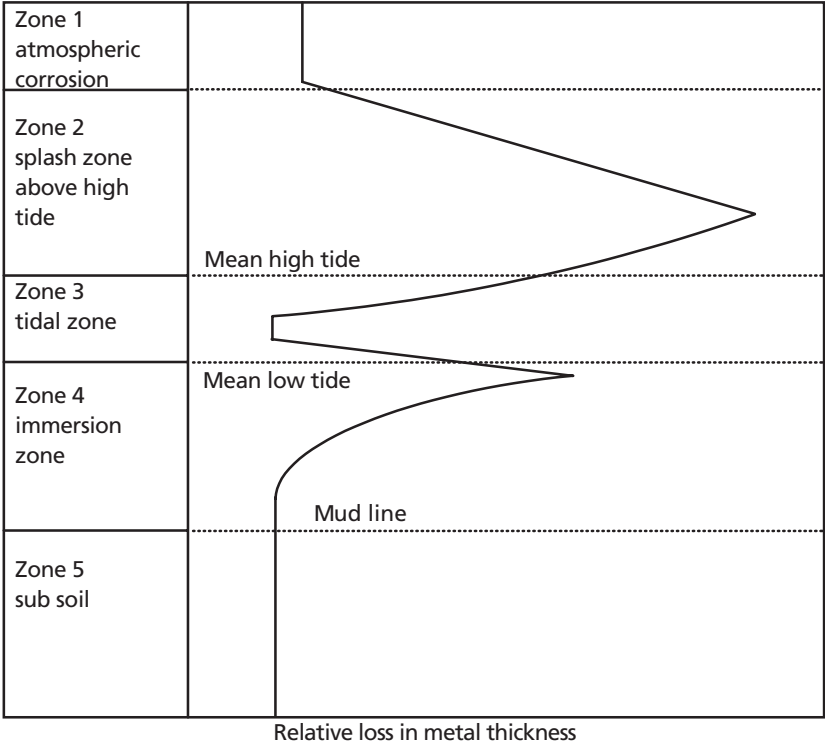


Figure 17: Corrosion profile on sheet pilings in seawater (schematic)
MTHW: Mean tidal high water (mean flood tide)
MTLW: Mean tide low water (mean ebb tide) [55]

Measurements in sheet pilings

Numerous measurements of corrosion rates on sheet pilings carried out in the Netherlands and the United Kingdom also confirm that in most cases maximum corrosion occurs in the tidal zone (TZ). Figure 18 shows the example of a typical corrosion profile on sheet pilings along the Netherlands coast [56]. The highest corrosion rates are always found at the mean tidal low water (MTLW) level or just below it.

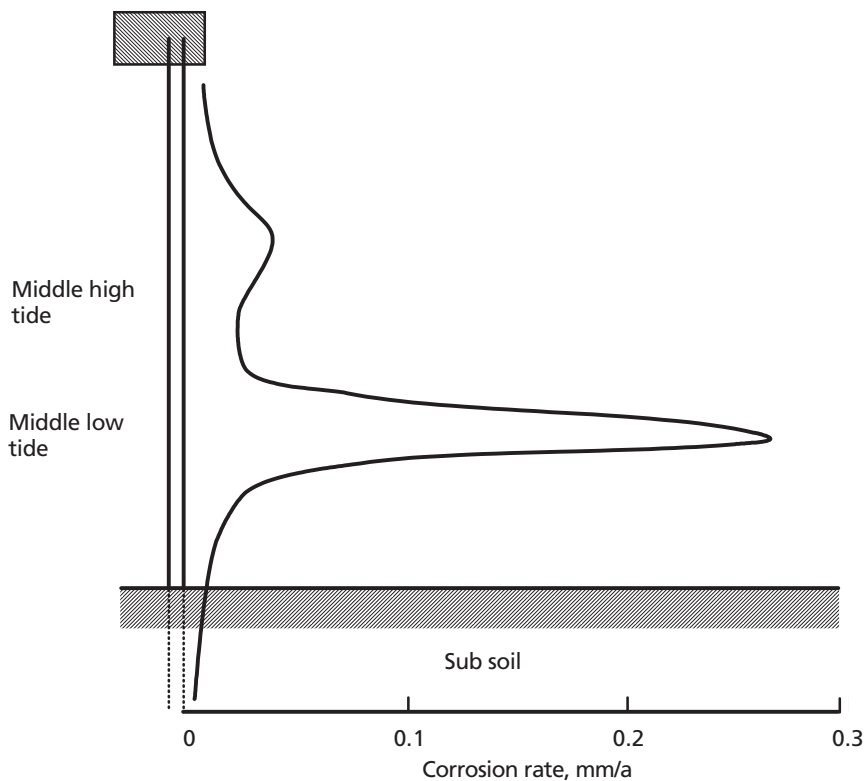


Figure 18: Corrosion on sheet pilings as dependent on tide level
MTHW: Mean tidal high water (mean flood tide)
MTLW: Mean tide low water (mean ebb tide) [56]

The results confirm the described measurements on multi-zone long samples and electrically shorted individual samples. These hull thickness measurements on 18-43 year-old sheet pilings at 8 Locations in the Netherlands revealed corrosion rates as follows:

Marine atmosphere:	0.05–0.07 mm/a (1.97–2.76 mpy)
Splash zone (SZ) and tidal zone (TZ):	0.12–0.27 mm/a (4.72–10.63 mpy)
Immersion zone:	0.03–0.09 mm/a (1.18–3.54 mpy)
Sea floor:	approx. 0.015 mm/a (0.59 mpy)

Drawn sheet pilings showed that the corrosion occurred in practical terms from the water side only. Even here, highly corroded parts were hardly corroded on the back – the fabrication marks on the unexposed sides were still readily legible after 42 years.

Similar results were also obtained for thickness reductions on 10–47 year-old sheet pilings in the UK in the Mediterranean area and in the Persian Gulf. The mean rates of corrosion determined are summarised in Table 22 [50]. The corrosion in the splash splash zones and tidal zones are therefore likely to determine the overall service life of a sheet piling – corrosion protection measures are absolutely necessary.

Location	The Netherlands	The UK	Mediterranean Sea	Persian Gulf
Atmosphere	0.05–0.07 (2.0–2.8)			
Splash zone		0.14 (5.5)	0.14 (5.5)	0.19 (7.5)
Tidal zone	0.12–0.27 (4.7–10.6)	0.08 (3.2)	0.05 (2.0)	0.05 (2.0)
Ebb tide zone (MTLW)		0.21 (8.3)	0.16 (6.3)	0.12 (4.7)
Immersion zone	0.03–0.09 (1.2–3.5)	0.09 (3.5)	0.04 (1.6)	0.04 (1.6)
Sea bottom	0.015 (0.8)	0.02 (0.8)		

MTLW: mean tidal low water (mean ebb tide)

Table 22: Hull thickness reduction on sheet pilings in mm/a (mpy) [50]

Local corrosion

The mainly similar behaviour of unalloyed and low-alloyed structural steels concerning the corrosion rate in seawater is finally due to the fact that the rusting process is controlled by oxygen access, which is not a material-dependent factor. On the other hand, the kinetics of the partial reaction iron dissolution, which determines the rest potential, is a material-dependent factor. The electrically conductive contact of materials or material parts with different rest potentials results in the formation of elements that may cause increased local corrosion depending on the potential level and area ratio. In practice, such elements occur at welding seams.

Welding seams, correctly done, corrode at about the same rate as the base material. Local corrosion in the welding area may result from differing chemical composition of the plate and welding deposit. Figure 19 shows the relative potentials of base material and deposit zone [57]. In the test, diluted seawater and anodic polarisation were used. This increases the indication sensitivity. In the case described in the left section, the welding deposit has a lower potential than the plate material, and since due to the area rule higher anodic current densities occur here, a higher corrosion rate would be expected in this area. Given the reversed potential ratios described in the right half of the picture, the plate is not at risk for corrosion if the cathode surface area of the welding deposit is small and the anodic surface of the plate is large. To avoid local corrosion in the welding deposit zone, the material and welding filler must be matched so that the welding deposit has an equal or more positive electrochemical potential in seawater.

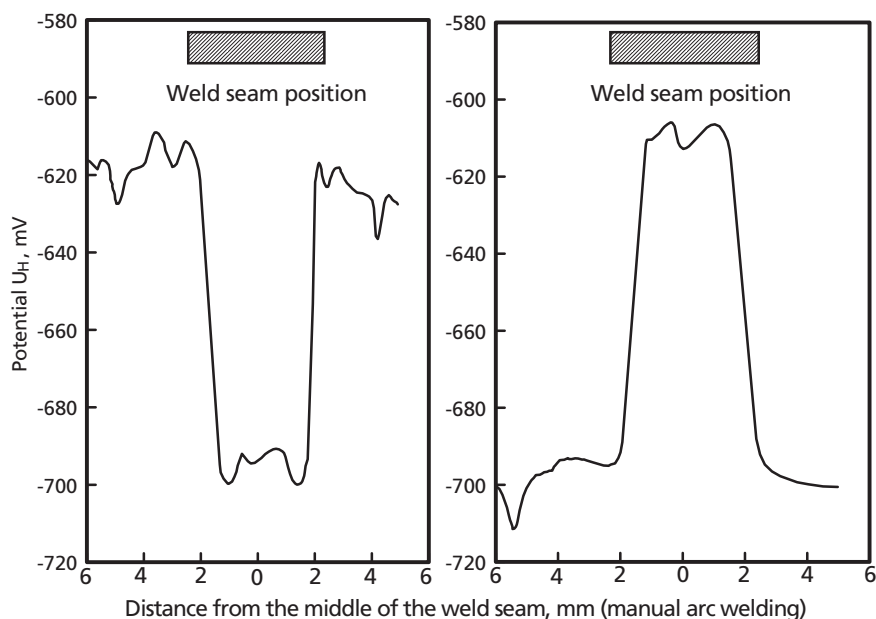


Figure 19: Potential variation at shipbuilding steels welding connections using different welding fillers [57]

Such potential/path curves provide an efficient basis for prediction of the practical behaviour of a welded connection [58, 59].

Locally raised corrosion in the welding seam zone is observed under certain conditions in higher-strength steels with manganese contents exceeding 1.2% in the heat affected zone adjacent to the welding seam. Tests show clearly that the formation of martensitic substructures, which may occur in higher-strength steels under unfavourable welding conditions, is responsible for the increased corrosion in this area [60–63].

Whereas natural exposure rust tests with unwelded plates in seawater show only a small influence of the Mn content, the corrosion may be clearly concentrated in the heat affected zone (HAZ) in welded samples with increasing manganese and/or carbon content. Reduced welding temperatures, i.e. faster cooling from welding heat, have the same effect on corrosion. Higher manganese and carbon contents in the steel and rapid heat dissipation during welding, e.g. if the plates are not preheated or at low ambient temperatures, martensite formation in the HAZ, and therefore selective corrosion, is increased. Sufficient preheating or subsequent heat treatment, for example stress-relief annealing, are reliable methods of preventing this type of corrosion, even in higher-strength steels [61].

Generally speaking, conditions for shallow pit and pitting corrosion are present if, due to covering layers of any type, oxygen reduction is inhibited to a lesser degree than iron dissolution, but the latter is not prevented from causing local damage to

the covering layer. This is always the case with porous covering layers. Depending on the density, thickness and adherence of the layers, the corrosion may be delayed, albeit shallow pit corrosion may be encouraged to varying degrees. Examples of such covering layers are casting crust, mill scale with oil film, residual paint coats or technically inappropriate coatings. Pitting corrosion may occur where covering layers and coatings are damaged or under local deposits.

For instance, between the blank surface of a silicon-steadied shipbuilding steel and scale surfaces in synthetic seawater a potential difference of 400 mV is measured. The corrosion current that then flows between surfaces of the same size is equivalent to a corrosion rate of 0.350 mm/a (13.8 mpy). Considering the area ratios at a welded connection, this results in welding seam corrosion of up to 3 mm/a (118 mpy) [57].

The removal of mill scale is generally helpful in terms of corrosion protection. Whereas in seawater unprotected steel loses its mill scale relatively quickly due to the surface removal rate, in brackish water it may adhere longer and, in the presence of oil films, result in pitting corrosion. Here as well, abrasive blasting can prevent the more serious pitting corrosion in favour of the less dangerous surface corrosion. Cathodic protection is a generally reliable means of preventing pitting corrosion.

Corrosion cracking

Under certain conditions, special forms of corrosion with cracking are observed in unalloyed and low-alloyed steels. With increasing use of higher-strength steels in seawater applications, the question of whether corrosion cracking in these steels can also occur in seawater becomes increasingly interesting.

Stress corrosion cracking

Under certain chemical or electrochemical conditions, e.g. pH reduction in crevices, under fouling and deposits or with the negative potential used for cathodic protection, a hydrogen reduction may occur at the steel/seawater interface. Under such critical conditions, higher-strength steels may conceivably develop hydrogen-induced stress corrosion cracking in seawater. This would be most likely in hardened zones of the welding seam under cathodic polarisation.

To test this aspect, bending samples from the welding seam zones of higher-strength steels with yield points of 355–890 N/mm² were exposed in the immersion, tidal and splash zones with free corrosion and under cathodic protection with zinc anodes. The steels S460N (A 572, DIN-Mat. No. 1.8901), S690Q (DIN-Mat. No. 1.8931) and S890Q (DIN-Mat. No. 1.8940) were tested with S355N (UNS K12709, DIN-Mat. No. 1.0545) as reference material (Table 23). Two different sample types were used, bend samples acc. to DIN 50915 [64] with crosswise butt-welded connections and U-bars with insert buildup welds lengthwise in the bending zone. Some of the samples were stress-relief annealed before bending, the others left in the welded state. All samples were still free of cracking after a test period of three years. Even maximum hardnesses of 400 HV10 in the heat affected zone do not

show a negative effect [24]. This result shows that, under static load, stress corrosion cracking in faulty welded connection of high-strength steels can be prevented by zinc anodes, under conditions of both free corrosion and cathodic polarisation.

<i>Material</i>	<i>C</i>	<i>Si</i>	<i>Mn</i>	<i>P</i>	<i>S</i>	<i>Al</i>	<i>Cr</i>	<i>Cu</i>	<i>Mo</i>	<i>Nb</i>	<i>Ni</i>	<i>V</i>
S355N, 1.0545	0.17	0.34	1.38	0.022	0.010	0.048	0.02	0.05			0.02	
S460N, 1.8901	0.19	0.48	1.57	0.017	0.005	0.028	0.02	0.17		0.03	0.43	0.17
S690Q, 1.8931	0.16	0.72	0.89	0.011	0.015	0.051	0.83	0.12	0.23		0.19	
S890Q, 1.8940	0.16	0.30	0.81	0.008	0.009	0.028	0.65	0.12	0.40		1.50	0.08

Table 23: Chemical composition of the higher-strength steels tested for hydrogen-induced stress corrosion cracking (mass%) [24]

However, this result applies only to the stress type considered here with constant elongation and under the condition that no conditions apply that would encourage local hydrogen absorption into the steel, for instance

- The presence of promoters, for instance in the form of sulphides from sulphate-reducing bacteria
- Locally reduced pH levels due to hydrolysis of steel corrosion products under deposits or in crevices
- Gradual plastic-dynamic deformations.

Bending samples made of the steel S500 (UNS T11342, 1.3247), for example, hardened to 467–481 HV30 by quenching in water, showed cracking in the heat affected zone of the welding seam. The cracks only occurred under exposure in the splash zone, in which the pH was low under rust blisters due to hydrolysis of the corrosion products [65].

The corrosion products, that are produced in corrosion of higher chromium-alloyed steels, contain chromium salts that lower pH levels considerably in the process of hydrolysis. To investigate the potential influence of this more pronounced pH level reduction, steels with different chromium contents were tested [66]. Table 75 lists the alloying contents of the steels used in order of increasing chromium content. These are four standard commercial types and four test melts. Bending samples were used as described in DIN 50915 [64]. The sample material was adjusted to different hardness values by means of simulated heat treatments.

No.	Steel	C	Si	Mn	P	S	Al	Cr	Cu	Mo	Ni
1	20MnNi6-5	0.21	0.41	1.61	0.006	0.009	0.015	0.08		0.04	0.63
2	TM	0.13	1.23	0.80	0.013	0.003	0.820	1.02	0.9	0.29	
3	TM	0.14	1.28	0.87	0.015	0.003	0.870	1.51	0.31	0.30	0.12
4	TM	0.14	1.21	0.82	0.015	0.004	0.800	1.95	0.30	0.30	
5	10CrMo9-10 UNS K21590, 1.7380	0.07	0.19	0.44	0.005	0.003	0.010	2.17		0.99	0.17
6	TM	0.15	1.29	0.86	0.018	0.004	0.930	2.57	0.29	0.29	
7	X12CrMo5 SAE 501, 1.7362	0.10	0.35	0.54	0.010	0.009	0.006	4.92	0.07	0.51	0.16
8	X20Cr13 SAE 420, 1.4021	0.20	0.21	0.27	0.029	0.004	0.025	13.10		0.03	0.15

TM: Test melts

Table 24: Chemical composition of steels tested (mass%) [66]

All test parameters and results are presented in Table 25 and Table 26.

No.	Steel	Cr content	Hardness HV10	Free corrosion	Cathodically polarised (zinc anode)
1	20MnNi6-5	0.08	350	0	0
			420	0	2
			480	0	2
2	TM	1.02	170	0	0
			260	0	0
			300	0	0
3	TM	1.51	170	0	0
			280	0	0
			370	2	0
4	TM	1.95	185	0	0
			215	0	0
			310	0	0
			420	2	0
5	10CrMo9-10 UNS K21590, 1.7380	2.17	250	0	0
			310	0	0
			360	0	0

TM = Test melt

Table 25: Results of stress corrosion cracking tests in bending samples after 12 months exposure time in the immersion zone (number of cracked samples in 3 parallel samples) [66]

Table 25: Continued

No.	Steel	Cr content	Hardness HV10	Free corrosion	Cathodically polarised (zinc anode)
6	TM	2.57	275	0	0
			310	0	0
			410	3	3
7	X12CrMo5 SAE 501, 1.7362	4.92	280	0	0
			350	0	0
			400	0	1
8	X20Cr13 SAE 420, 1.4021	13.10	230	0	0
			350	0	3
			400	3	3

TM = Test melt

Table 25: Results of stress corrosion cracking tests in bending samples after 12 months exposure time in the immersion zone (number of cracked samples in 3 parallel samples) [66]

As for the influence of the hardness factor, it is evident that beginning at about 300 HV10 cracking susceptibility is present in steels containing more than 1% chromium. The effect of the Cr content is quite clear. In the hydrolysis of the corrosion products it influences the pH level at the anodic areas. Therefore, as the Cr content increases in the steel, cracking susceptibility will also increase at comparable hardness levels, or hardness will shift to lower values with increasing Cr content.

The exposure zone also exerts an influence, as demonstrated by the samples exposed in the tidal zone and in the splash zone (Table 26). The effect of the chromium content was better defined in these two zones than in the immersion zone. This is understandable if one assumes that the acidic hydrolysing corrosion products are important factors in hydrogen-induced stress corrosion cracking (SCC). Particularly critical are then the well formed, stable aeration elements with anodic areas under rust blisters or fouling. These are, however, to be expected to a lesser extent in the tidal zone (TZ) than in the splash zone (SZ) and immersion zone (IZ), since in the tidal zone stationary aeration elements are more frequently disturbed by tidal movements. Differences between the splash zone and the immersion zone can be explained by the greater oxygen supply and more pronounced rusting in the splash zone. Therefore, the samples in the splash zone are most at risk for stress corrosion cracking.

Hardness HV10		Chromium content			Exposure zone			Potential	
< 300	> 300	≤ 2.5%	2.5–5%	> 5%	SZ	TZ	IZ	FK TZ/IZ	CCP TZ/IZ
7.6	36	14	25	56	40	26	10	26/10	14/16

SZ: splash zone; TZ: tidal zone; IZ: immersion zone
FK: free corrosion; CCP: cathodic corrosion protection

Table 26: Statistical evaluation of the stress corrosion cracking tests, number of cracked samples in percent [65]

The influence of the cathodic corrosion protection (CCP) by zinc anodes is not as clearly evident in the results. With regard to hydrogen-induced stress corrosion cracking cathodic polarisation can be potentially favourable or unfavourable:

- unfavourable due to the raised electrolytic hydrogen supply
- favourable due to avoidance of corrosion, and therefore of aeration elements and local corrosion scars
- favourable due to reduction of fouling and therefore of the occurrence of sulphate-reducing bacteria, which in free corrosion can supply sulphides locally as promoters of hydrogen uptake.

The varying effect of the CCP is therefore possibly due to an overlapping of these effects.

These tests provide a basis for conclusions concerning potential stress corrosion cracking under a completely static load. In plastic stress loads, especially in case of low elongation rates, the softer base material in comparison to the hardened welding seam zones may be at risk for hydrogen-induced stress corrosion cracking [25, 67–69].

Figure 20 shows force-elongation diagrams for four tensile tests with steel S355N (UNS K12709, 1.0545), two in air and two in nitrogen-flushed synthetic seawater with cathodic polarisation to $U_H = -0.76$ V. Until the end of uniform elongation, the elongation rate was $3.9 \times 10^{-6} \text{ s}^{-1}$ [69].

The seawater causes clear changes indicative of elongation-induced stress corrosion cracking (SCC). If elongation-induced SCC occurs and how much attention the risk deserves can be decided based on various criteria. In the example here, the width reduction in the area of uniform elongation Z_g , the fracture reduction Z and the energy at break W of the samples cracked in air must be compared with those of the samples cracked in the corrosive agent. The metallographic analysis also provides an essential evaluation criterion. Samples affected by hydrogen-induced stress corrosion cracking often show surface cracking and even internal cracking along their entire test length.

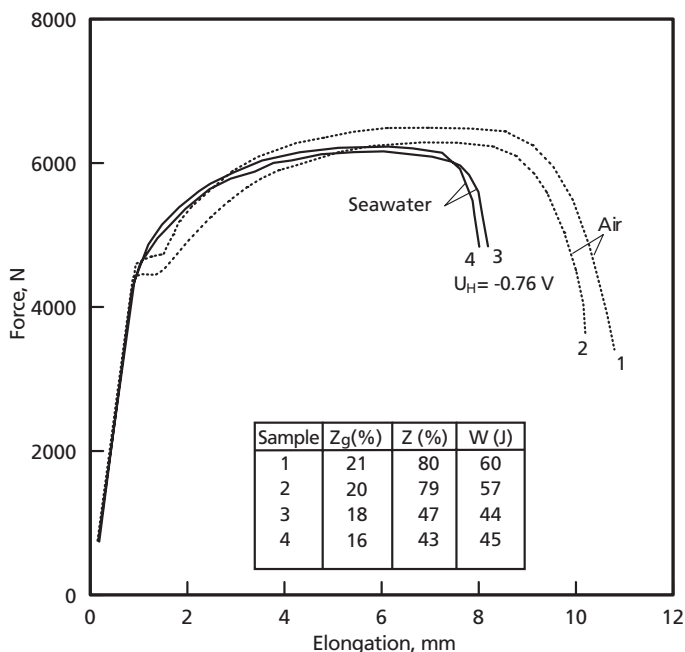


Figure 20: Force-elongation diagrams for tensile stress samples (elongation rate $3.9 \times 10^{-6} \text{ s}^{-1}$) made of structural steel S355N (UNS K12709, 1.0545) in air and in synthetic seawater with cathodic polarisation [69]
 Z_g : uniform elongation Z : elongation W : energy at break

Table 27 shows test results in gradual tensile test samples in synthetic seawater at different elongation rates. The characteristics with free corrosion potential differ practically not at all from those measured in air, whereas with cathodic polarisation the deformation parameters in air are no longer reached. The polarised tested samples also showed surface cracking in the entire test area. These results do not show any limitation of the range of critical elongation rate at the low-rate end. H-SCC subjected to free corrosion in seawater can therefore be excluded with a high degree of probability.

Test potential U_{H_2} V	Elongation rate s^{-1}								
	3.9×10^{-6}			8.7×10^{-7}			1.6×10^{-7}		
	Z_g , %	Z, %	W, J	Z_g , %	Z, %	W, J	Z_g , %	Z, %	W, J
-0.52	19	80	59	18	77	60	18	75	57
-0.75	13	43	45	16	40	45			
-1.05	13	31	40	13	33	42	13	23	40
In air	20	80	60						

Z_g : uniform elongation Z : elongation W : energy at break

Table 27: Results of gradual tensile tests in S355N (UNS K12709, 1.0545) in synthetic seawater with nitrogen flushing in comparison to air [69]

On the question of where the critical potential range for a possible H-SCC risk begins, Figure 21 shows the dependence of H-SCC susceptibility on potential for four higher-strength structural steels in seawater flushed with air [68, 69]. The materials are S355N (UNS K12709, 1.0545), the standard material for offshore structures, the normalised higher-strength fine-grained steel S460N (alloy base material C-Mn-Ni-Cu-V, A 572, 1.8901), and two water-tempered steels of strength class S500Q (alloy base material C-Mn-Ni-Mo-Nb, 1.8924) and S690Q (C-Mn-Cr-Ni-Mo-V, DIN-Mat. No. 1.8931). All four steels complied with offshore standards for metallic purity with maximum sulphur contents of 0.0020% (Table 28). Fracture reduction was selected as the characteristic for H-SCC damage. The corrosion current measured on the samples is also listed. At a free corrosion potential of $U_H = -0.45$ V there is still practically no damage and all steels achieve the fracture reduction values in air. At $U_H = -0.75$ V, all steels show the influence on fracture reduction, which becomes stronger the lower the potential and the greater, subsequently, the hydrogen supply becomes. The protective potential from contact with zinc anodes is about $U_H = -0.6$ V. According to these results, a corrosion cracking risk is not yet to be expected at this potential. Potentials further into the negative range should, however, be avoided.

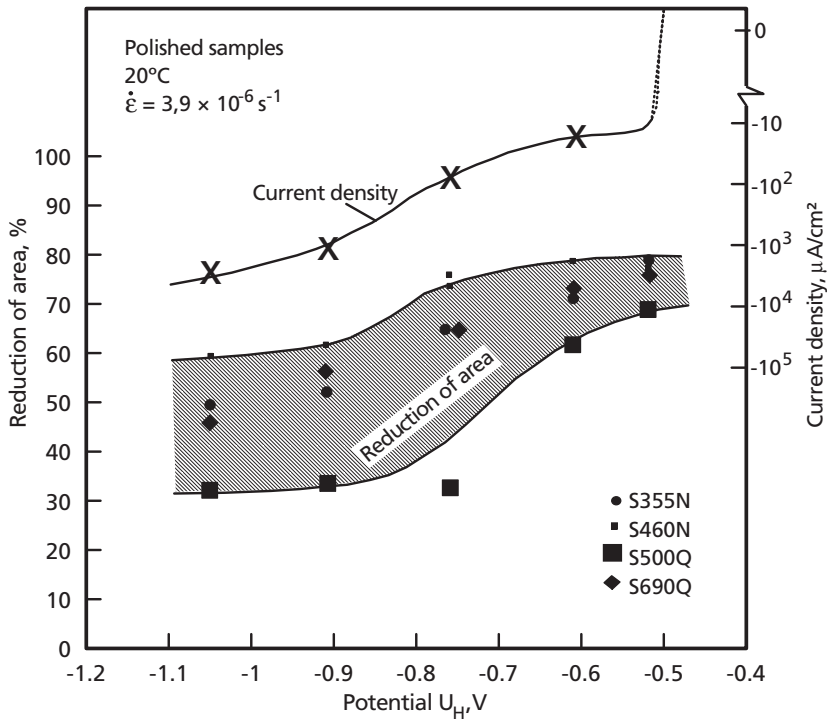


Figure 21: Influence of test potential on fracture reduction of area in gradual tensile tests of high-strength structural steels (S355N, S460N, S500Q, S690Q) in nitrogen-flushed synthetic seawater [69]

Steel	C	Si	Mn	P	S	Al	Cu	Mo	Ni	V	Nb	Cr	N
S355N	0.12	0.34	1.39	0.012	0.002	0.027	0.14		0.15		0.029		0.0075
S460N	0.13	0.43	1.52	0.011	0.002	0.020	0.59		0.69	0.08	0.025		0.0076
S500Q (1)	0.10	0.40	1.44	0.008	0.002	0.046	0.28	0.27	0.51		0.024		0.0055
S500Q (2)	0.10	0.53	1.42	0.015	0.002	0.041	0.23	0.28	0.41		0.004		0.0062
S690Q	0.16	0.23	1.07	0.010	0.002	0.051	0.26	0.50	1.25	0.08		1.19	0.0081

Table 28: Chemical composition of the steels (mass%) [68]

In exposure of fracture mechanics samples with welds showing cracking in the heat affected zone made of the steels in Table 79 in natural seawater under a completely static load, only steel S690Q (1.8931) showed a clear tendency to crack propagation [69].

The hydrogen uptake is increased in a pronounced manner by the presence of promoters, for example sulphide ions, so that under these conditions crack initialisation or propagation is possible even at less negative potentials. Sulphide ions can be produced at the steel surface by sulphate-reducing bacteria (SRB). Figure 22 shows that hydrogen uptake into the steel is clearly increased by sulphate-reducing bacteria at all potentials in comparison to sterile seawater. Two higher-strength low-alloyed steels, comparable to S500Q (1.8924) and S690Q (1.8931) were tested [70].

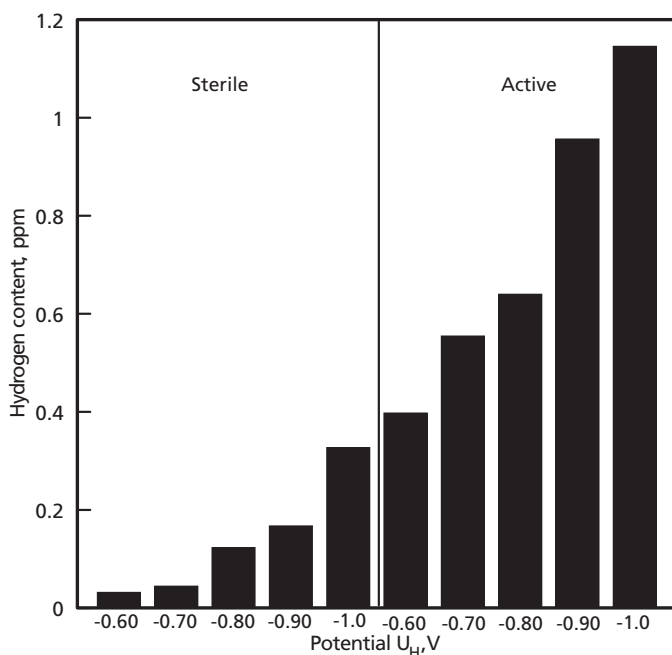


Figure 22: Influence of potentials on hydrogen uptake of steel in sterile and bioactive seawater [70]

Corrosion fatigue

Corrosion fatigue can take place in practically all mediums, hence in seawater as well. It is mainly dependent on the material, the material surface and the mechanical load parameters. In tests under alternating stress in seawater, no fatigue strength category is reached, but only stress-dependent fatigue strength values. Pronounced local corrosion also raises susceptibility to corrosion fatigue due to the notching effect of shallow pits or pitting. Smooth samples can be protected by means of cathodic polarisation, but notched samples cannot. Therefore, cathodic corrosion protection cannot prevent corrosion fatigue itself, but it can prevent critical corrosion shallow pits and therefore indirectly corrosion fatigue as well [71].

Offshore structures, the reliability and availability of which must be ensured for the planned service life period of approximately 30 years, are exposed to periodic stress loads due to wave movements of the ocean [72]. Therefore, a knowledge of fatigue behaviour of the steels used under the conditions of marine engineering are required to ensure reliable design in offshore structures. Although the behaviour of the overall structure or its critical components, such as welded pipe joints, are of interest, smaller samples are usually tested that simulate the heavily stressed elements of offshore structures ("hot spots"). Tests of smaller samples are performed for cracking initialisation, crack propagation and total failure of samples due to stress loads at constant amplitudes or resulting from a random stress load corresponding to a standardized stress sequence [73].

Tests carried out on 20 mm thick, butt-welded and unwelded bend samples made of the high-strength fine-grained structural steel P460N (StE 460, UNS K02900, 1.8905) focused on the parameters:

- Load frequency, including the values observed for real structures, down to 0.04 Hz. The commonest frequency in the open sea is about 0.2 Hz.
- Synthetic air-saturated seawater acc. to ASTM D1241 [74]; 293 to 296 K (20 °C to 23 °C); pH 8.2; oxygen content 7.5 mg/l.
- Natural seawater at 278 to 288 K (5 °C to 15 °C), to cover the influence of organic components and fouling.
- Electrochemical conditions corresponding to the practical situation in offshore structures:
 - Free corrosion in the splash zone with $U_H = -0.45$ V
 - Cathodic protection in the immersion zone with $U_H = -0.65$ V
 - and $U_H = -0.85$ V with possible overpolarisation.

The results are summarised in Figure 23–26 [75, 76].

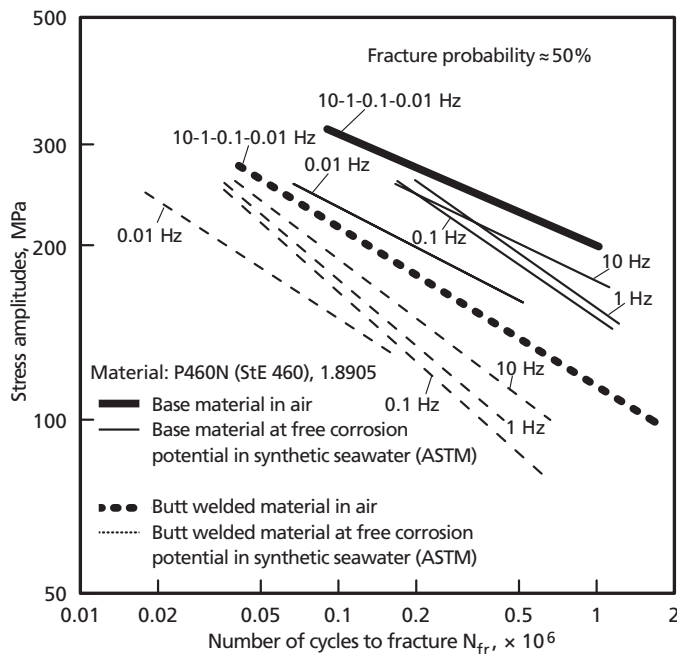


Figure 23: Influence of frequency on the service life of unwelded and welded samples made of P460N (StE 460, UNS K02900, 1.8905) in air and in synthetic seawater [73]

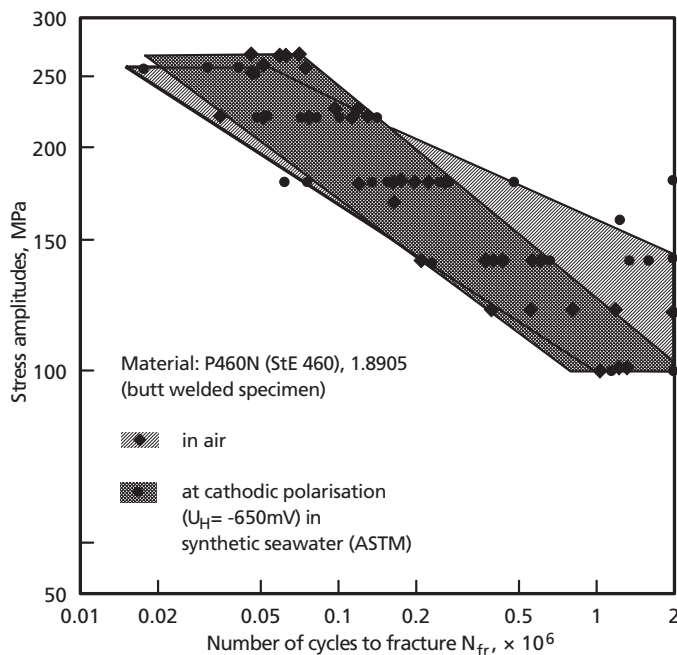


Figure 24: Influence of cathodic polarisation of $U_H = -0.65$ V on the service life of welded samples made of P460N (StE 460, UNS K02900, 1.8905) in synthetic seawater [73]

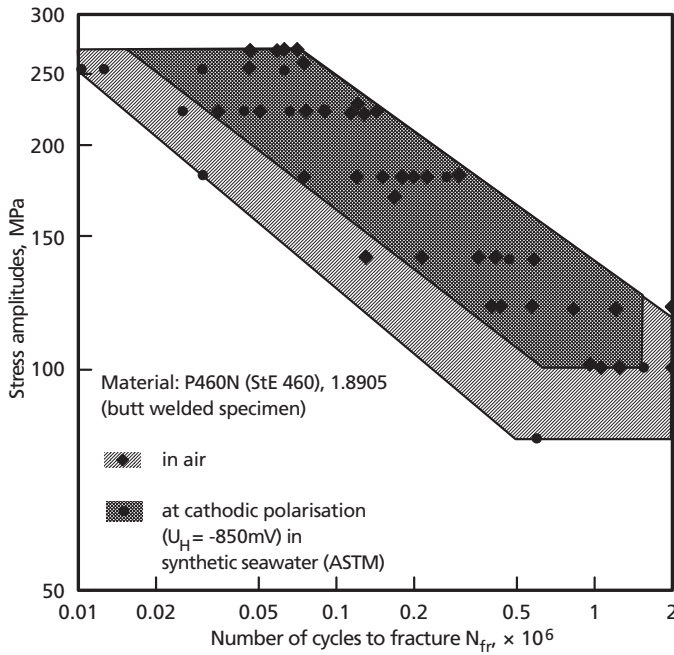


Figure 25: Influence of cathodic polarisation of $U_H = -0.85\text{ V}$ on the service life of welded samples made of P460N (StE 460, UNS K02900, 1.8905) in synthetic seawater [73]

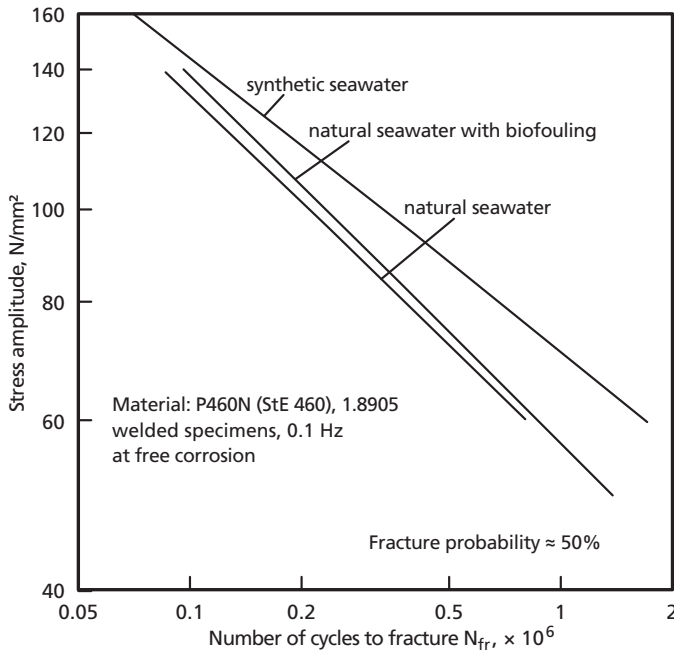


Figure 26: Influence of seawater type on the service life of welded samples made of P460N (StE 460, UNS K02900, 1.8905) [73]

Under conditions of free corrosion, the highly variable immersion periods at the used frequencies of 10–0.01 Hz have a clear influence on the service life of both welded and unwelded samples (Figure 23). With cathodic polarisation, the fatigue behaviour of the samples approaches closely to the samples exposed to air (Figure 24, Figure 25). A comparison of the behaviour in synthetic and natural seawater shows (Figure 26) that the number of tolerable cycles to fracture in natural seawater is much lower with fouling on the samples (55–65%) than in synthetic seawater and that the tolerable stress amplitude is about 75–80%. This influence of biological conditions in natural seawater must be taken into account when evaluated results of tests conducted in synthetic seawater.

When using large cast steel parts in offshore pipe connections, cast components with optimised geometries can reduce the load stresses. The connections to steel parts are realised as butt-welded seams with low stress concentrations removed from hot-spot areas. Figure 27 shows results of fatigue tests on butt-welded seams connecting the fine-grained structural steel S500N (StE 500, A 514, 1.8907) with cast steel G12MnMo7-4 (DIN-Mat. No. 1.5431). The samples were tested under exposure to alternate bending fatigue stress ($R = -1$) at $f = 10$ Hz and load control with constant amplitude and after two different load sequences (ECSC and WASH 1 collective), whereby the natural wave stress load on a platform in the North Sea is simulated. The tests were performed in synthetic seawater acc. to ASTM D1241 [74] at 288 K (15 °C) under conditions of free corrosion and partially also with cathodic polarisation at $U_H = -0.84$ V [77].

Under conditions of free corrosion and constant amplitude (S–N curves), a tolerable stress amplitude results about 20% lower than in air. With cathodic polarisation, the air exposure values are generally achieved once again. In tests with exposure to random stress loads as well, cathodic polarisation extends the fatigue life.

To simulate “hot-spot” conditions at pipe welding seams in offshore structures, angled welding samples made of the standard steel type for offshore structural elements P355N (StE 335, 1.0545, cf. UNS K01600) in the immersion zone were tested in synthetic seawater as per ASTM. The bending tests with $R = -1$ were carried out with a real load collective derived from wave statistics in the North Sea. The maximum bending stress amplitude of the collective was $+135 \text{ N/mm}^2$ or $+150 \text{ N/mm}^2$ at test frequencies of $f = 0.2$ Hz, 1 Hz and 10 Hz. The results in Figure 28 show that there is no significant influence of frequency on crack initialisation, but that there is such a frequency influence on crack propagation, whereby the propagation rate becomes much higher as the frequency drops. Comparative tests in a test solution with three times the salt content showed no further accelerating influence. The application of a test medium modified in this way therefore does not constitute an efficient method of shortening test times [78].

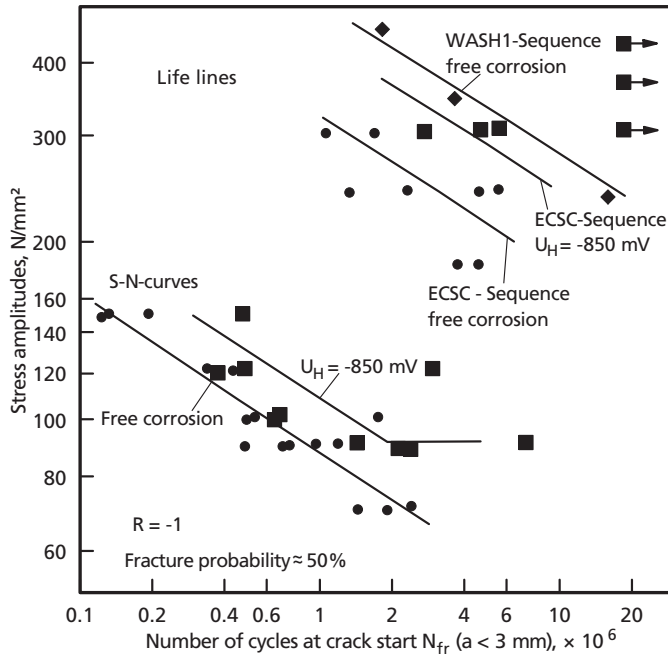


Figure 27: Fatigue properties in a fine-grained structural steel to steel casting butt-welded connection G12MnMo7-4 (DIN-Mat. No. 1.5431) under different test conditions [73]

Test conditions: Synthetic seawater as per ASTM D1241 [74], 288 K (15 °C), pH 8.1, 10 Hz, $a < 3$ mm

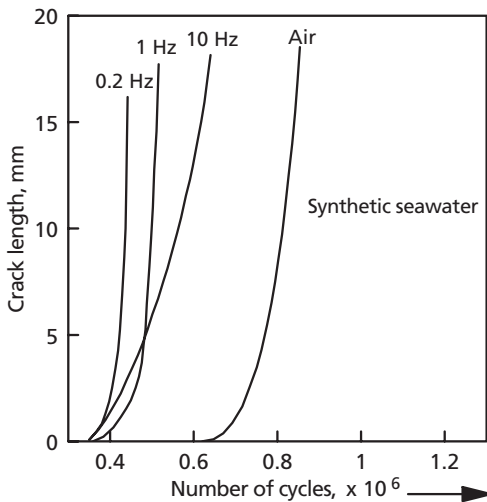


Figure 28: Corrosion fatigue in welded angle samples made of P355N (StE 335, 1.0545, cf. UNS K01600) in air and synthetic seawater, crack initialisation and crack propagation at maximum collective stress of 150 N/mm² (load collective derived from North Sea wave statistics) [73]

Despite careful application of all structural and production standards, cracks may develop at critical locations and existing cracks may escape inspection. To obtain useful conclusions in spite of this situation concerning the service life and inspection intervals, parametric values on crack propagation under alternating stress and a reliable method of calculation are required.

A useful method of calculation for the crack propagation rate da/dN of welded steel samples under seawater conditions that provides a basis for predictions of fatigue behaviour, is described in [77]. As the results in Figure 29 make clear, use of this Paris equation results in a sufficiently accurate estimation of crack propagation in welded angle samples under temporally variable load amplitudes (ECSC sequence) based on crack propagation data obtained under constant load amplitude.

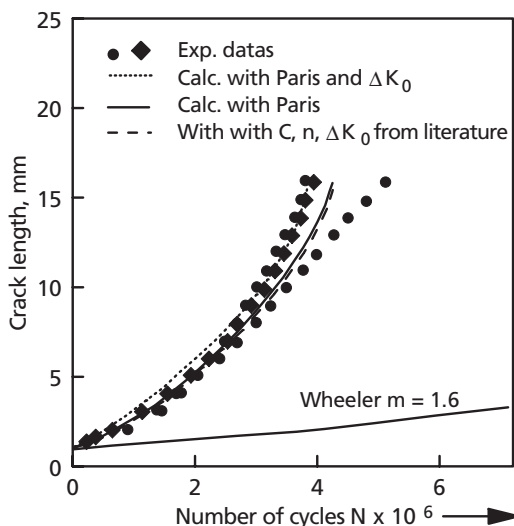


Figure 29: Comparison of experimentally obtained and calculated fatigue life in P355N (StE 335, 1.0545, cf. UNS K01600) [73]

Test conditions: $\sigma_a = 180/\text{N/mm}^2$, $R = -1$, ECSC load sequence

Crack propagation measurements were carried out on the steels S355N (StE 350, 1.0545), P450N (StE 460, 1.8905) and S690Q (StE 690, 1.8931) in air, nitrogen, hydrogen and synthetic seawater as per ASTM at 288 K (15 °C) with and without cathodic protection at $U_H = -0.63\text{ V}$ and $U_H = -1.0\text{ V}$ [77, 79]. The tests were carried out on CT samples under increasing load at $R = 0.1$ and at frequencies of 0.2 Hz, 1 Hz and 10 Hz. The results shown in Figure 30 and Figure 31 show no significant differences in crack propagation in the same medium for the steels tested.

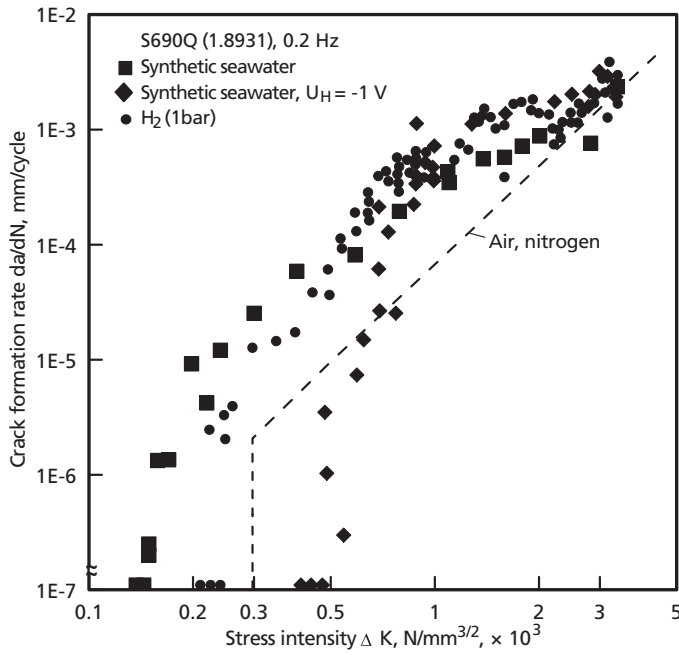


Figure 30: Relation between stress intensity and crack propagation in samples of the steels S690Q (1.8931) under different test conditions at a frequency of 0.2 Hz [73]

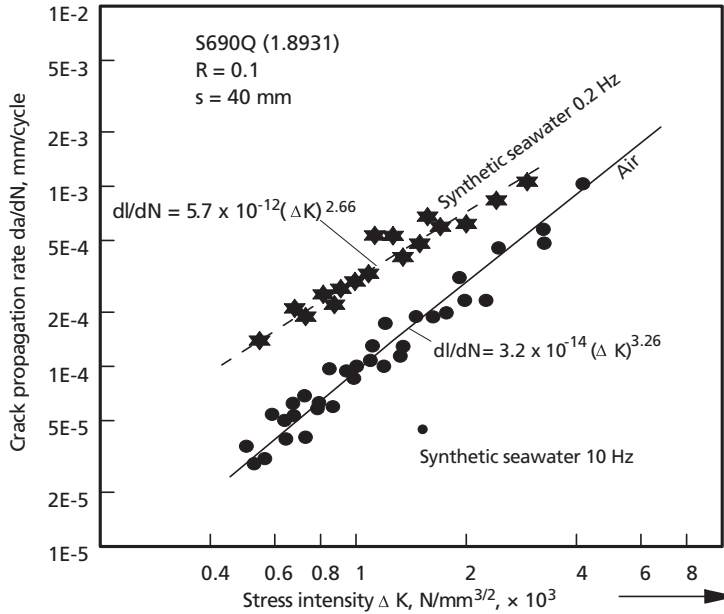


Figure 31: Influence of the test frequency on the relation between stress intensity and crack propagation in samples of the steels S690Q (1.8931) in synthetic seawater and in air [73]

The crack propagation rate is higher in synthetic seawater and hydrogen than in air and nitrogen (Figure 30). The greatest differences were detected at the lowest frequency of 0.2 Hz. At a frequency of 10 Hz, the crack propagation in seawater is no more rapid than in air (Figure 31). The constants of the Paris equation in Figure 31 apply to the test medium synthetic seawater at the frequencies 0.2 Hz and 1 Hz. Cathodic protection in seawater at $U_H = -1.0$ V and low stress intensities result in a lower crack propagation rate and a higher threshold value than in air. At high stress intensities, the crack propagation rate is, on the other hand, comparable with what is found in seawater with free corrosion. The higher threshold value under cathodic protection is probably due to the formation of $Mg(OH)_2$ or $MgCO_3$ deposits at the leading edge of the crack, which reduces the effective stress intensity. The threshold value for stress intensity for ΔK unstable crack propagation in these tests was:

- In air 250 N/mm^{3/2}
- Under conditions of free corrosion in synthetic seawater 195 N/mm^{3/2}
- With cathodic polarisation at $U_H = -0.63$ V 250 N/mm^{3/2}.

In tests of fatigue crack propagation in a high-strength, eutectoid, cold-drawn steel with 0.82% C, 0.6% Mn, 0.18% Si, 0.01% P and 0.024% S, used to make tension wire in prestressed concrete, it was observed that in seawater low frequencies and cathodic polarisation due to contact with zinc accelerate crack propagation [80].

The fatigue behaviour of welded samples can be improved by means of welding seam post treatment by means of WIG or plasma passes in the uppermost layer. The reason for this phenomenon is a low tension concentration due to improved welding seam geometry [81, 82]. Figure 32 and Figure 33 show the results of fatigue tests in untreated and WIG or plasma-aftertreated butt-welding seams in the fine-grained structural steel S355G3S (EH 36, UNS K11852, 1.0589) in air and in synthetic seawater [81]. In the test at constant load amplitude (Figure 32), both after-treatment methods, in air and in seawater, result in better values than are obtained for untreated welding seams. The plasma treatment is somewhat better than the WIG treatment. Under variable load amplitudes (Figure 33) in seawater, the fatigue behaviour of an untreated welding seam is approximately comparable to that of WIG-treated samples and only the plasma treatment results in somewhat higher service life values.

The dependence of corrosion fatigue behaviour on the parameters frequency, form of the load cycle, load level, temperature and potential was tested for a structural steel in an average strength class in [83]. The influence of cathodic protection on corrosion fatigue behaviour of welded connections and the optimised welding seam design is discussed in [84]. In corrosion fatigue tests of notched samples in natural seawater at potentials of cathodic protection, higher fatigue strength values result than in air as a result of lime deposits at the leading edge of the crack. The extent of these deposits depends on the protection current density in the notch, on sample dimensions and on the frequency, by which the exchange of electrolyte solution at the leading edge of the crack is determined [85].

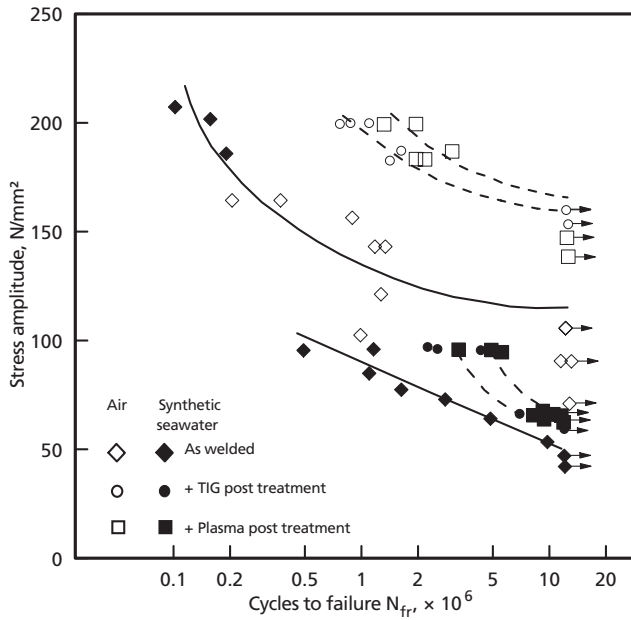


Figure 32: Influence of welding seam post treatment on fatigue behaviour in air and in synthetic seawater at a single load level in S355G3S (1.0589) [73]

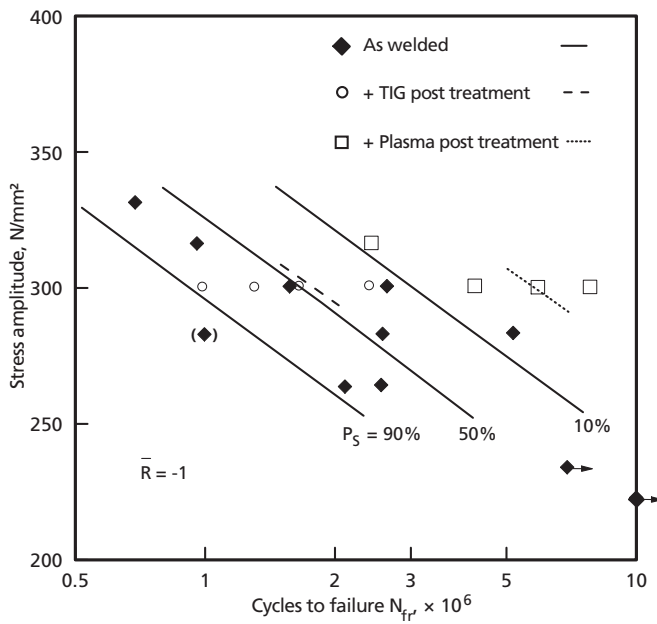


Figure 33: Influence of welding seam post treatment on fatigue behaviour in synthetic seawater under variable load amplitude in S355G3S (1.0589) [73]

Unalloyed cast iron and low-alloy cast iron

In the immersion zone in seawater, iron-carbon cast alloys show somewhat less corrosion than steels. Since cast parts usually have thicker walls, such structural elements often show longer useful lives than rolled materials. In the splash and tidal zones, the corrosion rates are, however, as much as one-third lower than is observed in unalloyed steel types [23, 86].

Corrosion rates differ only slightly in the various cast iron types. Grey cast iron (GC) is eroded somewhat more than cast iron with lamellar graphite (GCL) and ductile cast iron with graphite spheres (GCG). Table 29 lists the free corrosion potentials and corrosion rates for uniform surface corrosion in the cast iron types acc. to DIN EN 1561 [87], DIN EN 1563 [88] and DIN 1694 [89].

Free corrosion potential U_{H^+} , V	Corrosion rate, mm/a (mpy)		
	Immersion zone	Tidal zone	Splash zone
−0.3 to −0.5	0.08 to 0.12 (3.15 to 4.72)	0.05 to 0.09 (1.97 to 3.54)	0.02 to 0.05 (0.79 to 1.97)

Table 29: Free corrosion potential and corrosion rate of cast iron in seawater

Whereas in unalloyed steels the corrosion rates in the tidal zone are higher than in the immersion zone, the cast iron types show the highest corrosion rates in the immersion zone. This is also confirmed by exposure tests over a period of several years off Helgoland in which cast with lamellar graphite (GCL) and cast iron with spherical graphite (GCG) samples were exposed, in each case with and without addition of copper (Table 30) [86].

Type	C	Si	Mn	P	S	Cu	Mg
GCG	3.21	3.13	0.29	0.047	0.015	–	0.132
GCG + Cu	3.45	3.20	0.29	0.048	0.007	1.03	0.034
GCL	3.52	1.96	0.65	0.210	0.100	–	–
GCL + Cu	3.38	1.87	0.54	0.188	0.119	1.80	–

Table 30: Chemical composition of tested cast iron samples, in mass% of test melt [86]

The corrosion rates listed in Figure 34 were determined for these samples.

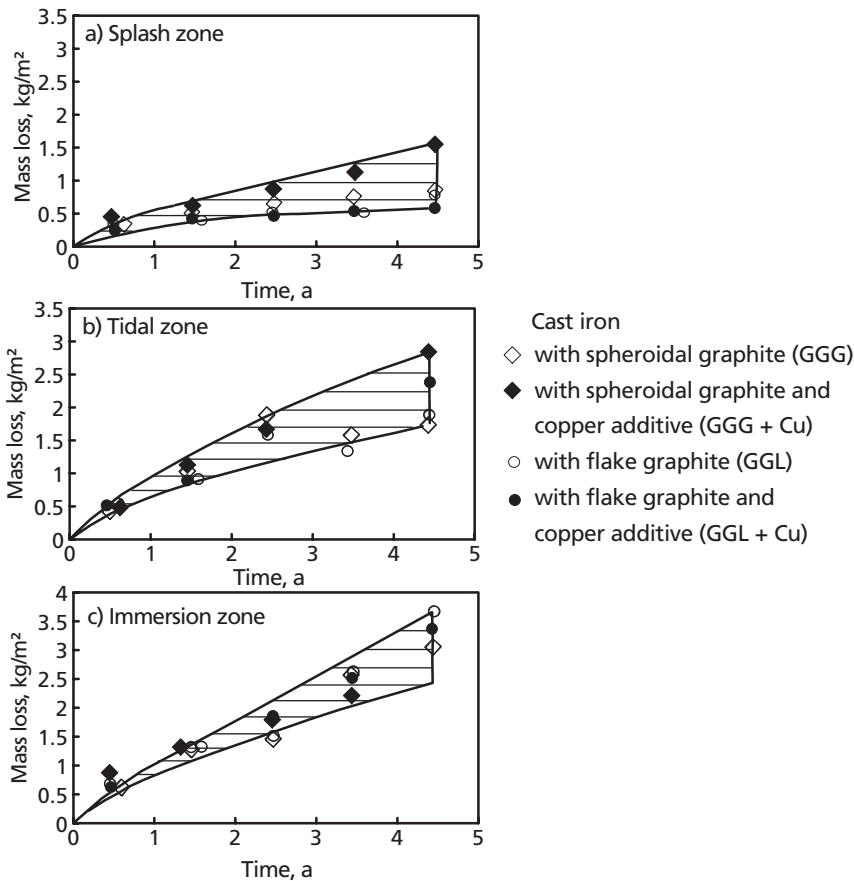


Figure 34: Mass losses in cast iron samples from Table 30 after exposure in the splash, tidal and immersion zones in seawater off Helgoland [86]

In the tidal zone and the immersion zone, no influence of graphite formation or addition of copper on the corrosion behaviour is recognisable. In the splash zone, on the other hand, the corrosion rates in the GCL samples are all at the lower limit of the scatter band. After the test period of 4.5 years, scatter ranges as follows were determined for surface corrosion:

Splash zone:	0.017–0.045 mm/a
Tidal zone:	0.050–0.078 mm/a (1.97–3.07 mpy)
Immersion zone:	0.067–0.100 mm/a (2.64–3.94 mpy)

These values correspond very closely to the scatter ranges in Table 29.

The influence of the structure (pearlite, ferrite, cementite, phosphide eutecticum, graphite in lamellar or spherical form) on the corrosion process in cast iron is mini-

mal. Alloying additions of nickel in amounts of about 1% also did not result in an improvement in corrosion behaviour. In exposure tests in synthetic seawater, after 220 test days, the corrosion rates listed in Table 31 were determined for different cast iron types [90]. The unalloyed steel St 37 (SAE 1015, DIN-Mat. No. 1.0037) was tested as a control.

Type	Corrosion rate, mm		Pitting corrosion factor
	Mean	Maximum	
GCL ferritic	0.023	0.25	10.9
GCG ferritic	0.030	0.44	14.7
Annealed cast iron	0.033	0.16	4.9
GCL pearlitic	0.030	0.28	9.3
GCL pearlitic/Ni	0.039	0.26	6.6
GCG/Ni	0.052	0.35	6.7
Grey cast iron, GC	0.035	0.35	10.0
St 37 (1.0037)	0.061	0.25	4.1

Table 31: Corrosion rates of cast iron in seawater after 220 days [90]

Cast iron with lamellar graphite shows a typical form of selective corrosion – graphitising (spongy), caused by the heterogeneous structure, whereby only the ferrite and pearlite are corroded. The external form structural element is maintained with a reduced loadbearing capacity, since corrosion products in combination with graphite, cementite and phosphide eutecticum remain behind. This form of corrosion occurs at locations at which the casting crust or a coating have been damaged or removed and is observed in particular in lower-oxygen waters, e.g. brackish water.

Cast iron pipelines have in some cases lasted for decades transporting seawater or salt solutions [91, 92].

High-alloy cast iron

Nickel-alloyed cast iron with content levels of 1–3% nickel is often used in pump casings, water chambers and other castings used in contact with seawater. The addition of nickel increases the strength and reduces the porosity of the casting, but has practically no influence on the corrosion resistance in seawater.

The austenitic cast iron alloys with 13–35% nickel and 1–5% chromium, also known under the commercial name Ni-Resist® [93], show, due to their austenitic structure, much better corrosion behaviour in stagnant and flowing seawater than unalloyed castings. The corrosion resistance increases markedly with increasing chromium content. The carbon may be present either as graphite in lamellar form

or as spherical graphite within the structure. The spherical graphite types generally show higher strength levels and much better elongation values than comparable types with lamellar graphite. Table 32 lists corrosion values for general corrosion and pitting corrosion in the materials GGL-NiCr 20 2 (A 436, DIN-Mat. No. 0.6660, Ni-Resist® type 2, ASTM A436 [94]) with 2.5% C, 2.3% Si, 1.2% Mn, 22.8% Ni and 2.0% Cr at different flow rates in aerated and non-aerated synthetic seawater [95].

Flow rate m/s	Aerated		Non-aerated	
	Surface corrosion mm/a (mpy)	Pitting corrosion mm/a (mpy)	Surface corrosion mm/a (mpy)	Pitting corrosion mm/a (mpy)
0	0.043 (1.69)	2.6 (102)	0.022 (0.87)	0.7 (27.6)
1.1	0.127 (5.00)	9.6 (378)	–	–
2.2	0.170 (6.69)	12.35 (486)	0.020 (0.79)	0.0
3.3	0.220 (8.66)	16.06 (632)	0.012 (0.47)	–
4.4	0.271 (10.7)	17.96 (707)	0.017 (0.67)	–

Table 32: Corrosion behaviour of Ni-Resist® (0.6660) at room temperature in synthetic seawater as per ASTM D1141 (1998) [7] with pH 8.2 [95]

In aerated seawater, the rates of surface corrosion and pitting corrosion both increase with the flow rate, whereas they remain very low in non-aerated seawater, regardless of the flow rate.

Some austenitic cast iron types may show a level of sensitivity to stress corrosion cracking in seawater and salt solutions at higher temperatures [96]. At high nickel contents of around 35%, pitting corrosion increases [97].

The austenitic nickel cast iron types are frequently used in pumps, valves and pipelines for transport of seawater or concentrated salt solutions in the process of seawater desalination [98].

The corrosion rates collected in Table 32 are taken from the various different areas of application [91, 93].

Conditions	Corrosion rate, mm/a (mpy)
Seawater, immersion zone	0.043–0.053 (1.7–2.1)
Seawater, 38–42 m/s	1.000–1.750 (39.4–68.9)
Seawater, 1.8 m/s, 316 K (43 °C)	0.225 (8.9)
Seawater, 1.5 m/s, 355 K (82 °C), deaerated	0.275 (10.8)
Seawater, 1.5 m/s, 363 K (90 °C), deaerated	0.175 (6.9)
Seawater, 1.5 m/s, 372 K (99 °C), deaerated	0.150 (5.91)

Table 33: Corrosion rates for austenitic nickel cast alloys in seawater and salt solutions [91, 93]

Table 33: Continued

Conditions	Corrosion rate, mm/a (mpy)
Salt solution, $c(\text{Cl}^-) = 300 \text{ g/l}$, pH 6, 283 K (10 °C)	0.050–0.058 (2.0–2.3)
Boiling 20% NaCl solution	0.004–0.008 (0.2–0.3)
Seawater desalination, 326 to 369 K (53 °C to 96 °C)	0.038–0.076 (1.5–3.0)

Table 33: Corrosion rates for austenitic nickel cast alloys in seawater and salt solutions [91, 93]

The silicon cast alloys with content levels of about 15% silicon show good resistance in seawater. Their corrosion rates are around 0.05–0.01 mm/a (2.0–0.4 mpy). They are also used as anodes for cathodic corrosion protection with external current with a material consumption level of 0.4–0.9 (kg/A a).

Ferritic chromium steels with < 13% Cr

The influence of the alloying elements – of chromium as well – up to a total level of about 5% is described in detail in Section “Unalloyed and low-alloyed steels/cast steel”. Steels with alloy contents at this level must be protected against corrosion just like unalloyed steels in the splash zone and tidal zone. Despite the much lower corrosion rate in the atmosphere in these materials, the use of weather-resistant steels without corrosion protection cannot be recommended in sea air either.

The steel X10CrAl7 (1.4713) with about 7% Cr shows, under exposure in the immersion zone and in the tidal zone, pronounced rusting, shallow pit corrosion and crevice corrosion under bolt washers. The cathodic protection effect of iron or zinc anodes is also unsatisfactory [99].

The high-strength steels of the American HY series with alloying contents of 2.5–5% Ni and 0.5–11.5% Cr, which are used for the pressure-bearing hulls of submarines and other diving devices due to their high strengths, can only be used in seawater in connection with the normal corrosion protection methods.

The corrosion resistance of stainless steels with much less than 17% chromium is insufficient to maintain an acceptable surface quality when exposed openly to the weather in marine atmosphere or in seawater over the longer term. These materials are, however, much more resistant to corrosion than the unalloyed and low-alloyed steels. They are used in atmospheric exposure when there is an emphasis on

- service life
- safety and
- low maintenance requirements

and no particular requirements apply as to appearance. For this reason, ferritic steels such as 1.4003 (E-4, X2CrNi12), 1.4512 (UNS S40900, X2CrTi12) and 1.4589 (UNS S42035, X5CrNiMoTi15-2) with chromium contents between 10 and 15% are becoming increasingly important in the construction of containers, wagons and

vehicles as well as in the construction of industrial facilities and environmental engineering. In a marine climate and in the splash zone, the corrosion levels are much higher than at inland locations due to the splash water and chloridic aerosols. It is true that here as well, after year-long exposure tests of the steels 1.4003 and 1.4512, no surface corrosion was observed. Surface corrosion tended to take the form of pitting corrosion with an average depth and diameter of < 0.3 mm. In crevices under plastic washers, however, pronounced crevice corrosion with depths > 1 mm occurred.

The ferritic steels with approx. 10-15% Cr can be considered as alternative construction materials to the low-alloyed steels for atmospheric corrosion loads under the following conditions:

- Requirement for a very high level of resistance to corrosion-related hull thickness reduction.
- The optical appearance is less important and rust spotting or rust coatings are not a problem. If a blank metal surface is to be maintained, higher-alloyed stainless steels must be used.

With this requirement profile, these steels can also be considered for applications in marine atmosphere or industrial atmospheres. The steels 1.4003 (X2CrNi12) and 1.4512 (X2CrTi12) are not likely to show any corrosion-related cross-sectional reductions, even over periods of several decades, with the exception of highly aggressive conditions. Crevice corrosion can be expected under heavy chloride exposure and in the presence of crevices. Such critical conditions do not result from seawater exposure only, but are also seen inland due to deicing salt, etc. The ferritic chromium steels are not, by the way, formulated with crevice corrosion resistance in mind [100].

Ferritic chromium steels with $\geq 13\%$ Cr

Steels containing more than 13% chromium are passive under normal conditions in seawater, so that a reduction of hull thickness due to uniform surface corrosion is negligible for all practical purposes, but they are at risk for pitting and crevice corrosion at low chromium and molybdenum content levels. Reliable protection against these corrosion types can only be achieved with the austenitic or ferritic-austenitic duplex steels with high content levels of chromium (20–30%) and molybdenum (5–7%) i.e. by materials with a high pitting resistance equivalent.

This does not mean the stainless steels with lower alloying contents are generally unsuitable for use in seawater. The corrosion conditions may differ widely depending on the particular application. Cathodic protection of the high-alloy steel is also often provided in composite structures by contact with structural elements made of unalloyed steel. This is one of the reasons why in many cases relatively low-alloyed stainless steels have proven effective in seawater. If necessary, these steels should be integrated in the cathodic protection system. In cases in which the lower-alloyed

standard stainless steels are used for reasons of availability or cost, these steels should in any case be integrated in the cathodic protection system.

The use of the term “stainless steels” refers according to DIN EN 10088-1 [101] to steels with alloying contents of at least 10.5% chromium and a maximum of 1.2% carbon, whereby the corrosion resistance of these steels is of primary importance.

Stainless, high-alloyed steels have a passive surface state in seawater as in nearly all neutral or low-acidic electrolyte solutions. To achieve this passive state, steels require a chromium content of at least 12%. Passive materials show practically no surface corrosion, but if the passivation layer is subjected to a constant local disturbance they may suffer from local corrosion.

Since the low surface corrosion level in all passive materials is normally not problematic in practice, listing corrosion rates for these materials makes little sense. In the case of pitting corrosion the values are misleading anyway, since the corrosion rates are normally calculated from mass loss figures.

Pitting corrosion only occurs in high-alloyed steels when the critical potential for pitting corrosion (pitting potential) is exceeded. In moving and aerated seawater at normal outdoor temperatures, the free corrosion potential of stainless steels is in the range $U_H = 0.4 \text{ V}$ to 0.5 V . Steels with pitting potentials above $U_H = 0.5 \text{ V}$ should therefore be resistant to pitting corrosion in seawater.

Pure chromium steels with about 11–18% Cr do not reach these values for pitting potential and are therefore not suited to a seawater stress load due to pronounced local corrosion, as shown by tests of the steels X2CrTi12 (SAE 409, 1.4512), X12Cr13 (SAE 410, 1.4006) and X6Cr17 (SAE 430, 1.4016). Even with small additions of other alloying elements, e.g. 2% molybdenum in the steel X2CrMoTi18-2 (SAE 444, 1.4521), pitting and crevice corrosion cannot be eliminated. The chromium steels with low chromium contents of 12–13% cannot be exposed to seawater due to this sensitivity to pitting and crevice corrosion without cathodic protection. Whereas the steel X2CrTi12 can be protected both by contact with iron and zinc anodes, this is only possible with zinc anodes for the steel X10CrAl13 (DIN-Mat. No. 1.4724) [99]. Crevice corrosion was found on the steel X3CrTi17 (SAE 430 Ti, 1.4510) after only 3 months in natural seawater, regardless of surface treatment [102].

As in all high-alloyed stainless steels, the ferritic steels are also subjected to a heat treatment to give them the most effective possible corrosion resistance. In particular, the idea is to eliminate precipitations of carbides or intermetallic phases that have developed in the course of forming. These are either not themselves corrosion-resistant or surrounded by areas with low alloying element content levels and therefore less resistant. So, the influence of precipitations was observed in a welded sample made of X6Cr17 (SAE 430, 1.4016) that had been exposed without post-heating and was corroded in particular where martensite had been produced at the grain boundary due to the welding heat [99].

Tests of ferritic CrMo steels show that pitting corrosion is suppressed in seawater and crevice corrosion can be reduced to low levels or long incubation periods at chromium contents of 25% and molybdenum contents of at least 3% [103, 104].

For instance, high-alloyed steels with 28% Cr + 4% Mo, 29% Cr + 4% Mo and 28% Mo + 4% Mo + 2% Ni after exposure of 9 months in natural seawater showed

absolutely no pitting or crevice corrosion under either flowing or stagnant conditions [105, 106].

Ferritic steels with 29% Cr + 4% Mo and 29% Cr + 4% Mo + 2% Ni have been developed for seawater exposure [107]. Their composition can be optimised by reducing carbon and nitrogen contents using modern steelmaking processes and adding stabilising elements [104].

In the ferritic chromium steels, the resistance to pitting and crevice corrosion depends on the pitting resistance equivalent $PRE = \% Cr + 3.3 \times \% Mo$. Steels with a pitting resistance equivalent of 32 are sufficiently resistant in seawater under normal conditions. Under critical conditions for crevice corrosion, materials with a pitting resistance equivalent of 35 are required [99].

Crevice corrosion also develops under deposits or fouling, e.g. under the basalt plates of barnacles. The microbiological slime often observed on the surface of stainless steels can shift the free corrosion potential in the positive direction so that the pitting potential of the steels is exceeded [108]. Pipes made of a chromium steel with 26% Cr and 1% Mo failed within a brief period with biological deposits, but remained resistant in deaerated and sterile seawater in desalination plants [109].

In exposure tests in the tidal and immersion zone of the natural North Sea waters off Helgoland, the 18% chromium steel X2CrMoTi18-2 (SAE 444, 1.4521) was attacked by pitting and crevice corrosion despite its molybdenum content. The superferritic steels X 1 CrMo 26 1 (DIN-Mat. No. 1.4131) and X1CrNiMoNb28-4-2 (25-4-4, 1.4575), on the other hand, remained free of pitting corrosion. Slight crevice corrosion was observed only in the steel X 1 CrMo 26 1 under washers. In special crevice corrosion samples, crevice corrosion occurred under washers made of both PVC and austenitic steel X2CrNiMoN17-13-5 (SAE 317 LMN, 1.4439) [99].

Superferrites with 20% Cr and 3.5% Mo or 5% Mo and with 28% Cr and 2% Mo, both with max. 0.0050% C and max. 0.0020% N, are resistant to pitting corrosion at room temperature in 3% NaCl solution. The critical pitting potential is shifted with increasing Mo content to higher temperatures. The addition of nickel has no influence on the pitting resistance equivalent of the steels, although it improves their crevice corrosion behaviour appreciably. Even under the following conditions, no crevice corrosion was found in the nickel-alloyed steel types:

- heat exchanger pipes with circulating seawater at 2 m/s–4 m/s and seawater brine with 10% salt content at temperatures of 398 and 403 K (125 °C and 130 °C)
- 3% NaCl solution at 353 K (80 °C), 2-year test period
- 15% NaCl solution at 333 K (60 °C), aerated and non-aerated, test period 1.5 years

In stress corrosion cracking tests with U-bend samples in boiling synthetic seawater, the nickel-free steels also remained free of stress corrosion cracking after a test period of 1,200 h, but they did show pronounced shallow pit and crevice corrosion. Nickeliferous samples were also resistant to stress corrosion cracking, and also showed no signs of local corrosion under these conditions [110].

The for the most part precipitation-free superferrite X1CrNiMoNb28-4-2 (25-4-4, 1.4575) with a nominal composition as in Table 34 and a pitting resistance equivalent of 33, also proves highly resistant to pitting corrosion [111].

% C	% Cr	% Ni	% Mo	% N	% Nb
≤ 0.020	27.0–29.0	3.0–3.5	1.8–2.5	≤ 0.030	≥ 12 × (C + N)

Table 34: Chemical composition of superferrite X1CrNiMoNb28-4-2 (25-4-4, 1.4575)

Figure 35 shows the dependence of pitting potentials on the temperature in aerated 3% NaCl solution for the superferrite X1CrNiMoNb28-4-2 (DIN-Mat. No. 1.4575) and for a number of austenitic steels (X2CrNiMoN17-13-5, DIN-Mat. No. 1.4439; X2CrNiMo18-15-4, DIN-Mat. No. 1.4438 and X6CrNiMoTi17-12-2, DIN-Mat. No. 1.4571).

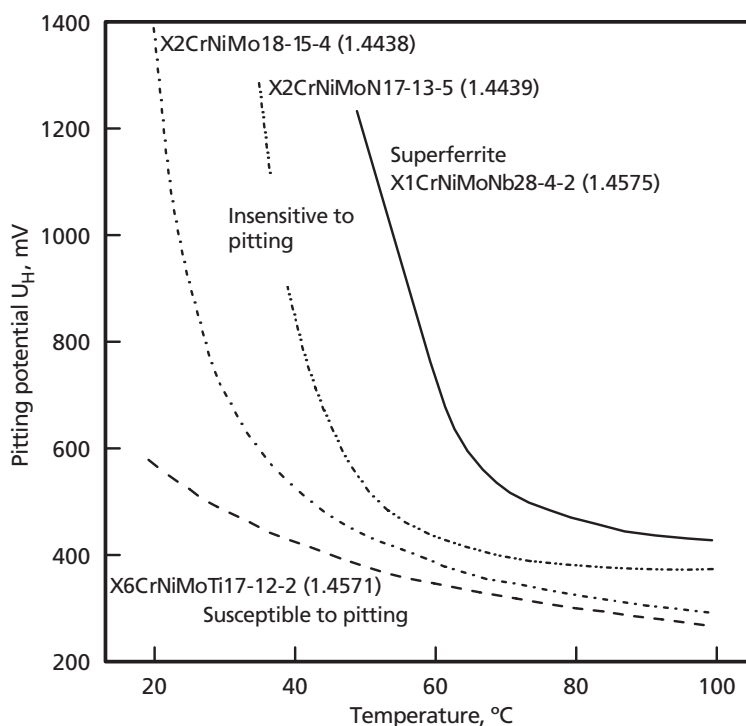


Figure 35: Pitting potentials of the superferrites X1CrNiMoNb28-4-2 (DIN-Mat. No. 1.4575) and standard austenites 1.4439, 1.4438 and 1.4571 in 3% NaCl solution as dependent on the temperature [111]

For exposure to saltwater and in seawater-cooled heat exchangers and condensers, the superferritic steels Monit[®] and Sea-Cure[®] have proved useful, in which the alloying elements are balanced so that good corrosion resistance and processability result without precipitation of critical chromium or molybdenum phases [112–114]. The chemical composition of the two materials is listed in Table 35.

	% C	% Cr	% Ni	% Mo	% Ti	% N
Monit [®]		25.0	4.0	4.0	0.40	≤ 0.025
Sea-Cure [®]	≤ 0.025	25.0–28.0	1.0–3.5	3.0–4.0	0.2–1.0	

Table 35: Chemical composition of Monit[®] and Sea-Cure[®] [112, 113]

The materials Monit[®] and Sea-Cure[®] are characterised by good resistance to pitting, crevice and stress corrosion cracking in seawater. The critical pitting corrosion temperature in the FeCl_3 test is 328 K (55 °C) and the critical crevice corrosion temperature is 318 K (45 °C). In Table 36, the pitting potentials of the two superferrites and the austenitic steels 1.4539 (SAE 904 L, X1NiCrMoCu25-20-5) and X3CrNiMo17-13-3 (SAE 316, 1.4436) measured in 5% NaCl solution are presented.

As ferritic steels, the materials Monit[®] and Sea-Cure[®] are highly resistant to stress corrosion cracking and remain free of cracking in the test in 40% CaCl_2 solution at 373 K (100 °C) and under a load of up to 90% of yield point, even after 5,000 h. Also, in the test for stress corrosion cracking sensitivity in a solution containing H_2S acc. to NACE Standard TM-01-77, the samples withstand a stress load at yield point level without cracking after the standard test period of 720 h.

Temperature K (°C)	Pitting potential U_{H} , V			
	Monit [®]	Sea-Cure [®]	X1NiCrMoCu25-20-5 1.4539	X3CrNiMo17-13-3 1.4436
333 (60)	1.19	1.10	0.74	0.37
353 (80)	0.92		0.53	0.28

Table 36: Pitting potentials in 5% NaCl solution at 333 and 353 K (60 °C and 80 °C) [112, 113]

A special form of crevice corrosion was observed in crevices between superferrite and austenitic standard steels in condenser pipes. Corrosion products, which lower the pH levels in the crevice, cause depassivation and increased corrosion on the ferritic steel. This form of corrosion, also known as dissimilar metal crevice (DMC) corrosion, does not occur with the combination of superferrites and superaustenites [115].

In a superferritic steel (ELI steel) with the composition 0.022% C, 24.9% Cr, 3.63% Ni, 3.52% Mo and 0.50% Ti a critical pitting corrosion temperature of over 333 K (60 °C) was determined in a seawater-like chloride sulphate solution. A chlorine addition to the solution shifts the corrosion potential in the positive direction, reducing the pitting resistance equivalent in the critical temperature range [116].

In martensitic steels the main objective of heat treatment is to set the strength of the material at a certain level, adjustable by selection of the annealing or tempering temperature. Tests of steel showed similar results in DIN-Mat. No. 1.4006 (X12Cr13) and DIN-Mat. No. 1.4542 (SAE 630, X5CrNiCuNb16-4) with an annealing temperature of 723 to 923 K (450 °C to 650 °C), whereby exposure in the seawater

resulted in stress corrosion cracking independent of load at annealing temperatures under 823 K (550 °C). In other exposure tests as well, stress corrosion cracking was found in steel DIN-Mat. No. 1.4532 (SAE 632, X8CrNiMoAl15-7-2) after tempering at 783 K (510 °C), even without an external stress load, but not after tempering at 838 K (565 °C).

The martensitic tempering steel X4CrNiMo16-5-1 (DIN-Mat. No. 1.4418) has proved resistant to stress corrosion cracking in stress corrosion cracking tests in seawater up to 333 K (60 °C) and stress loads of up to 90% of the 0.2% yield point, but did show pitting corrosion [117].

Hydrogen-induced stress corrosion cracking

Since martensitic steels are usually sufficiently seawater-resistant with only cathodic protection, it is possible that the hydrogen produced at the steel surface could initiate stress corrosion cracking. Tests in synthetic seawater with predefined potential demonstrated that the higher strength class of the same steel in each case was more sensitive than the lower-rated material and that the tempering steels brought up to very high strength levels are even more susceptible in this state. In the four tempering steels, the low strength class is equivalent to the standard strength listed in DIN EN 10088-3 [118] / SEW 400 [119]. It can be concluded based on this study that under conditions of free corrosion, that is without cathodic protection, stress corrosion cracking is not to be expected as long as the annealing temperatures for the lower strength class are above 823 K (550 °C) [120].

[121] also reports on problems of hydrogen-induced stress corrosion cracking and crevice corrosion in seawater condensers made of ferritic steels with 29% Cr in operation since 1980.

A variety of tests in synthetic seawater and natural seawater demonstrated that the heat-treatable steels 1.4122 (X39CrMo17-1), 1.4313 (UNS S41500, X3CrNiMo13-4), 1.4532 (UNS S15700, X8CrNiMoAl15-7-2), 1.4057 (UNS S43100, X17CrNi16-2), 1.4418 (X4CrNiMo16-5-1), 1.4542 (UNS S17400, X5CrNiCuNb16-4) are brought to a potential of $U_H = -0.35$ V by contact with unalloyed steel, effectively protecting them against pitting and crevice corrosion. It must be remembered within the framework of the cathodic protection these steels must have in seawater, that lower protective potentials may lead to hydrogen-induced stress corrosion cracking. This can already occur at the potential of $U_H = -0.65$ V arrived at with cathodic protection using zinc anodes [122–125].

High-alloy multiphase steels

Ferritic/pearlitic-martensitic steels

Ferritic-austenitic steels/duplex steels

The martensitic steels are normally chromium steels with 12–18% Cr, carbon contents of 0.1–1.2% and in some cases alloyed with molybdenum (up to 1.5%) or nickel (up to 3%). A subgroup is formed by steels with only about 0.05% C and a higher nickel content (4–5%), the soft or nickel martensitic steels. The mechanical properties of martensitic steels can be changed within a broad range by heat treatment (hardening or tempering) depending on the carbon content. Martensitic steels also include hardenable steel with about 0.04% C, 16% Cr, 4% Ni, 4% Cu.

Carbon content is of indirect consequence in martensitic steels only. Due to the formation of carbides, the entire amount of chromium and molybdenum in the material is not available for corrosion resistance. For this reason, the pitting resistance equivalent is misleading for martensitic steels. This disadvantage of the classic tempering steels with about 0.2–0.4% C can be compensated by nickel-martensitic or martensite-hardening steels with carbon contents of only about 0.02–0.05% C. The superiority of low-carbon steels DIN-Mat. No. 1.4418 (X4CrNiMo16-5-1) and DIN-Mat. No. 1.4542 (UNS S17400, X5CrNiCuNb16-4) in comparison to the high-carbon steels DIN-Mat. No. 1.4057 (UNS S43100, X17CrNi16-2) and DIN-Mat. No. 1.4122 (X39CrMo17-1) is demonstrated by the fact that exposure in the immersion zone off Helgoland caused crevice corrosion in all four steels, but that more pronounced crevice corrosion as well as pitting were observed in the steels DIN-Mat. No. 1.4057 and DIN-Mat. No. 1.4122.

Tests of tempered martensitic-ferritic Cr steels show that narrow, sharp notches or cracks result in corrosion fatigue. Damage to propeller vanes made of these steels is frequently caused by corrosion fatigue, so that careful inspection for flaws is absolutely necessary after production [126].

The austenitic-ferritic steels, because of their two structural components also known as duplex steels, are chromium-nickel steels with chromium contents of about 21%–27%, and nickel contents of 4%–5%. They are usually made with about 3% molybdenum, nitrogen additions and a carbon content of $< 0.03\%$. They reach the category of temperable martensitic steels with values for the 0.2% yield point of $> 450 \text{ N/mm}^2$ and are thus clearly above the austenitic steels. Worth mentioning are the good viscosity parameter values and the favourable fatigue strength properties of these steels, even in corrosive mediums.

For applications in seawater, the main steels used are X2CrNiMoN22-5-3 (2205, 1.4462), X3CrNiMoN27-5-2 (SAE 329, 1.4460) and the cast material GX8CrNiN26-7 (1.4347) [23]. The chemical compositions and the mechanical properties of these steels are in DIN EN 10088-1 to -3 [101, 127] and, for the cast material, in SEW 410 [128]. The content of alloying elements is formulated in duplex steels so that the two structural components – the ferrite and austenite phases, are present in the struc-

ture in a balanced ratio (usually 1:1) and the chromium content in the austenite is generally not below 17 mass%.

Superduplex steels have been developed with further improved corrosion properties. These contain about 25% Cr, 7% Ni, 3.5% Mo as well as nitrogen and, in some cases, other additives. By addition of nitrogen, both the mechanical properties – especially the viscosity – and the pitting resistance are equally improved. Figure 36 makes it clear that higher nitrogen contents in an austenitic-ferritic steel clearly raise the pitting potential with about 25% Cr, 5% Ni, 2.4% Mo and 3% Cu [129].

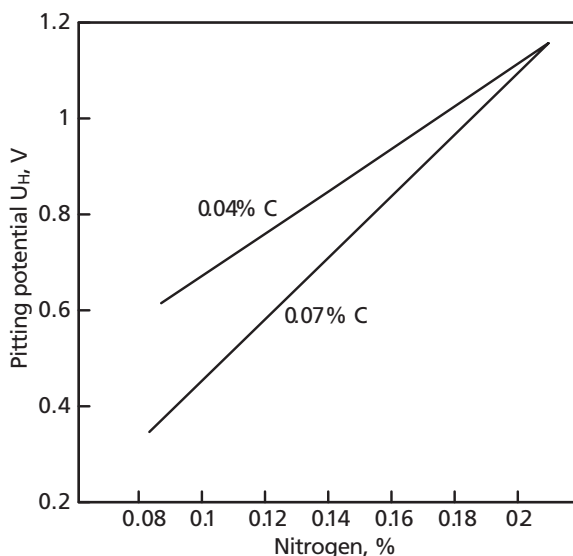


Figure 36: Influence of nitrogen on the pitting potentials of austenitic-ferritic steels in 3% NaCl solution at 303 K (30°C) [129]

In the iron(III) chloride test, these nitrogen-alloyed steels show higher values for the critical pitting and crevice corrosion temperatures than comparably alloyed nitrogen-free steels [130].

For the austenitic-ferritic steels, the nitrogen content is therefore also taken into account when calculating the **pitting resistance equivalent** acc. to

$$\text{PRE} = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo} + 16 \times \text{mass\% N}.$$

It must be remembered that the nitrogen component raises resistance to pitting corrosion, but that compared to steels with comparable content levels of chromium and molybdenum it is unable to compensate lower chromium or molybdenum components.

The ferritic-austenitic steels are passive in seawater due to their high chromium content and do not suffer from general corrosion. Their resistance to pitting and crevice corrosion is raised by the molybdenum and nitrogen components. The duplex steels have therefore proved their worth well in a wide range of marine engineering applications [131–134].

The types additionally alloyed with 1.5–2% copper are preferred in particular as casting alloys for pumps and propellers, also in contaminated brackish water [135–137].

The precipitation-hardened variants (PH steels) are used in seawater in cases in which higher strengths are required. Due to their much lower corrosion resistance levels, they require cathodic protection. It must be remembered that at potentials more negative than $U_H = -0.85$ V these steels must be expected to show stress corrosion cracking [114, 138, 139].

Under test conditions corresponding to those in a thermal seawater desalination plant with 3.5–10% salt content; pH 6.5–7; max. 401 K (128 °C) and a flow rate of 4 m/s, the ferritic-austenitic steel X 2CrNiMoSi 19 5 has not proved useful [140].

On tests of the influence of chlorination on pitting and crevice corrosion behaviour of steels of similar composition, one with a ferritic structure (UNS S44635, commercial name 25-4-4, cf. 1.4575, X1CrNiMoNb28-4-2, raised Mo content) and one with a ferritic-austenitic structure (UNS S31803; cf. 1.4462, X2CrNiMoN22-5-3) in aerated North Sea water at raised temperatures, see report in [141]. The samples made of 25% Cr alloyed ferritic steel S44635 were found to have pitting corrosion in the welding seam of autogenically welded samples only, under conditions of continuous chlorination which were due to precipitations. Crevice corrosion did not occur in this steel. The samples made of 22% Cr alloyed duplex steel S31803 showed pronounced crevice corrosion under continuous chlorination. In welding seams, pitting corrosion was also observed with intermittent chlorination.

Due to their structure, the austenitic-ferritic steels, e.g. DIN-Mat. No. 1.4462 (X2CrNiMoN22-5-3), show a high level of resistance to stress corrosion cracking in seawater at higher temperatures.

The higher-strength martensitic steels are at risk for stress corrosion cracking in seawater. The stress corrosion cracking can be prevented by means of cathodic corrosion protection, but the protective potential must be limited to about $U_H = -0.5$ V, since otherwise hydrogen-induced stress corrosion cracking may occur.

Due to their high content levels of alloying elements, the superduplex steels are susceptible to precipitation of σ phase when briefly heated to high temperatures (900 to 1200 K (627 °C to 927 °C)). This has a negative effect on the corrosion resistance [142].

Austenitic CrNi steels

DIN 50930-4 [143] recommends, for the purpose of determining the corrosion probability of stainless steels exposed to corrosion loads in water, the use of steels with a raised molybdenum content at a chloride ion content of the water exceeding about 200 mg/l [143]. This would, in principle, exclude the molybdenum-free CrNi steels from applications in seawater.

Practical experience and exposure tests covering periods of several years have demonstrated that, in the immersion zone under fouling, stainless austenitic standard steels with approx. 18% Cr, 9–16% Ni and up to 3% Mo may develop both

crevice and pitting corrosion. With increasing molybdenum content, the scope of pitting and crevice corrosion is decreased considerably, but crevice corrosion was still clearly seen under washers of bolted connections in a material containing 2.3% Mo. Steels showing no pitting and crevice corrosion, or only under particularly critical conditions, were those with 4.5% Mo [144–147].

The behaviour of austenitic steels in seawater demonstrates that only steels with a pitting resistance equivalent ($\% \text{Cr} + 3.3 \times \% \text{Mo}$) > 32 can be considered suitable for use in seawater. For steels with a lower pitting resistance equivalent, cathodic corrosion protection is an alternative. The protective potentials for molybdenum-free austenitic steels are about equivalent to the normal hydrogen potential, and the molybdeniferous standard steels with about 2.3% Mo are sufficiently protected at about the potential of copper [145]. The required protection current densities are low and a protective effect is maintained even if the cathodic protection fails occasionally. Since martensitic steels, tempered for high strength, react sensitively to hydrogen uptake, the protective potential for these materials should not lie farther into the potential range than $U_H = -0.35 \text{ V}$. In composite constructions with unalloyed steel, however, a protective potential of $U_H = -0.85 \text{ V}$ should be used. An attempt must be made to reduce the risk of hydrogen absorption by means of suitable distribution of the anodes. In austenitic steels, on the other hand, it is not necessary to limit the protective potential. In case of crevice corrosion, the effectiveness of cathodic corrosion protection is limited, depending on the crevice geometry.

In the tidal zone, and especially in the splash zone, corrosion on stainless steels is considerably less pronounced than in the immersion zone. Molybdeniferous standard steels can certainly be used here. Occasionally observed slight pitting or crevice corrosion will normally not affect the functionality of the structural element.

Table 37 lists the most common austenitic CrNi steels used in marine environments together with their pitting resistance equivalent.

<i>DIN-Mat. No.</i>	<i>Abbreviated designation</i>	<i>SAE/UNS</i>	<i>Pitting resistance equivalent</i>
1.4310	X10CrNi18-8	SAE 301	16
1.4301	X5CrNi18-10	SAE 304	17
1.3940	GX2CrNi18-13		17
1.3955	GX12CrNi18-11		17
1.4311	X2CrNi18-10	SAE 304 LN	17
1.4541	X6CrNiTi18-10	SAE 321	17
1.4550	X6CrNiNb18-10	SAE 347	17
1.4306	X2CrNi19-11	SAE 304 L	18
1.4308	GX5CrNi19-10	SAE 304 H	20
1.4552	GX5CrNiNb19-11	UNS J92710	20

Table 37: Austenitic CrNi steels for maritime applications

The free corrosion potentials of these molybdenum-free CrNi steels in natural and aerated seawater are within the range $U_H = 0.2$ V to 0.4 V. These steels are sufficiently passive to avoid serious general corrosion, but they must be integrated in the structural corrosion protection measures due to their sensitivity to pitting and crevice corrosion. This is often realised automatically since the steels have electrically conductive connections to low-alloyed steels or other less noble materials.

Parts made of the steel SAE 304 (X5CrNi18-10, DIN-Mat. No. 1.4301) were damaged by crevice corrosion after less than 6 months, whereas bolts made of the same material used as fasteners for unalloyed steel or aluminium were not damaged [114]. In condenser pipes cooled with seawater, the steels of the SAE 304 series failed after brief exposure due to massive pitting and crevice corrosion. [148]. The material also reacts to addition of chlorine to prevent fouling with an increased susceptibility to pitting corrosion [149].

Austenitic CrNiMo(N) steels

The CrNiMo steels with higher molybdenum contents are the stainless steels most commonly used in maritime engineering applications. Table 38 shows the most important of these steels, arranged in the order of their pitting resistance equivalent.

<i>DIN-Mat. No.</i>	<i>Abbreviated designation</i>	<i>SAE/UNS</i>	<i>Pitting resistance equivalent</i>
1.4401	X5CrNiMo17-12-2	cf. SAE 316	23
1.4404	X2CrNiMo17-12-2	cf. SAE 316 L	23
1.4406	X2CrNiMoN17-11-2	cf. SAE 316 LN	23
1.4429	X2CrNiMoN17-13-3	cf. SAE 316 LN	25
1.4435	X2CrNiMo18-14-3	cf. SAE 316 L	25
1.4436	X3CrNiMo17-13-3	cf. SAE 316	25
1.4571	X6CrNiMoTi17-12-2	SAE 316 Ti	24
1.4580	X6CrNiMoNb17-12-2	SAE 316 Cb	23
1.4581	GX5CrNiMoNb19-11-2		25
1.3951	G-X 4 CrNiMoN 22 15		26
1.3952	X2CrNiMoN18-14-3		25
1.4438	X2CrNiMo18-15-4	SAE 317 L	27
1.4439	X2CrNiMoN17-13-5	SAE 317 LMN	33
1.4463	GX6CrNiMo24-8-2		30

Table 38: Austenitic CrNiMo(N) steels for maritime applications

Table 38: Continued

<i>DIN-Mat. No.</i>	<i>Abbreviated designation</i>	<i>SAE/UNS</i>	<i>Pitting resistance equivalent</i>
1.4465	X1CrNiMoN25-25-2	SAE 310 MoLN	31
1.3964	X2CrNiMnMoNNb21-16-5-3	NITRONIC 50	36
1.4565	X2CrNiMnMoNbN25-18-5-4	UNS S34565	42
1.3914	X2CrNiMnMoNNb21-15-7-3		40
1.3974	X2CrNiMnMoNNb23-17-6-3		40

Table 38: Austenitic CrNiMo(N) steels for maritime applications

These steels are passive in seawater and show practically no surface corrosion. The pitting corrosion behaviour of steels with molybdenum contents of 2–3% is also much better than in the molybdenum-free austenitic steels. Whereas pitting rates in the range of 0.65–1.58 mm/a (25.6–62.2 mpy) were measured in the molybdenum-free steel SAE 304 (X5CrNi18-10) in slowly flowing seawater, the value for the steel SAE 316 with approx. 2.5% Mo (X5CrNiMo17-12-2) is 0.03–0.34 mm/a (1.18–13.4 mpy) [150].

The pitting depths listed in Table 39 show that pitting corrosion with pronounced fouling in the tidal zone can be worse than in the immersion zone and that stagnant conditions can constitute a much more critical situation than flowing seawater [151].

Following the chlorination of natural seawater with a flow rate of 1.5 m/s by means of addition of sodium hypochlorite it was observed that, at a residual content of 0.1–0.2 ppm chlorine, the colonisation of microorganisms on the steel surface and the reduction of oxygen by aerobic bacteria were controllable. The initialisation of local corrosion sites on high-alloyed steels (similar to DIN-Mat. No. 1.4436) was minimised and the corrosion rates were reduced compared to untreated water by two orders of magnitude [152]. Corrosion damage resulting from sulphate-reducing bacteria on heat exchanger parts made of 1.4539 (SAE 904 L) was also prevented by means of chlorination [153].

With increasing molybdenum content, the resistance of these steels to pitting corrosion increases, both as to the number and the depth of pitting corrosion sites. The sensitivity to crevice corrosion is also reduced with increasing molybdenum content. A minimum content of 4% Mo is considered necessary to reach a sufficient pitting resistance equivalent. To prevent crevice corrosion reliably, on the other hand, 6% Mo is necessary [104, 114, 154].

Steel	Test duration	Test conditions	Pitting corrosion depth, mm	
			greatest	mean
SAE 304 (1.4301, X5CrNi18-10)	1 year	immersion zone	0.99	0.20
	3 years		3.2 (perforated)	
SAE 316 (1.4401, X5CrNiMo17-12-2)	1 year	tidal zone pronounced fouling	0.86	0.64
	3 years		1.51	
SAE 316	60 d	8.22 m/s	< 0.025 mm/a (< 0.98 mpy)	
	30 d	43.20 m/s	0.005 mm/a (0.2 mpy)	

Table 39: Pitting corrosion behaviour of austenitic steels in seawater [151]

Long-term studies of condenser pipes made of the austenitic steels (DIN-Mat. No. 1.4438, X2CrNiMo18-5-4, 1.4439, X2CrNiMoN17-13-5 and 1.4558, X2NiCrAlTi32-20) under quasi-industrial conditions of thermal seawater desalination confirm that the pitting resistance equivalent of these steels increases with increasing molybdenum content, but also that a content level of 4.16% Mo was not sufficient to prevent pitting corrosion under the test conditions. In this test in brine 3.5–10% salt content, a pH level of 6.5–7 and a temperature of max. 401 K (128 °C), only the pipes made of titanium showed complete resistance [140].

The standard steels of the type SAE 316 (DIN-Mat. No. 1.4401, X5CrNiMo17-12-2) are not suitable for seawater-exposed pipes and fail as a result of pitting and crevice corrosion [155, 156]. The sensitivity to pitting corrosion of these standard steels can be further increased by deposits of maritime bacterial films [157]. Despite these facts, these steels are frequently used as materials for pump parts and have worked well as such because they are cathodically protected by contact with other parts made of less noble materials, e.g. pump casing made of cast iron [130]. [158] reports on tests of the cavitation behaviour of the pump materials GX5CrNiMo19-11-2 (DIN-Mat. No. 1.4408) in 3% NaCl solution.

The current-potential curves in Figure 37 show the breakthrough potentials for stable pitting corrosion (pitting potentials) of different steels (DIN-Mat. No. 1.3817, 1.4021, 1.4016, 1.4301, 1.4401, 1.4439) in seawater in comparison to redox potential [22]. Since a material cannot accept a potential higher than the redox potential of the relevant medium, only those steels with a breakthrough potential that is more positive than the redox potential are resistant to pitting corrosion.

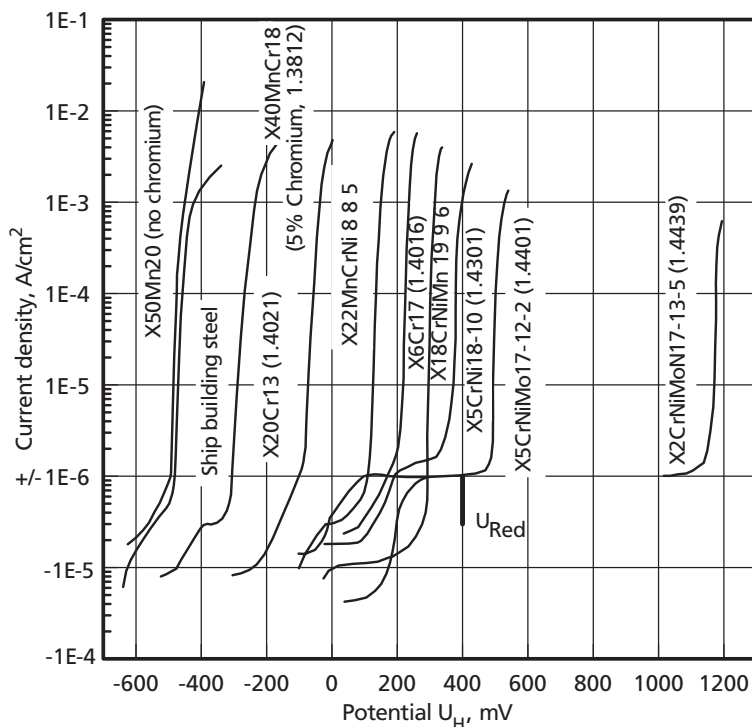


Figure 37: Pitting potential levels for different steels in seawater in comparison to redox potential [22]

Based on a very good pitting potential of $U_H = 1.1\text{--}1.2$ V, the expected excellent pitting resistance equivalent of the steel X2CrNiMoN17-13-5 (317 LMN, 1.4439) was confirmed in every respect in practical application. The material proved resistant to pitting and crevice corrosion, even in subsurface exposure and in contaminated seawater and brackish water [22].

The steel Al-6 X (UNS N08366) with 24% Ni, 20% Cr and 6% Mo is highly resistant to pitting and crevice corrosion in seawater and has been used successfully since 1974 in marine engineering systems [129].

Besides raising the content levels of chromium and molybdenum, higher nitrogen content can also improve a steel's resistance to pitting corrosion. Nitrogen shifts the pitting potential in the positive direction and also raises the crevice corrosion temperature in the iron(III) chloride test acc. to ASTM G48-97 [159]. The nitrogen content can therefore be taken into account when calculating the pitting resistance equivalent for steels with higher molybdenum contents. It must be remembered that the elements Cr, Mo and N can only contribute to improving resistance to local corrosion if they are in solution in the solid solution. In precipitations, for example in carbides or portions bound in σ phase they will not have this effect. Higher nickel

and nitrogen percentages reduce the tendency to σ phase formation, which is encouraged by higher Cr and Mo content levels [121].

In tests conducted in NaCl and CaCl₂ solutions as well, the positive influence of nitrogen in austenitic CrNi steels containing Mo and Si was confirmed [160]. The steel X1CrNiMoN25-22-2 (SAE 310 MoLN, 1.4466) with only 2% Mo, but 0.1% N, also shows a much improved pitting resistance equivalent in seawater in comparison to nitrogen-free material [161].

To put higher nitrogen contents in the steel into solution, a higher manganese content is required. The steel X2CrNiMnMoNbN25-18-5-4 (UNS S34565, 1.4565) shows excellent resistance to pitting and crevice corrosion in seawater and is used in seawater treatment or in cooling systems that use seawater. The critical pitting corrosion temperature in the FeCl₃ test acc. to ASTM G48-97 [159] is 358 to 636 K (85 °C to 90 °C) for the non-welded material and 348 K (75 °C) for WIG-welded samples. The critical crevice corrosion temperature was determined to be 323 K (50 °C) [162].

The steel X2CrNiMnMoNbN21-15-7-3 (DIN-Mat. No. 1.3914) with approx. 8% Mn, 3% Mo, 0.4% N and 0.2% Nb is described as a material that is useful in ship-building [163].

Tests of test alloys based on SAE 316 (DIN-Mat. No. 1.4401, X5CrNiMo17-12-2) with different content levels of manganese and sulphur showed that, at a given S content, Mn contents between 0.5 and 1.5% have no influence on corrosion behaviour. At Mn contents under 0.5%, the corrosion resistance level rises significantly. Falling S contents always have a positive effect on corrosion behaviour, regardless of how much manganese the metal contains. In the high-alloyed steel Al-6 X (UNS N08366), corrosion resistance increases at a given sulphur content when the Mn content is reduced. At Mn contents under 0.1% the corrosion behaviour is nearly independent of the S content. Additions of nitrogen had no effect on corrosion behaviour in these two steel types. The corrosion resistance of the steels X1NiCrMoCu25-20-5 (SAE 904 L, 1.4539), on the other hand, is clearly improved by N content levels of 0.2–0.3% [164].

A test alloy based on X4CrNiMoN19-16 with a raised Cr content of 23.42% and a nitrogen content of 0.41% shows a high pitting resistance equivalent as well as satisfactory resistance to crevice corrosion in seawater at ambient temperatures [165].

In the steel SAE 316 (1.4401, X5CrNiMo17-12-2) it was observed that in cathodically protected parts, within the potential range from $U_H = 0$ V to -0.36 V at temperatures under 303 K (30 °C), the efficiency of the cathodic protection is decisively reduced by biological activity after a brief period, whereupon the tendency to crevice corrosion increases accordingly. To sustain the necessary protection current, the potential must be reduced to about $U_H = -0.75$ V. At temperatures above 303 K (30 °C), the influence of fouling on cathodic protection is no longer noticeable, but at this point the crevice corrosion resistance of the material is no longer sufficient despite the cathodic protection [166].

Concerning threshold temperatures for pitting corrosion in stainless steels as dependent on the pitting resistance equivalent.

In the austenitic CrNi and CrNiMo steels, chloride-induced stress corrosion cracking may occur at temperatures above about 323 K (50 °C) [167]. With higher contents of molybdenum, and in particular nickel, the resistance to stress corrosion cracking is increased. At normal environmental conditions, stress corrosion cracking is therefore not to be expected on these steels in seawater [168].

The austenitic CrMn or CrMnNi steels with, for example, approx. 13% Cr, up to 16% Mn or 5% Mn + 5% Ni are interesting materials for shipbuilding due to their antimagnetic properties and their low price due to the low nickel content. A number of these steels, e.g. X40MnCr18 (DIN-Mat. No. 1.3817) or X50MnCrN19-5, are however susceptible to stress corrosion cracking in seawater. Depending on the chromium and carbon content, either transgranular or intergranular stress corrosion cracking is observed [168]. The chromium-free austenitic manganese steels are not sensitive to stress corrosion cracking, but they are also no longer passive and must be protected accordingly in seawater [169].

Austenitic CrNiMoCu(N) steels

Some copper-alloyed austenitic steels are used in marine engineering. At the copper contents used of up to about 4%, the copper has no inhibitory effect on floral or faunal fouling. Table 40 lists the most important of these steels with their pitting resistance equivalent.

<i>DIN-Mat. No.</i>	<i>Abbreviated designation</i>	<i>UNS</i>	<i>Pitting resistance equivalent</i>
1.4529	X1NiCrMoCuN25-20-7	N08925	44
1.4562	X1NiCrMoCu32-28-7	N08031	50
1.4563	X1NiCrMoCu31-27-4	N08028	37
1.4566	X3CrNiMnMoCuNbN23-17-5-3		40
1.4539	X1NiCrMoCu25-20-5	N08904	33
1.4536	GX2NiCrMoCuN25-20	J94650	27

Table 40: Austenitic CrNiMoCu(N) steels for maritime applications

Tests of austenitic CrNiMoCu(N) steels (DIN-Mat. No. 1.4547, J93254, 1.4529, N08925, 1.4539, N08904) and duplex steels with 25% Cr, 5% Ni and 4% Mo (DIN-Mat. No. 1.4501, S32760) in flowing seawater show that in untreated seawater the potential increases in the first 10–15 days due to the developing biofilm by about 0.2 V [170–172]. Chlorination with 0.1 ppm prevents the potential increase. Higher chlorine contents than are required to prevent the biofilm then result once again in a potential increase. The effect of chlorination can be critical in determining the potential levels, even at very low content levels, and therefore decisive for the pitting and crevice corrosion behaviour, depending on whether the biocidal or oxidant effect predominates [170].

The steel Sanicro® 28 (DIN-Mat. No. 1.4563, X1NiCrMoCu31-27-4) with 30–34% Ni, 26–28% Cr, 3–4% Mo and 0.6–1.4% Cu is characterised by good corrosion behaviour and a high level of resistance to erosion, even at higher flow rates, and is used in many different applications in marine engineering [173, 174].

The austenitic Cu-alloyed steel Uranus® B6 (DIN-Mat. No. 1.4539, X1NiCrMoCu25-20-5) can be used not only in seawater, but also in concentrated salt solutions at higher temperatures, e.g. for heat exchangers, up to 343 K (70 °C) [135].

The steel UNS S31254 with 1–1.5% Cu (DIN-Mat. No. 1.4547, X1CrNiMoCuN20-18-7) has proved completely resistant to local corrosion under the conditions of reverse osmosis for seawater desalination in high-pressure pipes. Its favourable mechanical properties also permit reduced wall thickness of parts in the high-pressure area as compared to the steel SAE 316, which has not demonstrated sufficient resistance [175].

The steel AVESTA 254 SMO® (DIN-Mat. No. 1.4547, X1CrNiMoCuN20-18-7) has a nominal composition of max. 0.020% C, 0.5% Mn, 20% Cr, 18% Ni, 6.1% Mo, 0.7% Cu and 0.2% N. With a pitting resistance equivalent of 46, the material can be expected to show good resistance to local corrosion. The pitting potential in 3% NaCl solution is $U_H = 1.25$ V. Table 41 lists the values determined in the FeCl₃ test for critical pitting corrosion temperature and critical crevice corrosion temperature in comparison to other austenitic steels SAE 316 L, SAE 904 L (DIN-Mat. No. 1.4404, 1.4539) [176].

<i>Steel</i>	<i>Pitting corrosion temperature, K (°C)</i>	<i>Crevice corrosion temperature, K (°C)</i>
SAE 316 L (1.4404)	284 (11)	< 285 (12)
SAE 904 L (1.4539)	315 (42)	293 (20)
AVESTA 254 SMO® (1.4547)	360 (87)	315 (45)

Table 41: Critical pitting and crevice corrosion temperatures in the FeCl₃ test of 1.4404, 1.4539 and 1.4547 [176]

These three steels were exposed for 1 year in the immersion zone in the North Sea 1 m below the surface under the following conditions:

- chloride concentration 12.8–17.4 g/l
- oxygen content 6.8–8.3 mg/l
- pH level 8.0–8.3
- temperature 273.50 to 293 K (0.5 °C to 20 °C).

The corrosion depths determined after the test period under washers are listed in Table 42.

In a Baltic Sea water test loop with

- chloride concentration 3.6–4.5 g/l
- oxygen content 7.0–8.9 mg/l
- pH level 7.0–7.9
- temperature 333 K (60 °C)
- flow rate 0.5 m/s,

the crevice corrosion depths, also listed in Table 42, were determined after one year.

Steel	Max. crevice corrosion depth, mm	
	North Sea, stagnant	Test loop Baltic Sea water, slow current
SAE 316 L (1.4404)	0.20	1.4
SAE 904 L (1.4539)	0.15	0.2
AVESTA 254 SMO® (1.4547)	0	0

Table 42: Crevice corrosion depths after 1 year in 1.4404, 1.4539 and 1.4547 [176]

Figure 38 shows the temperature-dependence of the pitting potentials in 0.5 M NaCl solution for the austenitic standard steels 1.4306 (SAE 304 L, X2CrNi19-11) and DIN-Mat. No. 1.4571 (SAE 316 Ti, X6CrNiMoTi17-12-3) in comparison to an austenitic steel containing Cu with the designation NSCD and compositions as in Table 43 as well as for the nickel-based alloy Incoloy® 825 (NiCr21Mo, DIN-Mat. No. 2.4858) and alloy AL-6 X (24%Ni, 21%Cr, 6%Mo) [177].

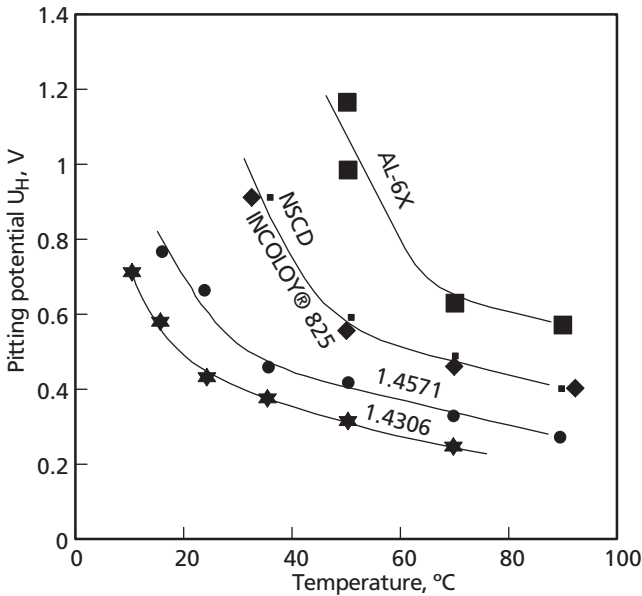


Figure 38: Pitting potentials in 0.5 M NaCl solution, pH 6.6, as dependent on temperature for stainless austenitic steels (AL-6 X, 1.4306, 1.4571, NSCD) and the Ni-based alloy Incoloy® 825 (DIN-Mat. No. 2.4858) [177]

% C	% Cr	% Ni	% Mo	% Cu
≥ 0.03	17	16	5.5	≥ 3

Table 43: Chemical composition of the steel NSCD (mass%) [177]

The stainless standard steels and high-alloyed steels listed in Table 44 were tested at 323 K (50 °C) in natural seawater as well as in aqueous solutions containing 300 ppm, 500 ppm, 1,000 ppm and 5,000 ppm chloride ions [178].

Name	DIN-Mat. No.	Cr	Ni	Mo	Mn	Cu	N
Standard austenites							
SAE 304 L	1.4306 X2CrNi19-11	18–20	8–12		2		
SAE 316 L	1.4404 (1.4435) X2CrNiMo17-12-2	16–18	10–14	2–3	2		
SAE 317 L	1.4438 X2CrNiMo18-15-4	18–20	11–15	3–4	2		
SAE 904 L	cf. 1.4539 X1NiCrMoCuN25-20-5	20	25	4.5	2	1.2	
Martensites							
SAE 410	cf. 1.4006 X12Cr13	12					
17-4PH	1.4548 (1.4542) X5CrNiCuNb17-4-4	16.5	4			4.0	
Superaustenites							
254 SMO®	1.4547 X1CrNiMoCuN20-18-7	20	18	6		0.7	0.2
654 SMO®	cf. 1.4652	24.5	22	7		0.4	0.5
1925 HMO	1.4529 X1NiCrMoCuN25-20-7	20.5	25	6	1	0.9	0.2
3127 HMO	cf. 1.4562 X1NiCrMoCu32-28-7	27	32	6.5	1.5	1.2	
20 Cb 3	cf. 2.4660 NiCr20CuMo	20	34	2	0.5		
Remanit® 4565	1.4565 X2CrNiMnMoNbN25-18-4	22–25	16–18	4–6	5–7	3.3	0.5

Table 44: Nominal alloying content of steels tested (mass%) [178]

Table 44: Continued

Name	DIN-Mat. No.	Cr	Ni	Mo	Mn	Cu	N
Superferrites							
Monit® 44635	cf. 1.4575	25	4	4			0.4
Remanit® 4575	1.4575 X1CrNiMoNb28-4-2	27–29	3–4.5	2–3			0.25
Duplex steel							
Duplex 2205	1.4462 X2CrNiMoN22-5-3	22	5.5	3			0.15

Table 44: Nominal alloying content of steels tested (mass%) [178]

With increasing chloride ion content of the solution, the pitting potential U_{pp} of the steels shifts in the negative direction. Figure 39 lists the pitting potential of the steels tested in seawater with their pitting resistance equivalents.

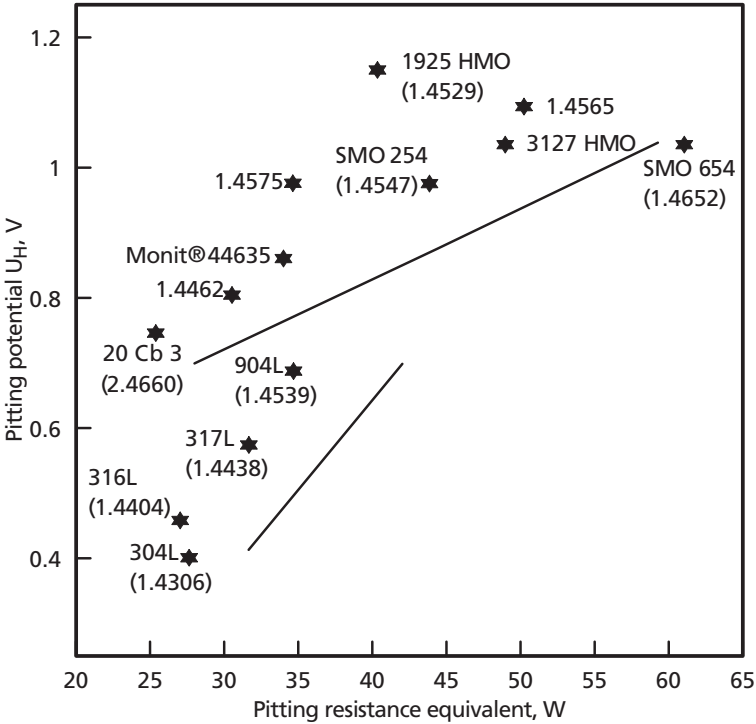


Figure 39: Dependence of pitting potential U_{pp} on the pitting resistance equivalent in natural seawater at 323 K (50 °C) [178]

The linear dependence of pitting potentials on the pitting resistance equivalent (PRE)

$$\text{PRE} = \% \text{Cr} + 3.3 \times \% \text{Mo} + 16 \times \% \text{N}$$

is confirmed. This applies both to the standard austenites and to the higher alloyed steels, whereby however the rising curves are different for the two groups.

Using special crevice corrosion samples that simulate the conditions of washers, the crevice corrosion behaviour of the 36 wrought alloys and 9 corresponding cast alloys made of molybdeniferous stainless steels and nickel-based materials listed in Table 45 were tested in filtered natural seawater at 303 K (30 °C) [179].

<i>Name</i>	<i>DIN-Mat. No.</i>	<i>Cr</i>	<i>Ni</i>	<i>Mo</i>	<i>Mn</i>	<i>Cu</i>	<i>N</i>
Austenites with 6–16% Ni							
SAE 316	1.4401 (1.4436), X5CrNiMo17-12-2	17.5	10.5	2.4	1.5		
SAE 317 L	1.4438, X2CrNiMo18-15-4	18–20	11–15	3–4	2		
SAE 216		20	6	2.5	8		0.35
Rex 734		21	9.5	2.5	3.8		0.4
SAE 304 LN	cf. 1.4439, X2CrNiMoN17-13-5	17	14	4	1.5		0.15
SAE 317 LM		19.5	14.5	4	1.5		
22-13-5		21	14	2.3	5		
Austenites with 17–40% Ni							
SAE 904 L	cf. 1.4539, X1NiCrMoCuN25-20-5	20	25	4.5	2	1.5	
4X (AL-4X)		20	25	4.5	1.5		
Jessop [®] 700		21	25	4.5	1.5		
254 SLX	cf. 1.4539, X1NiCrMoCuN25-20-5	20	25	4.5	1.5	1.5	
Jessop [®] 777		21	25.5	4.5	1.5	2	
6X (AL-6X)		20	25	6.5	1.5		
254 SMO [®]	1.4547, X1CrNiMoCuN20-18-7	20	18	6		0.8	0.2
20 Mod		22	25.5	5	1.5		
20 Cb 3	cf. 2.4660, NiCr20CuMo	20	33	2	0.5	3	
20 Mo 6		24	33	5.5	0.5	3	
254 SFER		30	22	2	1.5		0.15

Table 45: Nominal alloying content of the tested materials [179]

Table 45: Continued

<i>Name</i>	<i>DIN-Mat. No.</i>	<i>Cr</i>	<i>Ni</i>	<i>Mo</i>	<i>Mn</i>	<i>Cu</i>	<i>N</i>
Nickel alloys							
Incoloy® 825	2.4858, NiCr21Mo	22	44	3		1.5	
Hastelloy® alloy G	2.4618, NiCr22Mo6Cu	22	47	6	1.5	1.8	
Hastelloy® alloy G-3	2.4623, EL-NiCr23Mo7Cu	23	44	7	1	1.8	
Inconel® 625	2.4856	22	60	9			
Hastelloy® C-276	2.4819	16	55	16			
Superferrites							
Monit®	cf. 1.4575	25	4	4			0.4
Sea-Cure®	cf. 1.4575, X1CrNiMoNb28-4-2	25	2	3			0.2
SAE 439		18			1		
SAE 444	cf. 1.4521, X2CrMoTi18-2	19	1	2			
26-1		26		1			
26-1S		25		1			
29-4		3		4			
29-4C		29	1	4			
29-4-2		3	2	4			
Duplex steel							
Carpenter® 7-Mo	cf. 1.4460, X3CrNiMoN27-5-2	27	4	1.5			
44LN		25	6	1.5			0.2
Ferralium®	cf. 1.4507, X2CrNiMoCuN25-6-3	26	5.5	3	1	1.8	0.2

Table 45: Nominal alloying content of the tested materials [179]

A relative evaluation of the samples according to the four groups listed in Table 46 resulted after a test duration of 30 days.

Resistant, no corrosion sites	Relatively resistant, up to 7 corrosion sites	Moderately resistant, up to 20 corrosion sites	Not resistant
625 (2.4856)	4X	SAE 316 (1.4401)	SAE 304 LN (1.4439)
C-276 (2.4819)	254 SMO [®] (1.4547)	SAE 216	SAE 317 LM
29-4	6X	Rex 734	22-13-5
29-4C	20 Mod	SAE 317 L (1.4438)	
29-4-2	20 Mo 6	SAE 904 L (1.4539)	
Monit [®] (1.4575)	254 SFER	Jessop [®] 700	
625 cast (2.4856)	G (2.4618)	254SLX (1.5439)	
	G-3 (2.4623)	Jessop [®] 777	
	Ferralium [®] (1.4507)	20 Cb 3 (2.4660)	
	26-1	825 (2.4858)	
	26-1S	SAE 329	
	SC-1	SAE 439	
		SAE 444 (1.4521)	

Table 46: Relative crevice corrosion resistance of the materials from Table 45 [179]

An equivalent evaluation also resulted from the analysis of exposure tests with crevice corrosion samples made of the relevant alloys after 90 days in stagnant seawater at 303 K (30 °C) [180].

[181] reports positive experience with the austenitic 6% Mo steels on platforms in the North Sea. Damage due to crevice corrosion was only reported in parts exposed to seawater at temperatures above 323 K (50 °C).

The high-alloyed steels and nickel alloys are seeing increasing use in systems exposed to seawater. Especially under stagnant conditions and at higher temperatures, these materials were observed to develop pitting as well as crevice and stress corrosion cracking. In a testing system with natural seawater circulation the materials listed in Table 47 were tested for local corrosion for a period of one year under conditions of moving water (1 m/s) and at quasi stagnant conditions (0.1 m/s) in the form of pipes and plates, and welded, at 323 and 343 K (50 °C and 70 °C), for one year in each case [182–184]. The filler materials used with the materials for pipe and plate welding are listed in Table 48. For each material, a pipe section with the array in Figure 40 was installed. Using this array, the following test parameters were simulated and tested:

- pipe 1: surface corrosion and pitting corrosion
- pipes 1, 2 and 6: crevice corrosion at flange connections
- pipes 3, 5 and 6: corrosion at welded connections
- pipe 4: crevice corrosion an insertion connections
- pipe 6: heat transmission conditions due to external heating (temperature increase at inner wall of pipe approx. 7 K (7 °C))

Test parameters were simulated as follows on the plate samples arranged in a flow-through tank for each material corresponding to the array in Figure 41:

- sample 1: surface corrosion and pitting corrosion
- samples 2 and 4: corrosion at welded connections
- samples 3 and 5: crevice corrosion at processed welding seams
- sample 6: crevice corrosion at connections metal-to-metal, metal-to-PTFE disc, metal-to crevice block, as per the array in Figure 42
- samples 7 and 8: stress corrosion cracking in U samples with and without welding seam

<i>DIN-Mat. No./abbreviated designation</i>	<i>Ni</i>	<i>Cr</i>	<i>Mo</i>	<i>Cu</i>	<i>Fe</i>	<i>Other</i>
1.4439 X2CrNiMoN17-13-5	13.5	18	4.2		balance	0.15 N
1.4539 X1NiCrMoCuN25-20-5	25	20.5	4.7	1.6	balance	0.08 N
1.4529 X1NiCrMoCuN25-20-7	25	21	6.5	0.9	balance	0.20 N
1.4563 X1NiCrMoCu31-27-4	31	27	3.5	1.3	balance	0.05 N
2.4619 NiCr22Mo7Cu	48	22.5	7	2	20	0.35 Nb
2.4856 NiCr22Mo9Nb	62	22	9		3	3.5 Nb
2.4819 NiMo16Cr15W	58	16	16		5	4 W
2.4605 NiCr23Mo16Al	59	23	16		1	
1.4562 X1NiCrMoCu32-28-7	31	27	6.5	1.2	balance	0.2 N
1.4566 X3CrNiMnMoCuNbN23-17-5-3	18	24.5	4.3	0.6	balance	0.4N/6.2 Mn

Table 47: Materials tested in a natural seawater loop and in synthetic seawater, together with their essential alloying contents (mass%) [182, 183]

Pipes/Plates	Welding filler		
	Pipes	Plates	
	TIG manual	E hand	WIG manual
Material number (DIN-Mat. No.)			
1.4439	2.4831	1.4440	1.4440
1.4539	2.4831	2.4621	2.4831
1.4529	2.4831	2.4621	2.4831
1.4563	2.4831	2.4621	2.4831
2.4619		2.4621	2.4831
2.4856	2.4831	2.4621	2.4831
2.4819	2.4886	2.4887	2.4886
2.4605			2.4607
1.4562			2.4607
1.4566			2.4607

2.4831: G-NiCr50Nb, 2.4886: SG-NiMo16Cr16W, 1.4440: X2CrNiMo18-16-5, 2.4621: EL-NiCr20Mo9Nb, 2.4887: EL-NiMo15Cr15W, 2.4607: SG-NiCr23Mo16

Table 48: Welding fillers for the pipe and plate weldings [182, 183]

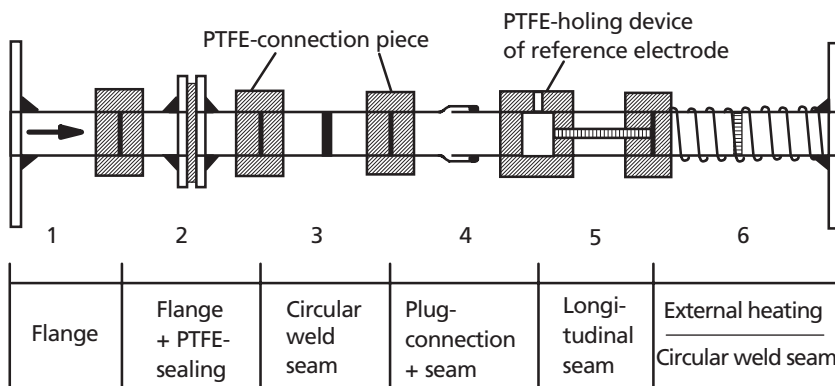


Figure 40: Arrangement of pipe samples in the series

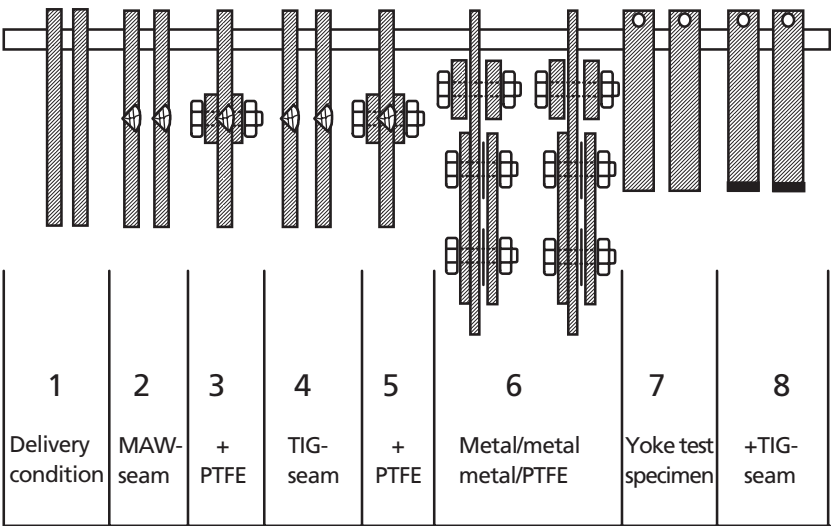


Figure 41: Arrangement of plate samples
(MAW: manual arc welding, TIG: tungsten inert gas welding)

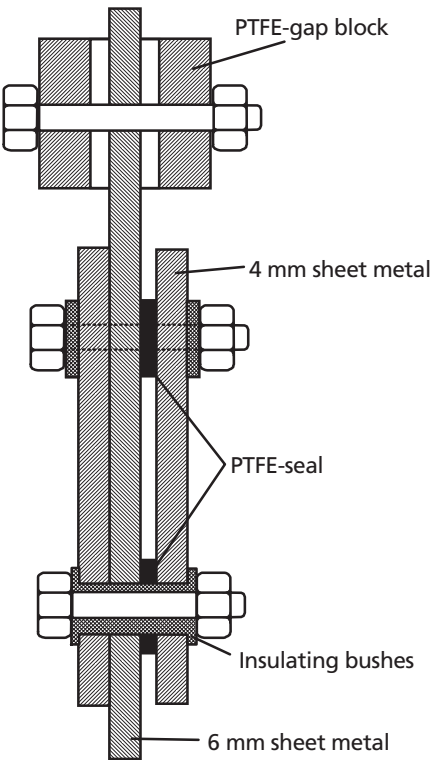


Figure 42: Details of crevice corrosion array in Figure 41

To supplement the study, the influence of low, moderate and very high flow rates was tested in laboratory experiments with the rotating disc electrode at 60–2000 min⁻¹ under potentiostatic conditions ($U_H = 0.5$ V) in synthetic seawater at 323, 343 and 363 K (50 °C, 70 °C and 90 °C), mainly in the materials 1.4529 (UNS N08925, X1NiCrMoCuN25-20-7), 1.4563 (UNS N08028, X1NiCrMoCu31-27-4) and 2.4856 (UNS N26625, NiCr22Mo9Nb).

The results of the exposure tests are listed in Table 51 to Table 56. Table 49 shows the distribution of resistance using the symbols for the pipe samples in Table 51 to Table 54 and Table 50 for the plate samples in Table 55 and Table 56.

Resistance	Corrosion level	Pitting corrosion	Crevice corrosion	Cut surfaces
Very good	none	○	□	△
Good	slight	⊕	▣	△
Satisfactory	moderate	●	■	▲
Unsatisfactory	pronounced	●	■	▲

Table 49: Distribution of resistance of pipe samples in Table 51 to Table 54

Depth, mm	Pitting corrosion	Crevice corrosion
None	○	□
< 0.1	⊕	▣
> 0.1 to < 0.5	●	■
> 0.5	●	■

Table 50: Distribution of resistance of plate samples in Table 55 and Table 56

DIN-Mat. No.	Abbreviated designation	Flange	Flange + PTFE seal	Circular weld seam	Insert connection + seam	Longitudinal seam	Circular weld seam + heating
		1	2	3	4	5	6
1.4439	X2CrNiMoN17-13-5	○ □ △	● ■ △	○ □ △	○ ▣ ▲	○ □ ▲	○ □ ▲
1.4539	X1NiCrMoCuN25-20-5	○ □ ▲	○ □ ▲	● ¹⁾ □ ▲	○ □ ▲	○ □ ▲	○ □ ▲
1.4529	X1NiCrMoCuN25-20-7	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △
1.4563	X1NiCrMoCu31-27-4	○ □ △	○ □ △	○ □ ▲	○ □ ▲	○ □ △	○ □ △
2.4856	NiCr22Mo9Nb	● ¹⁾ □ △	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △
2.4819	NiMo16Cr15W	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △

1) Defect in welding

Table 51: Evaluation of pipe samples at 323 K (50 °C) and 0.1 m/s (symbols see Table 49)

DIN- Mat. No.	Abbreviated designation	Flange	Flange + PTFE seal	Circular weld seam	Insert connection + seam	Longitudinal seam	Circular weld seam + heating
		1	2	3	4	5	6
1.4439	X2CrNiMoN17-13-5	○□△	○■△	○□△	○□△	○□△	○□△
1.4539	X1NiCrMoCuN25-20-5	○□▲	○□▲	● ¹⁾ □△	○□△	○□△	○□△
1.4529	X1NiCrMoCuN25-20-7	○□△	○□△	○□△	○□△	○□△	⊕□△
1.4563	X1NiCrMoCu31-27-4	○□△	○□△	○□▲	○□▲	○□△	○□△
2.4856	NiCr22Mo9Nb	○□△	● ¹⁾ □△	○□△	○□△	○□△	○□△
2.4819	NiMo16Cr15W	○□△	○□△	○□△	○□△	○□△	○□△

1) Defect in welding

Table 52: Evaluation of pipe samples at 323 K (50 °C) and 1 m/s (symbols see Table 49)

DIN- Mat. No.	Abbreviated designation	Flange	Flange + PTFE seal	Circular weld seam	Insert connection + seam	Longitudinal seam	Circular weld seam + heating
		1	2	3	4	5	6
1.4439	X2CrNiMoN17-13-5	○□△	○□△	○□△	○□△	○□▲	○□△
1.4539	X1NiCrMoCuN25-20-5	○□△	○□△	○□△	⊕□△	○□△	○□▲
1.4529	X1NiCrMoCuN25-20-7	○■ ¹⁾ △	○□△	○□△	⊕□△	○□△	○□ ¹⁾ △
1.4563	X1NiCrMoCu31-27-4	○□△	○□△	○□△	○□△	○□▲	●□ ¹⁾ △
2.4856	NiCr22Mo9Nb	○□△	○□△	○□△	○□△	○□△	○□ ¹⁾ △
2.4819	NiMo16Cr15W	○□△	○□△	○□△	○□△	○□△	○□△

1) Defect in welding

Table 53: Evaluation of pipe samples at 343 K (70 °C) and 0.1 m/s (symbols see Table 49)

DIN-Mat. No.	Abbreviated designation	Flange	Flange + PTFE seal	Circular weld seam	Insert connection + seam	Longitudinal seam	Circular weld seam + heating
		1	2	3	4	5	6
1.4439	X2CrNiMoN17-13-5	○ □ ▲	○ □ △	○ □ △	○ □ ▲	○ □ ▲	○ □ ▲
1.4539	X1NiCrMoCuN25-20-5	○ □ ▲	○ □ ▲	○ ■ ¹⁾ △	○ □ △	○ □ △	○ □ △
1.4529	X1NiCrMoCuN25-20-7	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △	○ ■ ¹⁾ △
1.4563	X1NiCrMoCu31-27-4	○ □ ¹⁾ △	○ □ ▲	○ □ △	○ □ △	○ □ △	○ □ △
2.4856	NiCr22Mo9Nb	● ¹⁾ □ △	● ¹⁾ □ △	○ □ △	○ □ △	○ □ △	○ □ △
2.4819	NiMo16Cr15W	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △	○ □ △

1) Welding fault

Table 54: Evaluation of pipe samples at 343 K (70 °C) and 1 m/s (symbols see Table 49)

DIN-Mat. No.	Abbreviated designation	As delivered	MAW seam	MAW + crevice block	WIG seam	WIG + crevice block	Crevice corrosion array	
		1	2	3	4	5	Metal/ metal	Metal/ PTFE
1.4439	X2CrNiMoN17-13-5	○ □	○ □	○ □	○ □	○ □	○ □	○ ■
1.4539	X1NiCrMoCuN25-20-5	○ □	○ □	○ □	○ □	○ □	○ □	○ □
1.4529	X1NiCrMoCuN25-20-7	○ □	○ □	○ □	○ □	○ □	○ □	○ □
1.4563	X1NiCrMoCu31-27-4	○ □	○ □	○ □	○ □	○ □	○ □	○ □
2.4619	NiCr22Mo7Cu	○ □	○ □	○ □	○ □	○ □	○ □	○ ■
2.4856	NiCr22Mo9Nb	○ □	○ □	○ □	○ □	○ □	○ □	○ □
2.4819	NiMo16Cr15W	○ □	○ □	○ □	○ □	○ □	○ □	○ □

MAW: manual arc welding, WIG: tungsten inert gas welding

Table 55: Evaluation of plate samples at 323 K (50 °C) and < 0.1 m/s (symbols see Table 50)

DIN-Mat. No.	Abbreviated designation	As delivered	MAW seam	MAW + crevice block	WIG seam	WIG + crevice block	Crevice corrosion array	
		1	2	3	4	5	Metal/ metal	Metal/ PTFE
1.4439	X2CrNiMoN17-13-5	○ □	○ □	○ ■	● □	○ ■	○ □	○ ■
1.4539	X1NiCrMoCuN25-20-5	○ □	○ □	○ □	○ □	○ □	○ □	○ ■
1.4529	X1NiCrMoCuN25-20-7	○ □	○ □	○ □	○ □	○ ■	○ □	○ ■
1.4563	X1NiCrMoCu31-27-4	○ □	○ □	○ □	○ □	○ □	○ □	○ ■
2.4619	NiCr22Mo7Cu	○ □	○ □	○ □	○ □	○ □	○ □	○ ■
2.4856	NiCr22Mo9Nb	○ □	○ □	○ □	○ □	○ □	○ □	○ □
2.4819	NiMo16Cr15W	○ □	○ □	○ □	○ □	○ □	○ □	○ □
2.4605	NiCr23Mo16Al	○ □	○ □	○ □	○ □	○ □	○ □	○ □
1.4562 ¹⁾	X1NiCrMoCu32-28-7	○ □	○ □	○ □	○ □	○ □	○ □	○ □
1.4566 ¹⁾	X3CrNiMnMoCuNbN23-17-5-3	○ □	○ □	○ □	○ □	○ □	○ □	○ □

1) after 9 months exposure time

Table 56: Evaluation of plate samples at 343 K (70 °C) and < 0.1 m/s (symbols see Table 50)

MAW: manual arc welding

TIG: tungsten inert gas welding

Overall test results:

- The nickel alloys 2.4856 (N26625, NiCr22Mo9Nb), 2.4819 (N10276, NiMo16Cr15W) and 2.4605 (N06059, NiCr23Mo16Al) are corrosion resistant under all test conditions in natural seawater at 323 and 343 K (50 °C and 70 °C).
- Under unfavourable crevice conditions, crevice corrosion may occur in the steels 1.4439 (S31726, X2CrNiMoN17-13-5), 1.4539 (N08904, X1NiCrMoCuN25-20-5) and 1.4563 (N08028, X1NiCrMoCu31-27-4) at temperatures as low as 323 K (50 °C). At 343 K (70 °C), only the steels 1.4562 (N08031, X1NiCrMoCu32-28-7) and 1.4566 (X3CrNiMnMoCuNbN23-17-5-3) are resistant to crevice corrosion.
- Local corrosion is only to be expected on the state-of-the-art overalloyed welding seams in the presence of welding faults.
- The steels tend to appear more susceptible to crevice corrosion in natural seawater than in synthetic seawater.
- Stress corrosion cracking was not observed under the selected test conditions.

The dependence of pitting corrosion and flow rate observed in CrNi steels in NaCl solutions [185, 186] was confirmed only for the lowest-alloyed steel 1.4439 (S31726, X2CrNiMoN17-13-5).

When the exposure tests in natural seawater were carried out, the samples were normally removed from the immersion and tidal zones, usually at certain intervals, usually once a year, including those intended for multiple-year exposure, then freed of adherent fouling, cleaned, evaluated and returned to exposure. In DIN 50917-2 [187], such samples are designated as “disturbed” long-term samples in contrast to “undisturbed” long-term samples, which latter are not removed and cleaned, and thus are also not evaluated, during their exposure time. To determine the comparability of the test results in these two test categories, samples made of high-alloyed stainless steels, the long-term behaviour of which in disturbed samples is known from previous tests, were tested in undisturbed exposure of 4 years and 7 years in the immersion zone off Helgoland [147]. The steels tested are listed in Table 57. The results of evaluation of the critical sites for crevice corrosion under the PVC washers at the fixation holes in the samples are listed in Table 58.

Designation	DIN-Mat. No.	Abbreviated designation	C	Si	Mn	P	S	Cr	Ni	Mo	N	Nb
SAE 316 L	1.4435	X2CrNiMo18-14-3	0.019	0.26	1.67	0.0029	0.007	17.27	13.65	2.60		< 0.01
SAE 317 LMN	1.4439	X2CrNiMoN17-13-5	0.032	0.40	1.64	0.012	0.005	17.30	13.63	4.25	0.14	< 0.01
2205	1.4462	X2CrNiMoN22-5-3	0.032	0.53	1.61	0.014	0.008	21.77	5.43	3.09	0.10	< 0.01
25-4-4	1.4575	X1CrNiMoNb28-4-2	0.009	0.44	0.26	0.013	0.006	27.49	3.89	2.24	0.01	0.38

Table 57: Composition of the steels tested (mass%) [147]

Designation	DIN-Mat. No.	Pitting resistance equivalent $\%Cr + 3.3 \times \%Mo$	Exposure time years	Number	Depth of crevice corrosion sites, mm							
					Front				Back			
					1	2	3	4	1	2	3	4
SAE 316 L	1.4435	26	4	8	0.50	0.85	0.35	1.90	1.45	1.05	0.50	2.90
			7	8	0.93	0.64	0.69	0.34	1.23	2.27	1.24	1.29
SAE 317 LMN	1.4439	31	4	8	0.15	0.70	1.15	0.65	0.41	0.05	0.30	0.85
			7	8	0.93	0.70	0.45	0.37	0.59	0.67	0.25	0.60
2205	1.4462	32	4	7	0.50	1.30	0.75	0.60	0.00	0.98	0.48	0.15
			7	4	1.26	0.74	0.00	0.00	0.54	0.00	0.00	0.00
25-4-4	1.4575	35	4	2	1.20	1.10	0.00	0.00	0.00	0.00	0.00	0.00
			7	2	0.24	1.23	0.00	0.00	0.00	0.00	0.00	0.00

Table 58: Number of crevice corrosion sites under PVC washers and their maximum depth in mm after 4 years and after 7 years of undisturbed exposure in the immersion zone [147]

Whereas in disturbed long-term samples in the steels 1.4462 (2205), and especially the superferrites 1.4575 (25-4-4), crevice corrosion was a rare and isolated occurrence, the crevice corrosion in the steel 1.4435 (SAE 316 L) was comparatively pronounced in both disturbed and undisturbed samples. The resistance order of the steels resulting from both disturbed and undisturbed long-term exposure,

$$1.4575 \gg 1.4462 > 1.4439 \gg 1.4435$$

which corresponds essentially to the categorisation resulting from laboratory analyses, e.g. based on critical crevice corrosion temperatures, is seen in (Table 59).

In comparison to the undisturbed exposures over a period of 4 years, the samples exposed for 7 years did not show any more pronounced corrosion. The number of crevice corrosion sites under the PVC discs was not greater, nor was deeper corrosion present on the whole. With increasing fouling, in the course of the longer exposure time, the oxygen access to the crevice-free cathode surfaces is apparently also blocked to the extent that the stronger corrosion in the crevice comes to a standstill.

DIN-Mat. No.	Temperature, K (°C)
1.4435 SAE 316 L	278 (5)
1.4439 SAE 317 LMN	293 (20)
1.4462 2205	293 (20)
1.4575 25-4-4	308 (35)

Table 59: Critical crevice corrosion temperatures [147]

Test solution: 3% NaCl solution, Potential: $U_H = 0.95$ V, Duration: 24 h

Nickel

Among the nickel materials, the nickel-based alloys alloyed with chromium and molybdenum are to a great extent resistant to local corrosion in seawater, even at higher temperatures. They are used, even though the higher-alloyed stainless steels do not meet the requirements.

With the nickel-copper materials, pitting or crevice corrosion are to be expected under unfavourable conditions, e.g. a lack of aeration or under fouling.

The uniform surface corrosion of unalloyed nickel in seawater is minimal – under 0.025 mm/a (0.98 mpy). The material is, however, highly susceptible to pitting corrosion, particularly in stagnant water, so that its practical applications are quite limited. The pitting corrosion is exacerbated in stagnant or only moderately moving water by fouling or other deposits. Following exposure in the immersion zone, pitting depths of 1–1.04 mm were measured after 500 days [151, 188–191].

In tropical waters, the corrosion values for nickel are higher than in the temperate climatic zones. The pitting depths reach approx. 3 mm after only 1 year, after which the penetration rate drops. Figure 43 and Figure 44 show the results of exposure tests of nickel and nickel alloys in the seawater of the Panama Canal Zone. Whereas in the immersion zone pitting depths of over 3 mm were reached, the values in the tidal zone were about 1.6 mm [192].

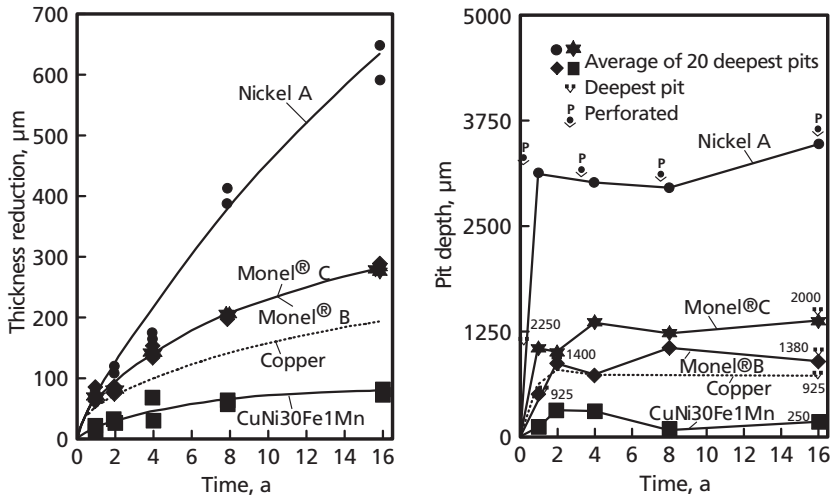


Figure 43: Pitting corrosion of Ni, NiCu (Monel® C, NiCu30Fe2.1; Monel® B, NiCu30Fe1.8 cf. 2.4360) and CuNi alloys (CuNi30Mn1Fe, 2.0882) in the immersion zone, mean values for the 20 deepest sites [192]

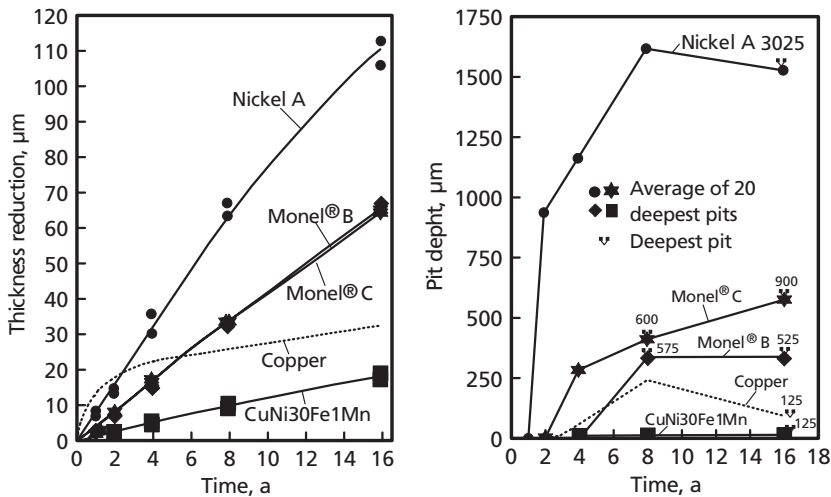


Figure 44: Pitting corrosion of Ni, NiCu- (Monel® C, NiCu30Fe2.1; Monel® B, NiCu30Fe1.8 cf. 2.4360) and CuNi alloys (CuNi30Mn1Fe, 2.0882) in the tidal zone, mean values for the 20 deepest sites [192]

In tests in seawater with pH 8.2 and 6.5 ppm O₂ at 293 K (20 °C), it was observed with pure nickel (Ni 99.99) that under increasing hydrostatic pressure (101.3 kPa, 1013.2 kPa, 10132.5 kPa, 30397.5 kPa) both surface corrosion and pitting corrosion decrease [193].

Nickel is generally resistant in marine atmospheres.

Nickel is electrochemically nobler than many other metals. This can be observed in composite constructions in which other metals are to be protected from the risk of contact corrosion.

Nickel-chromium alloys

Nickel-chromium-iron alloys (without Mo)

The molybdenum-free NiCr or NiCrFe alloys, e.g. NiCr15Fe (Inconel® 600, DIN-Mat. No. 2.4816) or NiCr21Fe (X10NiCrAlTi32-21 Inconel® 800, DIN-Mat. No. 1.4876), are passive in seawater and thus show only minimal surface corrosion, but they are highly susceptible to pitting corrosion with pitting depths up to 3 mm after 2 years in stagnant or slowly moving seawater, and are therefore unsuitable for use under maritime conditions without corrosion protection [194].

Nickel-chromium-molybdenum alloys

The seawater-exposed nickel-chromium alloys usually contain molybdenum as well to raise their resistance to pitting and crevice corrosion. Table 60 lists the main relevant NiCrMo alloys together with their pitting resistance equivalents.

<i>Abbreviated designation</i>	<i>DIN-Mat. No.</i>	<i>UNS</i>	<i>Pitting resistance equivalent</i>
NiCr21Mo	2.4858	N08825	27
NiCr22Mo7Cu	2.4619	N06985	41
NiCr22Mo9Nb	2.4856	N06625	46
G-NiCr22Mo9Nb			46
NiMo16Cr15W	2.4819	N10276	64
G-NiMo16Cr15W			64
NiMo16Cr16Ti	2.4610	N06455	60
G-NiMo17Cr	2.4686		60
NiCr23Mo16Al	2.4605	N06059	72

Table 60: Seawater-exposed nickel-chromium-molybdenum alloys

These materials are also designated by various commercial names, for example

- Incoloy® 825 (DIN-Mat. No. 2.4858), Inconel® 625 (DIN-Mat. No. 2.4856)
- Hastelloy® C-4 (DIN-Mat. No. 2.4610), Hastelloy® C-276 (DIN-Mat. No. 2.4819)
- Alloy C-276 (DIN-Mat. No. 2.4819), Alloy 625 (DIN-Mat. No. 2.4856)
- Nicrofer® 6020 hMo (DIN-Mat. No. 2.4856), Nicrofer® 4221 (DIN-Mat. No. 2.4858)
- Uranus® 625 (DIN-Mat. No. 2.4856), Uranus® 825 (DIN-Mat. No. 2.4858)

The free corrosion potentials of these alloys are at $U_H = 0$ V to 0.1 V. They are shifted in the positive direction by increasing aeration and stronger water movement and in the negative direction by decreasing aeration and stagnation. Different potentials may be established under fouling or a biofilm.

These materials are passive in seawater and, up to temperatures of 333 K (60 °C), practically resistant to uniform surface corrosion. The resistance to pitting and crevice corrosion and the critical pitting and crevice corrosion temperatures are determined mainly by the content levels of chromium and molybdenum and therefore increase with the pitting resistance equivalent. The materials listed in the Table are resistant to stress corrosion cracking in seawater, even at higher temperatures, and less sensitive to corrosion fatigue. They are also suitable for use at higher flow rates up to about 20 m/s [23].

The DIN-Mat. No. 2.4856 (NiCr22Mo9Nb), for example, has proved its worth in heavy-duty structural elements of seawater pumps due to its strength and corrosion resistance, even under alternating stresses. It maintains resistance even under critical crevice conditions and stress loads from hydrogen sulphide and is also suitable for use as a plating material [130].

The NiCrMo alloys show excellent resistance in marine atmosphere and under exposure to splash water [195].

Nickel-copper alloys

Materials with the alloy base material nickel-copper show minimum corrosion in seawater at a composition of 67% nickel and 33% copper. Materials with this base material composition are used in many marine engineering applications. The most important of these materials are listed in Table 61.

Abbreviated designation	DIN-Mat. No.	UNS	Specifications in
NiCu 30 Fe	2.4360	N04400	DIN 17743 [196]
NiCu 30 Al	2.4375	N05500	DIN 17743 [196]
G-NiCu 30 Nb	2.4365	N24130	DIN 17730 [197]
G-NiCu30Si4	2.4368	–	DIN 17730 [197]

Table 61: Seawater-exposed nickel-copper materials

As in the CuNi alloys CuNi30Mn1Fe (DIN-Mat. No. 2.0882) and CuNi30Fe2Mn2 (DIN-Mat. No. 2.0883), resistance in the NiCu30 alloys is also improved by additions of about 1.0–2.5% Fe and up to 2% Mn. With a free corrosion potential in the range of $U_H = -0.35$ V to 0 V, these materials are passive in seawater up to temperatures of about 333 K (60 °C) and are not sensitive to general corrosion. The copper content of these materials is not sufficient to prevent fouling.

[170] describes pitting corrosion damage in pipes that transport seawater made of the NiCu alloy Monel[®] 400 (NiCu30Fe, DIN-Mat. No. 2.4360), which damage is ascribed to a rise in potential in the critical area due to the biofilm. Continuous chlorination with 0.8 ppm chlorine was sufficient to reduce the potential back into the passive range of the material.

Pitting and crevice corrosion may occur in stagnant or hardly moving seawater. After 2 years under these conditions, corrosion depths up to 0.8 mm were observed [194]. Figure 43 and Figure 44 on nickel also provide information on pitting corrosion behaviour of the NiCu30Fe alloys in comparison to nickel and CuNi30Mn1Fe.

As Table 62 makes clear, local corrosion can be prevented effectively by the use of iron or zinc anodes [198].

<i>Material</i>	<i>Cathodic protection</i>	<i>Test duration, months</i>	<i>Maximum corrosion depth, mm</i>	<i>Corroded surface, %</i>
NiCu 30 Fe, UNS	no	3	0.30	60
N04400, 2.4360	no	12	0.75	94
	with steel anode	12	0	0
	with zinc anode	12	0	0

Table 62: Effectiveness of cathodic protection against pitting and crevice corrosion [198]

The nickel-copper alloys show higher resistance to cavitation than the copper-nickel materials or the austenitic nickel cast alloys and are therefore frequently used in pump parts and in heat exchangers, whereby however cathodic protection is recommended due to the risk of pitting corrosion [130, 199].

In seawater desalination plants using the distillation methods, parts made of NiCu30Fe (DIN-Mat. No. 2.4360) have proved useful up to temperatures of 423 K (150 °C), particularly at higher flow rates [98, 200, 201].

Chlorination of seawater with resulting chlorine contents of 1–4 mg/l has practically no influence on the pitting corrosion behaviour of Monel[®] 400 (NiCu30Fe, DIN-Mat. No. 2.4360) [202]. In [170], pitting corrosion damage in seawater-carrying pipes made of NiCu alloy Monel[®] 400 is described, which damage is ascribed to a potential increase in the critical area due to the biofilm. Continuous chlorination with a content level of 0.8 ppm chlorine was sufficient to reduce the potential back into the material's passive range.

[203] reports on damage due to intergranular stress corrosion cracking in bolts made of the material Monel[®] K-500 with 2.3–3.2% Al (NiCu30Al, DIN-Mat. No.

2.4375), equivalent to NiCu30Fe. Heavy-duty bolts in underwater risers, with cathodic protection, failed after brief exposure due to hydrogen-induced stress corrosion cracking. To avoid critically raised hardness values, heat treatment is recommended accordingly.

Table 63 provides an overview of the behaviour of nickel-based alloys in seawater, listed under their commercial names; examples of their applications are listed in [204].

<i>Name</i>	<i>DIN-Mat. No.</i>	<i>Ni</i>	<i>Cr</i>	<i>Cu</i>	<i>Mo</i>	<i>Fe</i>	<i>Mn</i>	<i>Al</i>	<i>Ti</i>	<i>Nb/Ta</i>
Monel [®] 400 NiCu39Fe	2.4360	65		32		1.5	1.0			
Monel [®] K-500 NiCu30Al	2.4375	64		30		1.0	0.8	2.8	0.6	
Incoloy [®] 825 NiCr21Mo	2.4858	42	21.0	2.0	3.0	30			1.0	
Inconel [®] 625 NiCr22Mo9Nb	2.4856	61	21.5		9.0	2.5	0.3	0.2	0.2	3.65
Nimonic [®] 75 NiCr20Ti	2.4951	75	19.5			4.0			0.4	
Nimonic [®] 80A NiCr20TiAl	2.4452	75	19.5					1.4	2.4	
Nimonic [®] 81		66	30.0					0.9	1.8	
Nimonic [®] 901 NiCr13Mo6Ti3	2.4662	42.5	12.5		5.7	35.0		0.3	2.9	

Table 63: Frequently used seawater-exposed Ni-based alloys (mass%) [204]

In flowing seawater, the corrosion rate of these materials is below 0.025 mm/a (0.98 mpy).

In stagnant seawater, after 3 years of exposure, the maximum pitting corrosion depths in Table 64 were measured, clearly demonstrating the positive influence of the Cr and Mo content in these alloys.

<i>Alloy</i>	<i>Abbreviated designation</i>	<i>DIN-Mat. No.</i>	<i>Max. pitting depth mm</i>
Monel [®] 400	NiCu39Fe	2.4360	1.07
Monel [®] K-500	NiCu30Al	2.4375	0.86
Incoloy [®] 825	NiCr21Mo	2.4858	0.03
Inconel [®] 625	NiCr22Mo9Nb	2.4856	0.00

Table 64: Maximum pitting corrosion depths after 3 years in stagnating natural seawater of Ni-based alloys [204]

The four alloys show practically the same levels of good corrosion resistance at high flow rates (Table 65).

Alloy	Abbreviated designation	DIN-Mat. No.	Corrosion/erosion rate mm/a (mpy)
Monel [®] 400	NiCu39Fe	2.4360	0.010 (0.39)
Monel [®] K-500	NiCu30Al	2.4375	0.010 (0.39)
Incoloy [®] 825	NiCr21Mo	2.4856	0.008 (0.31)
Inconel [®] 625	NiCr22Mo9Nb	2.4856	0.000

Table 65: Corrosion rates in flowing seawater of Ni-based alloys (flow rate approx. 43 m/s) [204]

The corrosion behaviour of nickel and 14 nickel alloys was tested in comparison to titanium and stainless austenitic steel (Table 66) by means of exposure in stagnant and flowing natural seawater (flow rate 0.23 m/s) over a period of 1.6 years [205].

Name	DIN-Mat. No.	Abbreviated designation	Ni	Cr	Mo	Co	Fe	Cu	Al
Ni 200	2.4066	Ni99.2	> 99.0				0.4	0.25	
Monel [®] 400	2.4360	NiCu30Fe	63–70				2.5	balance	
Monel [®] K-500	2.4375	NiCu30Al	63–70				2.0	balance	0.9–2.3
Inconel [®] 600	2.4816	NiCr15Fe	> 72.0	14–17			6–10	0.5	
Inconel [®] 617	2.4663	NiCr23Co12Mo	53.9	22.5	8–9	12.7	0.13	0.23	1.0
Inconel [®] 625	2.4856	NiCr22Mo9Nb	balance	20–23	8–10		< 3.0		0.4
Inconel [®] 706	–	–	39–44	14.5–17.5			balance	0.30	0.4
Inconel [®] 718	2.4668	NiCr19NbMo	50.55	17–21	2.8–3.0	1.00	balance	0.30	0.20–0.80
Alloy 20	2.4660	NiCr20CuMo	32–38	19–21	2–3		balance	3.0–4.0	
Incoloy [®] 800	1.4876	X10NiCrAlTi32-20	30–35	19–23			balance	0.75	0.15–0.60

Table 66: Nominal compositions of the tested materials (mass%) [205]

Table 66 Continued

Name	DIN-Mat. No.	Abbreviated designation	Ni	Cr	Mo	Co	Fe	Cu	Al
Incoloy [®] 825	2.4858	NiCr21Mo	38–46	19.5–23.5	2.5–3.5		balance	1.5–3.0	0.2
Hastelloy [®] C-276	2.4819	NiMo16Cr15W	balance	14.5–16.5	15–17	2.5	4.0–7.0		
MP 35N	2.4999	MP35N	33–37	19–21	9.0–10.5	balance	1.0		
TiAl6V4	3.7165	TiAl6V4					0.4		5.5–6.5
SAE 304	1.4301	X5CrNi18-10	8–10.5	18–20			balance		

Table 66: Nominal compositions of the tested materials (mass%) [205]

The seawater had an electrical resistance level of 19.5 Ω cm, a pH level of 8.0, a temperature in the range of 290 to 305 K (17 °C to 32 °C) (mean value 300 K (27 °C)) and a mean oxygen content of 11.8 mg/l.

Some of the samples were cathodically protected by contact with iron or zinc anodes. The corrosion potential was measured at intervals throughout the entire exposure duration and the depth of the crevice corrosion sites was determined. Table 67 shows the corrosion depth results in stagnating seawater and Table 68 shows the results in flowing seawater.

Name	Abbreviated designation	DIN-Mat. No.	Corrosion depth after 1.6 a, mm			
			Crevice area		Remaining area	
			Max. value	Mean value	Max. value	Mean value
Ni 200	Ni99.2	2.4060	2.06	1.10	0.46	0.15
Monel [®] 400	NiCu30Fe	2.4360	0.43	0.29	0.28	0.15
Monel [®] K-500	NiCu30Al	2.4375	0.05	0.04	0.10	0.06
Inconel [®] 600	NiCr15Fe	2.4816	0.46	0.30	0.15	0.05
Inconel [®] 617	NiCr23Co12Mo	2.4663	0	0	0	0
Inconel [®] 625	NiCr22Mo9Nb	2.4856	0	0	0	0

1) perforated

Table 67: Corrosion depths in samples in stagnant seawater [205]

Table 67 Continued

Name	Abbreviated designation	DIN-Mat. No.	Corrosion depth after 1.6 a, mm			
			Crevice area		Remaining area	
			Max. value	Mean value	Max. value	Mean value
Inconel [®] 706	–	–	1.27	0.89	0	0
Inconel [®] 718	NiCr19NbMo	2.4668	0.81	0.46	0	0
Alloy 20	NiCr20CuMo	2.4660	0.31	0.19	0	0
Incoloy [®] 800	X10NiCrAlTi32-20	1.4876	2.5 ¹⁾	–	–	–
Incoloy [®] 825	NiCr21Mo	2.4858	0.23	0.11	0.08	0.05
MP 35N	MP35N	2.4999	0	0	0	0
TiAl6V4	TiAl6V4	3.7165	0	0	0.02	0.02
Hastelloy [®] C-276	NiMo16Cr15W	2.4819	0	0	0	0
SAE 304	X5CrNi18-10	1.4301	1.5 ¹⁾	–	–	–

1) perforated

Table 67: Corrosion depths in samples in stagnant seawater [205]

Name	Abbreviated designation	DIN-Mat. No.	Corrosion depth after 1.6 a, mm			
			Crevice area		Remaining area	
			Max. value	Mean value	Max. value	Mean value
Ni 200	Ni99.2	2.4060	2.75 ¹⁾	–	2.74	–
Monel [®] 400	NiCu30Fe	2.4360	1.55 ¹⁾	–	0.56	0.23
Monel [®] K-500	NiCu30Al	2.4375	0.31	0.18	0.23	0.10
Inconel [®] 600	NiCr15Fe	2.4816	1.06 ¹⁾	–	0.20	0.06
Inconel [®] 617	NiCr23Co12Mo	2.4663	0.18	0.15	0.03	

1) perforated

Table 68: Corrosion depths in samples in flowing seawater [205]

Table 68 Continued

Name	Abbreviated designation	DIN-Mat. No.	Corrosion depth after 1.6 a, mm			
			Crevice area		Remaining area	
			Max. value	Mean value	Max. value	Mean value
Inconel [®] 625	NiCr22Mo9Nb	2.4856	0.05	–	0	0
Inconel [®] 706	–	–	1.56 ¹⁾	–	0.13	0.09
Inconel [®] 718	NiCr19NbMo	2.4668	1.55	0.58	0	0
Alloy 20	NiCr20CuMo	2.4660	1.67	0.23	0.03	0.03
Incoloy [®] 800	X10NiCrAlTi32-20	1.4876	2.5 ¹⁾	–	2.23	1.87
Incoloy [®] 825	NiCr21Mo	2.4858	1.60	0.43	0.05	0.03
MP 35N	MP35N	2.4999	0	0	0	0
TiAl6V4	TiAl6V4	3.7165	0	0	0	0
Hastelloy [®] C-276	NiMo16Cr15W	2.4819	0	0	< 0.02	< 0.02
SAE 304	X5CrNi18-10	1.4301	1.5 ¹⁾	–	–	–

1) perforated

Table 68: Corrosion depths in samples in flowing seawater [205]

Only the highly molybdeniferous materials Hastelloy[®] C-276 (DIN-Mat. No. 2.4819), MP 35N (DIN-Mat. No. 2.4999), Inconel[®] 625 (DIN-Mat. No. 2.4856) and TiAl6V4 (DIN-Mat. No. 3.7165) proved completely corrosion-resistant under all test conditions. The materials Monel[®] K-500 (DIN-Mat. No. 2.4375), Inconel[®] 617 (DIN-Mat. No. 2.4663) and Incoloy[®] 825 (DIN-Mat. No. 2.4858) also show sufficient resistance in stagnant seawater without cathodic protection. In all materials, cathodic protection with both iron and with zinc anodes in stagnant and flowing seawater reduced local corrosion to levels under 0.075 mm after exposure for 1.6 years. This also applies to the materials exposed to free corrosion conditions that were perforated after this time period.

Nickel-molybdenum alloys

The chromium-free nickel-molybdenum alloys, for example NiMo28 (DIN-Mat. No. 2.4617, Hastelloy® B-2), show only minimal amounts of surface corrosion in seawater, but are nonetheless practically unsuitable for use in seawater because of their sensitivity to pitting and crevice corrosion.

Other nickel alloys

The NiSi alloys, e.g. those containing 85% Ni, 10% Si and 3% Cu, are not suitable for use in seawater due to their sensitivity to local corrosion. Under the commercial designation Nimonic®, the NiCrCo alloys listed in Table 69 are used for certain applications at high temperatures in maritime environments, for example in combustion chambers or ship turbine components [204].

Name	Abbreviated designation	DIN-Mat. No.	Ni	Cr	Mo	Al	Ti
Nimonic® 90	NiCr20Co18Ti	2.4669/2.4632	59	19.5	1.5	2.5	
Nimonic® 91	–	–	47.5	28.5	1.2	2.3	
Nimonic® 101	–	–	balance	24.2	1.5	1.4	2.0
Nimonic® 105	NiCo20Cr15MoAlTi	2.4634	53	15.0	5.0	4.7	1.2
Nimonic® 115	NiCo15Cr15MoAlTi	2.4636	59	14.2	4.0	5.0	4.0

Table 69: NiCrCo alloys for applications involving seawater exposure (mass%)

Zinc

Seawater-exposed applications of zinc are restricted almost exclusively to use as a coating material on steel or for galvanic anodes in cathodic corrosion protection. In actual practice, zinc alloys are used with aluminium. The contaminations in the form of lead and iron must be reduced to a minimum to avoid passivation. Refined zinc 99.995% is used as the basic material. The current yield approaches closely to the theoretical yield of zinc. The rest potentials are in the range from $U_H = -0.752$ V to -0.800 V and the operating voltage U_T is about 0.25 V to 0.35 V. Operating voltage U_T is defined as the difference between the protective potential of the protection object and the potential of the working anode [206]. Of all galvanic anode materials, zinc has the highest ratio of weight to current yield, approx. $11 \text{ kg}/(\text{A a})$.

The anodic activity of zinc anodes is reduced by an iron content level of only 0.0015% , as demonstrated by experiments in synthetic seawater with a total salt content of 3.5% at 293 K (20°C). The activity level is further reduced as the Fe content

increases. Al, Cd and Hg content improve activity appreciably [207]. Table 70 lists the compositions of a number of zinc anodes [208].

To protect hot pipelines on the sea bottom, electrodes made of pure and highly pure zinc are not suitable, since they are subject to intergranular corrosion beginning at temperatures of 325 K (52 °C). Anodes with additions of 0.02% Mg or 0.05% Cd show pitting corrosion. When designing the AlZn anodes recommended for this purpose, the much lower current yield under these conditions must be taken into account [209–211].

Zinc anodes containing aluminium zinc anodes are also susceptible to intergranular corrosion at temperatures above 298 K (25 °C) due to the selective dissolution of an Al-rich phase at the grain boundaries [212]. This corrosion increases as the temperature rises. That is why, the SGH anode type II with max. 0.005% Al, 0.003% Cd and 0.0014% Fe, which is not susceptible to intergranular corrosion, is recommended in ASTM B418-73 [208, 213].

<i>Anode</i>	<i>Al</i>	<i>Cd</i>	<i>Fe</i>	<i>Pb</i>	<i>Cu</i>	<i>Si</i>	<i>Zn</i>
Hi-Amp	0.1–0.3	0.025–0.06	max. 0.003	max. 0.006			balance
Mil-A-18001H	0.1–0.5	0.025–0.15	max. 0.005	max. 0.006	max. 0.005	max. 0.125	balance
ASTM B428-73 [214] Type 1	0.1–0.4	0.03–0.10	max. 0.005				balance

Table 70: Composition of zinc anodes for use in seawater (mass%) [208]

As a construction material, zinc is sometimes used for diecasting parts.

The corrosion rates for zinc in a marine atmosphere are about 0.025 mm/a (0.98 mpy) and in seawater about 0.050 mm/a (1.97 mpy). With increasing motion, the corrosion rate increases appreciably to reach about 0.200 mm/a (7.87 mpy) at a flow rate of 2 m/s.

In contrast to zinc coatings, massive zinc parts in seawater also suffer from pitting corrosion. In zinc coatings, local corrosion is prevented by the circumstance that the outer layer of pure zinc has a less noble potential than the iron-zinc alloy layer, resulting in cathodic protection.

Zinc coating

In the hot-dip galvanising process (hot-galvanising), layer thicknesses of 0.040–0.150 mm are produced on the steel surface. This coating consists of an iron-zinc alloy layer at the phase limit to the steel and a layer of pure zinc over that. The protective effect of the coating is determined by the layer thickness of both layers. In the initial stress load phase, covering layers are formed by the reaction of the zinc coating with the seawater. After this, a stationary phase of corrosion is reached with mainly linear corrosion rates at an order of magnitude of 0.010–0.012 mm/a (0.39–0.47 mpy).

Following exposure of galvanised steel samples in the North Sea water off Helgoland, the guideline values listed in Table 71 for the corrosion rate were estimated based on the evaluation of decomposition processes in the layer and on metallographic tests of the samples after a total of 6 years [215].

Galvanisation process	Layer thickness, mm	Corrosion rate, mm/a (mpy)		
		Splash zone	Tidal zone	Immersion zone
Spray galvanisation	0.100	0.012 (0.47)	0.025 (0.98)	0.025 (0.98)
Hot galvanisation 600 g/m ²	0.085	0.008 (0.30)	0.012 (0.47)	0.012 (0.47)
Hot galvanisation 1200 g/m ²	0.170	0.010 (0.39)	0.012 (0.47)	0.012 (0.47)

Table 71: Corrosion rates of zinc in seawater [215]

After the pure zinc layer is eaten away, the brown discolouration increases and iron corrosion products from the iron-zinc alloy phase are integrated in the covering layer. This brown discolouration is therefore not a sign of rust perforation and thus of reduced protective effect of the zinc plating. Rather, the covering layers formed from the alloy phase are less soluble than those formed from the pure zinc phase, resulting in a lower erosion rate of the alloy layer. Since thicker zinc platings also contain a higher percentage of the iron-zinc alloy phase, they also provide improved corrosion protection. Local corrosion does not occur in hot-galvanised structural elements in seawater, since the outer layers always exert a galvanic protective effect on the electrochemically nobler alloy phase beneath, or on the base material.

Zinc plating layers transformed by a heat treatment at 903 K (630 °C) completely into iron-zinc alloy phase (galvannealing) showed much better behaviour in the exposure zones. The corrosion protective effect of the hot-dip galvanised layers in seawater is thus not determined only by layer thickness, but also by the layer structure [216].

In thermal-sprayed zinc coatings, layer thicknesses of 0.050–0.150 mm are the maximum reached. These layers consist mainly of pure zinc, with a certain amount of zinc oxide and pores depending on the layer thickness and spraying technique. The much lower protective effect of spray galvanisation at the same layer thickness is probably due to the lack of the iron-zinc alloy phase.

Bibliography

- [1] Temperly, T. G.
Corrosion phenomena in coastal areas of the Persian Gulf
Corros. Sci. 5 (1965), p. 581–589
- [2] Lyman, J.; Abel, R. B.
Chemical aspects of physical oceanography
J. Chemical Education 35 (1958) 3, p. 113–115
- [3] Riley, J. P.; Chester, R.
Introduction to marine chemistry
Academic Press, London, 1971
- [4] Cox, R. A.
The physical properties of seawater, Chapter 3
in Riley, J. P.; Skirrow, G. "Chemical Oceanography", Vol. 1
Academic Press, N.Y.C. and London, 1965
- [5] DIN 81249-1 (12/2011)
Korrosion von Metallen in Seewasser und Seeatmosphäre; Teil 1: Begriffe, Grundlagen
(Corrosion of metals in sea water and sea atmosphere; part 1: Definitions, basic information) (in German)
Beuth Verlag GmbH, Berlin
- [6] DIN 50905-4 (01/1987)
Korrosion der Metalle;
Korrosionsuntersuchungen;
Durchführung von chemischen Korrosionsversuchen ohne mechanische Belastung in Flüssigkeiten im Laboratorium
(Corrosion of metals; corrosion testing in liquids under laboratory conditions without mechanical stress) (in German)
Beuth Verlag GmbH, Berlin
- [7] ASTM D1141-90 (1992) e1
Standard specification for substitute ocean water
ASTM American Society for Testing and Materials, West Conshohocken (PA/USA)
- [8] Rahmel, A.; Schwenk, W.
Korrosion und Korrosionsschutz von Stählen
(Corrosion and corrosion protection of steels) (in German)
Verlag Chemie, Weinheim, 1977, p. 91
- [9] Sverdrup, H. U.; Johnson, M. H.; Fleming, R. H.
The Oceans
Prentice-Hall Inc., New York, 1942
- [10] Fox, C. J. J.
Conseil permanent international pour l'exploration de la mer, Copenhagen (Permanent international Council for sea exploration) (in French)
Publication de circonstance 41 (1967)
- [11] White, J. H.; Yaniv, A. E.; Schick, H.
The corrosion of metals in the water of the Dead Sea
Corros. Sci. 6 (1966), p. 447
- [12] Forschungsbericht der Europäischen Gemeinschaft Kohle und Stahl
Research report of the European Union carbon and steel (in German)
No. 7210 KB/303, 1980
- [13] McIlhenny, W. F.; Zeitoun, M. A.
Chem. Eng. 81 (1969), p. 251
- [14] Rogers, T. H.
Marine Corrosion Handbook
McGraw Hill Comp. Canada Ltd., New York, Toronto, London, 1960
- [15] Brauns, E.; Schwenk, W.
Korrosion unlegierter Stähle in Seewasser
(Corrosion of unalloyed steels in seawater) (in German)
Stahl Eisen 87 (1967), p. 713–718
- [16] Schwenk, W.
Prinzipien der Korrosion und des Korrosionsschutzes in Meerwasser
(Principles of corrosion and corrosion protection in seawater) (in German)
Schiff & Hafen/Kommandobrücke (1983) 2 (special edition), p. 9–14
- [17] Lorenz, K.; Medawar, G.
Über das Korrosionsverhalten austenitischer Chrom-Nickel-(Molybdän-)Stähle mit und ohne Stickstoffzusatz unter besonderer Berücksichtigung ihrer Beanspruchbarkeit in chloridhaltigen Lösungen
(On the corrosion behaviour of austenitic chromium-nickel-(molybdenum) steels with and without addition of nitrogen with special consideration of their strain in chloride containing solutions)

- (in German)
Thyssen-Forschung 1 (1969) 3, p. 97–108
- [18] Edström, J. O.; Carlén, J. C.; Kämpinge, S.
Anforderungen an Stähle für die chemische Industrie
(Standards for steels for the chemical industry) (in German)
Werkst. Korros. 21 (1970) 10, p. 812–821
- [19] Herbsleb, G.
Effect of FeS and MnS inclusions on pit nucleation in pitting corrosion of steel
Stahl Eisen 93 (1973) 18, p. 837–839
- [20] Lee, T. S.; Kain, R. M.; Oldfield, J. W.
The effect of environmental variables on crevice corrosion of stainless steels in seawater
Mater. Performance 23 (1984) 7, p. 9
- [21] Kain, R. M.
Crevice corrosion behaviour of stainless steel in sea water and related environments
Corrosion 40 (1984) 6, p. 313–321
- [22] Bäumel, A.; Horn, E. M.; Siebers, G.
Entwicklung, Verarbeitung und Einsatz des stickstofflegierten, hochmolybdänhaltigen Stahles X3CrNiMoN 17 13 5
(Development, processing and use of nitrogen-alloyed, high molybdeniferous steels X3CrNiMoN 17 13 5) (in German)
Werkst. Korros. 23 (1972) 11, p. 973
- [23] DIN 81249-2 (11/1997)
Korrosion von Metallen in Seewasser und Seeatmosphäre; Teil 2: Freie Korrosion in Seewasser
DIN 81249-2 (05/2013)
Corrosion of metals in sea water and sea atmosphere – Part 2: Free corrosion in sea water
Beuth Verlag GmbH, Berlin
- [24] Bartels, W.; Drodten, P.; Grimme, D.
Beitrag zum Spannungsrißkorrosionsverhalten geschweißter höherfester Baustähle in Meerwasser
(Report on the stress corrosion cracking behaviour of welded higher-strength structural steels in seawater) (in German)
Stahl Eisen 103 (1983) 14, p. 719–721
- [25] Pöpperling, R.; Schwenk, W.; Venkateswarlu, J.
Wasserstoffinduzierte Spannungsrißkorrosion von Stählen durch dynamisch-plastische Beanspruchung in promotorfreien Elektrolytlösungen
(Hydrogen-induced stress corrosion cracking of steels by dynamic-plastic stress load in promotor-free electrolyte solutions) (in German)
Werkst. Korros. 36 (1985) 9, p. 389–400
- [26] Brauns, E.; Ternes, H.
Investigation into the transcrystalline stress-corrosion cracking of chromium-nickel steels in hot chloride solutions
Werkst. Korros. 19 (1968) 1, p. 1–19
- [27] Risch, K.
Nachbehandlung von Halbzeugen und Apparaten aus austenitischen Stählen zur Vermeidung von Spannungsrißkorrosion
(Aftertreatment of semi-finished products apparatuses of austenitic steels to prevent stress corrosion cracking) (in German)
Chem.-Ing.-Tech. 51 (1979) 5, p. 402–406
- [28] Copson, H. R.
Physical Metallurgy of Stress Corrosion Fracture
- [29] DIN 81249-3 (11/1997)
Korrosion von Metallen in Seewasser und Seeatmosphäre. Teil 3: Kontaktkorrosion in Seewasser
DIN 81249-3 (09/2012)
Corrosion of metals in sea water and sea atmosphere – Part 3: Galvanic corrosion in sea water
Beuth Verlag GmbH, Berlin
- [30] Kuron, D.; Kilian, R.; Gräfen, H.
Measuring system for the compilation of galvanic corrosion tables
Material combination in seawater and brackish water
Z. Materialtech. 1 (1980) 11, p. 382–386
- [31] Kuron, D.
Aufstellung von Kontaktkorrosionstabellen für Werkstoffkombinationen in Wässern
(Summary of contact corrosion tables for material combinations in waters)

- in: Behrens, D.; Rahmel, A. "Ergebnisse des Forschungs- und Entwicklungsprogramms 'Korrosion und Korrosionsschutz', vol. 3 (1981–1983), p. 519–520
 DECHEMA e. V., Frankfurt am Main, 1984
- [32] Henrikson, S.; Asberg, M.
 Corrosion potentials and galvanic corrosion currents for various material combinations in Baltic Sea water
 7. Scandinavian Corrosion Congress, Trondheim, 1975, p. 371–384
- [33] Hodgekiess, T.; Lim, C. W.
 Aspects of galvanic corrosion behaviour of a range of materials in seawater
 Corros. Sci. 35 (1993) 1–4, p. 269–283
- [34] Francis, R.
 Galvanic corrosion of high alloy stainless steels in sea water
 Br. Corros. J. 29 (1994) 1, p. 53–57
- [35] Hargarter, E.
 Kontaktkorrosion bei verschiedenen Metallpaarungen in Meerwasser (Contact corrosion at different metal pairs in seawater) (in German)
 FE-KKs- Project No. H/9/1
 FE-KKs-vol. 5 (1990) p. 431–433
 DECHEMA e. V., Frankfurt am Main
- [36] Hargarter, E.; Sass, H.
 Kontaktkorrosion zwischen verschiedenen Werkstoffen in Meerwasser (Contact corrosion between different materials in seawater) (in German)
 Jahrbuch der Schiffbautechnischen Gesellschaft, Hamburg, vol. 80 (1986) p. 105–106
- [37] Hargarter, E.
 Contact corrosion in seawater
 6. WEMT Symposium, Travemünde, June, 1987, STG No. 3003, D1-D6
- [38] DIN EN 10025-1 (02/2005)
 Warmgewalzte Erzeugnisse aus Baustählen – Teil 1: Allgemeine technische Lieferbedingungen (Hot rolled products of structural steels – Part 1: General technical delivery conditions) (in German)
 Beuth Verlag GmbH, Berlin
 DIN EN 10025-2 (04/2005)
 Warmgewalzte Erzeugnisse aus Baustählen – Teil 2: Technische Lieferbedingungen für unlegierte Baustähle (Hot rolled products of structural steels – Part 2: Technical delivery conditions for non-alloy structural steels) (in German)
 Beuth Verlag GmbH, Berlin
- [39] DIN EN 10083-1 (10/2006)
 Vergütungsstähle – Teil 1: Allgemeine technische Lieferbedingungen (Steels for quenching and tempering – Part 1: General technical delivery conditions) (in German)
 Beuth Verlag GmbH, Berlin
 DIN EN 10083-2 (10/2006)
 Vergütungsstähle – Teil 2: Technische Lieferbedingungen für unlegierte Stähle (Steels for quenching and tempering – Part 2: Technical delivery conditions for non-alloy steels)
 Beuth Verlag GmbH, Berlin
 DIN EN 10083-3 (01/2007)
 Vergütungsstähle – Teil 3: Technische Lieferbedingungen für legierte Stähle (Steels for quenching and tempering – Part 3: Technical delivery conditions for alloy steels)
 Beuth Verlag GmbH, Berlin
- [40] DIN EN 10025-1 (02/2005)
 Warmgewalzte Erzeugnisse aus Baustählen – Teil 1: Allgemeine technische Lieferbedingungen (Hot rolled products of structural steels – Part 1: General technical delivery conditions) (in German)
 Beuth Verlag GmbH, Berlin
 DIN EN 10025-3 (02/2005)
 Warmgewalzte Erzeugnisse aus Baustählen – Teil 3: Technische Lieferbedingungen für normalgeglühte/normalisierend gewalzte schweißgeeignete Feinkornbaustähle (Hot rolled products of structural steels – Part 3: Technical delivery conditions for normalised/normalised rolled weldable fine grain structural steels) (in German)
 Beuth Verlag GmbH, Berlin
 DIN EN 10025-4 (04/2005)
 Warmgewalzte Erzeugnisse aus Baustählen – Teil 4: Technische Lieferbedingungen für thermomechanisch gewalzte schweißgeeignete Feinkornbaustähle (Hot rolled products of structural steels –

- Part 4: Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels) (in German)
Beuth Verlag GmbH, Berlin
- [41] DIN EN 10293 (06/2005)
Stahlguss für allgemeine Anwendungen (Steel castings for general engineering uses) (in German)
Beuth Verlag GmbH, Berlin
- [42] DIN EN 10213-1 (01/1996)
Technische Lieferbedingungen für Stahlguß für Druckbehälter – Teil 1: Allgemeines
DIN EN 10213-1 (01/2008)
Steel castings for pressure purposes (in German)
Beuth Verlag GmbH, Berlin
DIN EN 10213-3 (01/1996) withdrawn
Technische Lieferbedingungen für Stahlguß für Druckbehälter – Teil 3: Stahlsorten für die Verwendung bei tiefen Temperaturen
(Technical delivery conditions for steel castings for pressure purposes – Part 3: Steel grades for use at low temperatures) (in German)
Beuth Verlag GmbH, Berlin
DIN EN 10293 (06/2005)
Stahlguss für allgemeine Anwendungen
DIN EN 10293 (04/2015)
Steel castings – Steel castings for general engineering uses (in German)
Beuth Verlag GmbH, Berlin
- [43] Werkstoffblatt XAMAR 36
(Materials data sheet XAMAR 36) (in German)
Thyssen steel AG, Duisburg, November, 1993
- [44] Baudot, M. H.; Chaudron, M. G.
Organisation général of the essais élaboration et préparation of the échantillons mis en mer
(General organization of the tests development and preparation of the samples put in the sea) (in French)
Rev. Metallurg. Mem. 43 (1946), p. 3
- [45] Kennedy, E. R.; Wilson, J. S.
New York harbour corrosion – Port of New York authority conducts pile survey
Mater. Protection 6 (1967) 1, p. 53
- [46] Southwell, C. R.; Alexander, A. L.
Corrosion of metals in tropical waters. Structural ferrous metals
Mater. Protection 9 (1970) 1, p. 14
- [47] Masumoto, H.; Otoguro, Y.; Okazaki, T.; Kado, A.; Shimada, H.; Matsukura, K.; Watanabe, T.; Fujimoto, T.
Development and future trends of weldable seawater corrosion resistant steels
Nippon Steel Techn. Rep. Overseas 8 (1976) 5, p. 1–10
- [48] Friehe, W.
Einfluß höherer Aluminiumgehalte in Stählen auf das Korrosionsverhalten im Meerwasser
(Influence of higher aluminium contents in steels on the corrosion behaviour in the seawater) (in German)
Stahl Eisen 96 (1976) 12, p. 567–572
- [49] Blekkenhorst, F.; Ferrari, G. M.; Wekken, C. J. van der Ijsselin, F. P.
Development of high strength low alloy steels for marine applications; Part I: Results of long term exposure tests on commercially available and experimental steels
Br. Corros. J. 21 (1986) 3, p. 163–176
- [50] Songa, T.
Konferenz “Stahl in Meerwasser”, p. 1–64
(Conference “Steel in seawater”) (in German)
Paris, 5.-8.10.1981 Commission of the European Unions
- [51] Kurisu, T.; Imazu, T.; Nishiyama, N.; Suzuki, S.; Okumura, T.; Kyuno, T.
MARIWEL –seawater corrosion resistant steel for welded structures
Kawasaki Steel Technical Report No. 7, March 1983, p. 27–33
- [52] Drodten, P.
Einfluß von Schwefelgehalt, Schwefelverteilung und Desoxidationsart auf die Korrosion von Stahl in Meerwasser
(Influence of sulphur content, sulphur distribution and desoxidation manner on the corrosion of steel in seawater) (in German)
Stahl Eisen 101 (1981) 4, p. 75

- [53] Martini, A.; Mennenöh, S.
Über die Ausbildung von
Makroelementen an Spundbohlen in
Meerwasser
(On the development of macroelements
on sheet piles in seawater) (in German)
Stahl Eisen 101 (1981) 1, p. 79–85
- [54] Grimme, D.
Stähle für die Meerestechnik und deren
Korrosionsverhalten
(Steels for marine engineering and their
corrosion behaviour) (in German)
Stahlbau (1985) 6, p. 187–189
- [55] La Que, F. L.
Corrosion testing procedures
Amer. Soc. Test. Mater. 51 (1951), p. 495–
582
- [56] Wijngaard, B. H.
Spundwandkorrosion in Meerwasser
(Sheet piling corrosion in seawater)
(in German)
Stahl Eisen 102 (1982), p. 583–584
- [57] Bäuml, A.
Selektive Korrosion an
Verbindungsschweißen von Stählen
(Selective corrosion on joint-welding of
steels) (in German)
Werkst. Korros. 17 (1966) 4, p. 299–307
- [58] Mennenöh, S.; Tenhaven, U.
Das Verhalten von
Unterpulverschweißnähten in
Meerwasser
(The behaviour of submerged welding
joints in seawater) (in German)
Werkst. Korros. 23 (1972) 11, p. 1016
- [59] Bäuml, A.
Korrosionsprognose für den Bereich der
Schweißnaht
(Corrosion prognosis for the welding
seam area) (in German)
Werkst. Korros. 23 (1972) 7, p. 546
- [60] Lundin, S.
Erfahrungen bei Korrosionsprüfungen
von Schweißnähten an verschiedenen
Schiffbaustählen in Seewasser
(Experience during corrosion tests of
welding seams on different shipbuilding
steels in seawater) (in German)
Schiff und Hafen 24 (1972) 3, p. 187–194
- [61] Drodten, P.
Korrosionserscheinungen an
Schweißverbindungen aus Werkstoffen
des Schiffbaus
(Corrosion phenomena on welded joints
of materials in the shipbuilding industry)
(in German)
Arch. Eisenhüttenwes 44 (1973) 12,
p. 953–954
- [62] Adrian, H.; Drodten, P.; Engell, H.-J.;
Grimme, D. Herbsleb, G.; Horstmann,
D.; Mennenöh, S.; Schwenk, W.
Effect of metallurgical development om
the corrosion of carbon and low alloy
construction steels for ship building and
harbour construction
Corros. Sci. 17 (1977), p. 143–153
- [63] Herbsleb, G.
Ursachen und Untersuchungen örtlicher
Korrosion der Schweißnaht an Blechen
und Rohren aus un- und niedriglegierten
Stählen
(Reasons and tests of local corrosion of
the welding seam on brasses and pipes of
unalloyed and low-alloyed steels
Schweißtechnik 39 (1985), p. 21–24,
40–44
- [64] DIN 50915 (09/1993)
Prüfung von unlegierten und
niedriglegierten Stählen auf
Beständigkeit gegen interkristalline
Spannungsrißkorrosion in nitrathaltigen
Angriffsmitteln; Geschweißte und
ungeschweißte Werkstoffe
(Testing the resistance of unalloyed and
low alloy steels to intergranular stress
corrosion cracking by attack of nitrate
medium; welded and unwelded
materials) (in German)
Beuth Verlag GmbH, Berlin
- [65] Bäuml, A.
Feinkorn- und Kesselbaustähle: Prüfung
auf Neigung zur Rißbildung
(Fine-grained-steel and boiler
construction steels: tests concerning the
inclination to form cracks) (in German)
Stahl Eisen 104 (1984) 10, p. 513
- [66] Drodten, P.; Schwenk, W.; Grimme, D.;
Haumann, W.
Corrosion of low alloy steel in seawater
Report EUR 14333, 1993-VII
Technische Forschung Stahl, 1993

- [67] Drodten, P.; Kaiser, H.-J.; Müsken, B.; Pircher, H.
behaviour of high-strength structural steels exposed to seawater
Thyssen Techn. Ber. 22 (1990) 1, p. 53–67
- [68] Großerlinden, R.; Pircher, H.
Wasserstoffinduzierte Korrosion von niedriglegierten Stählen in wässrigen Medien
(Hydrogen-induced corrosion of low-alloyed steels in aqueous media)
(in German)
Werkst. Korros. 38 (1987) 2, p. 57
- [69] Drodten, P.; Pircher, H.
Untersuchungen zur Rißkorrosion hochfester Baustähle in Meerwasser
(Tests on the crevice corrosion of high-strength structural steels in seawater)
(in German)
Werkst. Korros. 47 (1996) 1, p. 1-8
- [70] Robinson, M. J.; Kilgallon, P. J.
Hydrogen embrittlement of cathodically protected high-strength, low alloy steels exposed to sulphate-reducing bacteria
Corrosion 50 (1994) 8, p. 626-635
- [71] Pöpperling, R.; Schwenk, W.; Vogt, G.
Potentialabhängigkeit der Schwingungsrißkorrosion von höherfestem Dalbenstahl in Salzwässern
(Potential-dependence of corrosion fatigue of higher-strength dolphin steel in saltwaters)
(in German)
Werkst. Korros. 29 (1978) 7, p. 445–451
- [72] Hasselmann, K.; Ross, D. B.; Müller, P.; Sell, W.
J. Physical Oceanography 6 (1976), p. 200
- [73] Helms, R.; Richter, B.; Sonsin, C. M.
Spannungsriß- und Schwingungsrißkorrosion von Stählen
(Stress corrosion cracking and corrosion fatigue in steels)
(in German)
in: Gräfen, H.; Rahmel, A. "Korrosion verstehen – Korrosionsschäden vermeiden", vol. 1, p. 227–245
Verlag Irene Kuron, Bonn, 1994
- [74] ASTM D1241-68 (2000)
Standard specification for materials for soil-aggregate subbase, base, and surface courses
ASTM American Society for Testing and Materials, West Conshohocken
(PA/USA)
- [75] Helms, R.; Henke, H.; Bork, C.-P.
Schwingungsrißkorrosion von Baustahl in Offshore-Konstruktionen bei unterschiedlichen Frequenzen und Umgebungsbedingungen
(Corrosion fatigue of structural steel in offshore constructions at different frequencies and environment conditions)
(in German)
Werkst. Korros. 39 (1988) 10, p. 441
- [76] Helms, R.; Henke, H.
Corrosion fatigue of structural steel in offshore structures in synthetical and natural seawater
Werkst. Korros. 43 (1992) 12, p. 558–559
- [77] Oberparleiter, W.; Schütz, W.
Berechnung des Rißfortschrittsverhaltens geschweißter Proben aus Offshore-Stählen in Meerwasser zur Abschätzung der Lebensdauer von Offshore-Komponenten
(Calculation of the crack propagation behaviour of welded samples of offshore steels in seawater for the estimation of the service life of offshore-components)
(in German)
Werkst. Korros. 39 (1988) 8, p. 369–378
- [78] Oberparleiter, W.
Einfluß von Prüffrequenz und Salzgehalt des Korrosionsmediums auf die Korrosionermüdung von Stählen bei betriebsähnlichen Lastabläufen
(Influence of the test frequency and NaCl- content of fatigue life of steels under a realistic load sequence)
(in German)
Werkst. Korros. 37 (1986) 7, p. 391
- [79] Bohnenkamp, K.; Esdohr, J.
Untersuchungen zur Schwingungsrißkorrosion von Stählen in Meerwasser
(Investigations of corrosion fatigue of steel in seawater)
(in German)
Werkst. Korros. 38 (1987) 4, p. 155–165
- [80] Martin, A.; Sanchez-Galvez, V.
Environmentally assisted fatigue crack growth in high strength eutectoid cold drawn steel
Br. Corros. J. 23 (1988) 2, p. 96

- [81] Schmitt-Thomas, Kh. G.; Meisel, H.; Reich, E.
Beeinflussung des Schwingungsrißkorrosions-Verhaltens verschweißter Proben durch das WIG- und Plasmanachbehandlungsverfahren (Influence of TIG- and plasma post-weld treatment on corrosion fatigue behaviour of welded specimens) (in German) *Werkst. Korros.* 35 (1984) 7, p. 321
- [82] Olivier, R.; Grimme, D.; Lachmann, B.; Müsgen, B.
Untersuchungen zur Betriebsfestigkeit von geschweißten Offshore-Konstruktionen in Meerwasser (Investigations on the service strength of welded offshore constructions in seawater) (in German) *Stahl Eisen* 106 (1986) 1, p. 33
- [83] Scott, P. M.; Thorpe, T. W.; Silvester, D. R.
Rate-determining process for corrosion fatigue crack growth in ferritic steels in seawater *Corros. Sci.* 23 (1983) 6, p. 559–575
- [84] Hartt, W. H.
Cathodic protection and fatigue of offshore structures *Mater. Performance* 20 (1981) 11, p. 50–54
- [85] Hartt, W. H.; Hooper, C.
Endurance limit enhancement of notched, 1018 steel in sea water – specimen size and frequency effects *Corrosion* 36 (1980) 3, p. 107–112
- [86] Drodten, P.
Das Korrosionsverhalten von Gußeisen in Land-, See- und Industrieluft und in Meerwasser (The corrosion behaviour of cast iron in country, sea and industry air and in seawater) (in German) *Stahl Eisen* 90 (1970) 19, p. 1038–1042
- [87] DIN EN 1561 (08/1997)
Gießereiwesen – Gußeisen mit Lamellengraphit
DIN EN 1561 (01/2012)
Founding – Grey cast irons (in German) Beuth Verlag GmbH, Berlin
- [88] DIN EN 1563 (10/2005)
Gießereiwesen – Gusseisen mit Kugelgraphit
DIN EN 1563 (03/2012)
Founding – Spheroidal graphite cast irons (in German) Beuth Verlag GmbH, Berlin
- [89] DIN EN 13835 (02/2003)
Gießereiwesen – Austenitische Gusseisen
DIN EN 13835 (04/2012)
Founding – Austenitic cast irons (in German) Beuth Verlag GmbH, Berlin
- [90] Speidel, P.; Wittmoser, A.
Gießerei *Techn. Wissenschaftl. Beihefte* (1960) 29, p. 1607–1617
- [91] Sefing, F. G.
Cast Irons
in: LaQue, F. L.; Copson, H. R. “Corrosion resistance of metals and alloys”, 2. ed, p. 355–374
Reinhold Publishing Corporation, New York, 1963
- [92] LaQue, F. L.
The corrosion resistance of ductile iron *Corrosion* 14 (1958) p. 485
- [93] Product Information
Company publication No. 41, 1966
International Nickel Deutschland, Düsseldorf
- [94] ASTM A436-84 (1997) e1
Standard Specification for Austenitic Grey Iron Castings
ASTM American Society for Testing and Materials, West Conshohocken (PA/USA)
- [95] Craig, B. D.; McClymonds, L. A.
A potentiometric study of the corrosion of Ni-resist in sea water *Corrosion* 37 (1982) 8, p. 485
- [96] Miyasaka, M.; Ogure, N.
Stress corrosion cracking of austenitic cast irons in seawater and brine, and its prevention *Corrosion* 43 (1987) 10, p. 582

- [97] Sürý, P.; Hiltbrunner, K.
Untersuchungen zum Einfluß des Nickelgehaltes auf die Korrosionseigenschaften von Gußeisen (Tests on the influence of the Nickel content on the corrosion properties of cast iron) (in German)
Arch. Eisenhüttenwesen 50 (1979) 11, p. 493
- [98] White, R. A.
Selection of material for multistage flash seawater conversion plants
Mater. Protection 4 (1965) 3, p. 48
- [99] Bock, H. E.; Kügler, A.; Lennartz, G.; Michel, E.
Das Verhalten von höherlegierten Stählen in Meerwasser (behaviour of higher alloyed steels in seawater) (in German)
Stahl Eisen 104 (1984) 11, p. 61
- [100] Company publication
Korrosionsbeständigkeit der nichtrostenden Stähle an der Atmosphäre (Corrosion resistance of stainless steels in atmosphere) (in German)
Informationsstelle Edelstahl Rostfrei, Düsseldorf, January, 1996
- [101] DIN EN 10088-1 (09/2005)
Nichtrostende Stähle – Teil 1: Verzeichnis der nichtrostenden Stähle
DIN EN 10088-1 (12/2014)
Stainless steels – Part 1: List of stainless steels (in German)
Beuth Verlag GmbH, Berlin
- [102] Sydberger, T.
Influence of the surface state on the initiation of crevice corrosion on stainless steels
Werkst. Korros. 32 (1981) 3, p. 119
- [103] Streicher, M. A.
Development of pitting resistant Fe-Cr-Mo alloys
Corrosion 30 (1974) 3, p. 77
- [104] Bond, A. P.; Bertoli, C.; Dundas, H. J.
Corrosion resistance of stainless steels in seawater
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981) p. 1–10
- [105] Vaccari, J. A.
Neue ferritische Stähle gegen Spannungsrisskorrosion bei erleichterter Verarbeitung (New ferritic steels against stress corrosion cracking with easier treatment) (in German)
Mater. Eng. 82 (1975) 7, p. 24
- [106] Streicher, M. A.
Microstructures and some properties of Fe-28%Cr-4%Mo alloys
Corrosion 30 (1974) 4, p. 115
- [107] Maurer, J. R.
Development and application of new high technology stainless alloys for marine exposure
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981), p. 11–29
- [108] Johnsen, R.; Bardal, E.
Cathodic properties of different stainless steels in natural seawater
Corrosion 41 (1985) 5, p. 296
- [109] Dillon, C. P.
Use of low interstitial 26Cr-1Mo stainless steel in chemical plants
Mater. Performance 14 (1975) 8, p. 36
- [110] Kieshey, H.; Lennartz, G.; Brandis, H.
Korrosionsverhalten hochchromhaltiger, ferritischer, chemisch beständiger Stähle (Corrosion behaviour of highly chromiumiferous, ferritic, chemically resistant steels) (in German)
Werkst. Korros. 27 (1976) 6, p. 416
- [111] Brandis, H.; Kieshey, H.
Superferrit
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981), p. 93–102
- [112] Gemmel, G.; Nordin, S.
Monit[®] and 904L –two high alloy stainless steels for seawater applications
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981), p. 69–80
- [113] Tverberg, J. C.; Magnusson, K.
The seawater alternative, superferritic stainless steels
Stainless Steel Europe 5 (1993) 10, p. 52–55
- [114] Tuthill, A. H.
Usage and performance of nickel-containing stainless steels in both saline and natural waters and brines
Mater. Performance 27 (1988) 7, p. 47

- [115] Maurer, J. R.
Long term tests of dissimilar metal crevice corrosion in filtered seawater
Mater. Performance 33 (1994) 4, p. 51–54
- [116] Moretti, G.; Quartarone, G.; Tassan, A.; Zingales, A
Pitting corrosion behaviour of superferritic stainless steel in waters containing chloride
Werkst. Korros. 44 (1993) 1, p. 24–30
- [117] Knorr, W.; Köhler, H. J.
Ein nichtrostender Vergütungsstahl mit hohen Festigkeits- und Zähigkeitswerten für den Maschinen- und Apparatebau (A martensitic stainless steel with high strength and impact properties for chemical and mechanical engineering purposes) (in German)
Werkst. Korros. 32 (1981) 9, p. 371
- [118] DIN EN 10088-3 (09/2005)
Nichtrostende Stähle – Teil 3: Technische Lieferbedingungen für Halbzeug, Stäbe, Walzdraht, gezogenen Draht, Profile und Blankstahlerzeugnisse aus korrosionsbeständigen Stählen für allgemeine Verwendung
DIN EN 10088-3 (12/2014)
Stainless steels – Part 3: Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes (in German)
Beuth Verlag GmbH, Berlin
- [119] Steel-iron material data sheets SEW 400 (2/1997)
Nichtrostende Walz- und Schmiedestähle (Stainless rolled steels and forged steel) (in German)
Verlag Stahleisen mbH, Düsseldorf
- [120] Brochure
Korrosionsbeständigkeit der austenitischen Chrom-Nickel-Stähle gegenüber Meerwasser
(Corrosion resistance of austenitic chromium-nickel-steels in seawater) (in German)
Informationstelle Edelstahl Rostfrei, Düsseldorf
- [121] Sedriks, A. J.
New stainless steels for seawater service
Corrosion 45 (1989) 6, p. 510
- [122] Bock, H. E.; Lennartz, G.
Verhalten von hochlegierten Chromvergütungsstählen in Meerwasser unter besonderer Berücksichtigung der H-induzierten Spannungsrißkorrosion (behaviour of high-alloyed of chromium tempering steels in seawater under special consideration of the H-induced stress corrosion cracking) (in German)
in: Behrens, D.; Rahmel, A. “Ergebnisse des Forschungs- und Entwicklungsprogramms ‘Korrosion und Korrosionsschutz’”, vol. 3 (1981–1983), p. 455–463
DECHEMA e. V., Frankfurt am Main
- [123] Lennox jr., T. J.; Peterson, M. H.
Corrosion resistance and cathodic protection of recently developed stainless steel alloys in sea water
Mater. Performance 15 (1976) 6, p. 24
- [124] Lennartz, G.
Verhalten von hochlegierten Chromvergütungsstählen in Meerwasser unter besonderer Berücksichtigung der H-induzierten Spannungsrißkorrosion (behaviour of high-alloyed of chromium tempering steels in seawater under special consideration of the H-induced stress corrosion cracking) (in German)
Ergebnisse des Forschungs- und Entwicklungsprogramms “Korrosion und Korrosionsschutz”
Werkst. Korros. 35 (1984) 6, S. 301
- [125] Bock, H. E.
Verhalten von hochlegierten Chromvergütungsstählen und aushärtbaren nichtrostenden Stählen in Meerwasser unter besonderer Berücksichtigung der H-induzierten Spannungsrißkorrosion (behaviour of high-alloyed chromium tempering steels and hardening stainless steels in seawater under special consideration of the H-induced stress corrosion cracking) (in German)
Ergebnisse des Forschungs- und Entwicklungsprogramms “Korrosion und Korrosionsschutz”
Werkst. Korros. 35 (1984) 6, S. 303

- [126] Tenge, P.; Gjertsen, G.
Corrosion fatigue cracking from surface defects in marine propeller blades
7. Scandinavian Corrosion Congress, Trondheim, (1975), p. 279–296
- [127] DIN EN 10088-2 (09/2005)
(Nichtrostende Stähle – Teil 2: Technische Lieferbedingungen für Blech und Band aus korrosionsbeständigen Stählen für allgemeine Verwendung)
DIN EN 10088-2 (12/2014)
Stainless steels – Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes (in German)
Beuth Verlag GmbH, Berlin
DIN EN 10088-3 (09/2005)
Nichtrostende Stähle – Teil 3: Technische Lieferbedingungen für Halbzeug, Stäbe, Walzdraht, gezogenen Draht, Profile und Blankstahlerzeugnisse aus korrosionsbeständigen Stählen für allgemeine Verwendung
DIN EN 10088-3 (12/2014)
Stainless steels – Part 3: Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes (in German)
Beuth Verlag GmbH, Berlin
- [128] Stahl-Eisen-Werkstoffblätter SEW 410 (5/1988)
Nichtrostender Stahlguß; Technische Lieferbedingungen
(Stainless cast steel, technical delivery condition) (in German)
Verlag Stahleisen mbH, Düsseldorf
- [129] Clark, C. A.; Guha, P.
Improvements in corrosion resistance, mechanical properties and weldability of duplex austenitic/ferritic steels
Werkst. Korros. 34 (1983) 1, p. 27–31
- [130] Glover, T. J.
Recent developments in corrosion-resistant metallic alloys for construction of seawater pumps
Mater. Performance 27 (1988) 7, p. 51
- [131] Koren, M.; Hochörtler, G.
Eigenschaften des ferritisch-austenitischen Stahles
X3CrNiMoN 26 6 4
(Properties of the ferritic-austenitic steel X3CrNiMoN 26 6 4) (in German)
Stahl Eisen 102 (1982) 10, p. 509
- [132] Machin, R.; Guha, P.
The use of potentiostatic techniques in the development of improved stainless steels for chemical plant
Werkst. Korros. 25 (1974) 1, p. 40
- [133] Larson, B.; Gripenberg, H.; Mellström, R.
Special stainless steels for topside equipment on offshore platforms
Stainless Steel '84 (Proc. Conf.), Göteborg, September 1984, p. 452
The Institute of Metals, London, 1985
- [134] Carpenter, M. D.; Francis, R.; Philips, L. M.; Oldfield, J. W.
Electrochemical tests to assess resistance to crevice corrosion in seawater of some duplex stainless steels
Br. Corros. J. 21 (1986) 1, p. 45
- [135] Desolneux, J. P.
Korrosionsprobleme in chlorhaltigen Medien: Lösungsmöglichkeiten durch einige nichtrostende Spezialstähle
(Corrosion problems in chlorine containing media: possible solutions by some stainless special steels)
(in German)
Werkst. Korros. 28 (1977) 5, p. 325
- [136] Mayoud, R.; Béchet, S.
Uranus® 50 –half a century of successful experience
Molybdenum Mosaic 7 (1984) 1, p. 15
- [137] Product Information: L4/3m/8.86/LA7, Aug. 1986
Ferralium® Alloy 255 –hochfester korrosionsbeständiger Edelstahl
(Ferralium® Alloy 255 –high-strength corrosion resistant noble steel)
(in German)
Langley Alloys Ltd., Slough, Berks. (GB)
- [138] Davis, J. A.; Gehring jr., G. A.
The effect of velocity on the sea water corrosion behaviour of high performance ship materials
Mater. Performance 14 (1975) 4, p. 32

- [139] Burnell, G.; Hardie, D.; Parkins, R. N. Stress corrosion and hydrogen embrittlement of two precipitation hardening stainless steels
Br. Corrosion J. 22 (1987) 4, p. 229
- [140] Herbsleb, G.
Korrosionsverhalten von Rohren aus Titan und nichtrostenden Stählen bei der Prüfung in einer Meerwasser-Kreislaufanlage für Korrosionsversuche an Kondensatorrohren
(Corrosion behaviour of titanium pipes and stainless steels during tests in a seawater-circulation plant for corrosion tests on condenser pipes) (in German)
Arch. Eisenhüttenwes. 49 (1978) 11, p. 545
- [141] Wallén, B.; Henrikson, S.
Effect of chlorination on stainless steels in seawater
Werkst. Korros. 40 (1989) 10, p. 602
- [142] Wilms, M. E.; Gadgh, V. H.; Krougman, J. M.; Ijsseling, F. P.
The effect of sigma phase precipitation at 800 °C on the corrosion resistance in seawater of a high-alloyed duplex stainless steel
Corros. Sci. 36 (1994) 5, p. 871–881
- [143] DIN 50930-4 (02/1993)
Korrosion der Metalle; Korrosion metallischer Werkstoffe im Innern von Rohrleitungen, Behältern und Apparaten bei Korrosionsbelastung durch Wässer; Beurteilung der Korrosionswahrscheinlichkeit nichtrostender Stähle
DIN EN 12502-4 (03/2005)
Protection of metallic materials against corrosion – Guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 4: Influencing factors for stainless steels
Beuth Verlag GmbH, Berlin
- [144] Kügler, A.; Lennartz, G.; Bock, H. E.
Natur-Korrosionsversuche mit nichtrostenden Stählen auf Helgoland (Natur-corrosion tests with stainless steels on Helgoland) (in German)
Stahl Eisen 96 (1976), p. 21–27
- [145] Kügler, A.; Bohnenkamp, K.; Lennartz, G.; Schäfer, K.
Einfluß des Molybdängehaltes nichtrostender austenitischer Stähle auf die Korrosionsbeständigkeit in Seewasser bei Naturversuchen auf Helgoland (Influence of the molybdenum content of stainless austenitic steels on the corrosion resistance in seawater during nature tests on Helgoland) (in German)
Stahl Eisen 92 (1972) p. 1026–1030
- [146] Bock, H. E.; Kügler, A.; Lennartz, G.; Michel, E.
The behaviour of highly alloyed materials in sea water
Schiff und Hafen (1983) 2, p. 18–23
- [147] Arlt, N.; Drodten, P.; Grimme, D.; Lennartz, G.; Michel, E.; Schwenk, W.
Korrosionsverhalten von niedrig- und hochlegiertem sowie beschichtetem Stahl bei ungestörter Langzeitauslagerung in natürlichem Meerwasser (Corrosion behaviour of low- and high-alloyed as well as coated steel during undisturbed long-time exposure in natural seawater) (in German)
Stahl Eisen 99 (1990), p. 71–75
- [148] Baker, D. W.; Heaton, W. E.; Patient, B. C.
The evaluation of stainless steels for condenser tubes nest construction
Corros. Sci. 12 (1972) 3, p. 247
- [149] Thomas, D. E.; Lucas, K. E.; Peterson, M. H.; Christian, D. K.
Effects of electrolytic chlorination on marine materials
Mater. Performance 27 (1988) 7, p. 36
- [150] Company information, No. 34, 1967
International Nickel Deutschland GmbH, Düsseldorf
- [151] Covert, R. A.; Todd, B.; Weiden, B. A.
IMAS 69, International Marine and Shipping Conference, London, June 1969, Sekt. 11, p. 21
- [152] Ventura, G.; Traverso, E.; Mollica, A.
Effect of NaClO biocide additions in natural seawater on stainless steel corrosion resistance
Corrosion 45 (1989) 4, p. 319
- [153] Scott, P. J. B.; Davies, M.
Microbiologically influenced corrosion of alloy 904L
Mater. Performance 28 (1989) 5, p. 57

- [154] Schäfer, K.
Korrosionstagung, Travemünde, March 1972
- [155] Leistikow, S.; Simen, R.; Wolf, I.
Verdeckte Lochkorrosion am Werkstoff Nr. 1.4571 in stagnierendem Meerwasser (Covered pitting corrosion of material no. 1.4571 in stagnant seawater) (in German) *Werkst. Korros.* 38 (1987) 7, p. 380
- [156] Baker, D. W. C.; Heaton, W. E.; Patient, B. C.
The evaluation of stainless steels for condensor tubes nest construction *Corros. Sci* 12 (1972) 3, p. 247
- [157] Dexter, S. C.; Gao, G. Y.
Effect of seawater biofilms on corrosion potential and oxygen reduction of stainless steel *Corrosion* 44 (1988) 10, p. 717
- [158] Feller, H. G.
Untersuchungen der Kavitationskorrosion an Pumpenwerkstoffen in Meerwasser (Tests of the cavitation corrosion in pump materials in seawater) (in German) *Werkst. Korros.* 33 (1982) 5, p. 288
- [159] ASTM G48-97e1
Standard test methods for pitting and crevice corrosion resistance of stainless steels and related alloys by use of ferric chloride solution
ASTM American Society for Testing and Materials, West Conshohocken (PA/USA)
- [160] Herbsleb, G.; Westerfeld, K.-J.
Der Einfluß von Stickstoff auf die korrosionschemischen Eigenschaften lösungsgeglühter und angelassener austenitischer 18/10 Chrom-Nickel-Molybdän-Stähle. III. Loch- und Spannungsrißkorrosionsverhalten in wäßrigen Lösungen von NaCl und MgCl₂
(The influence of nitrogen on the corrosion chemical properties of solution-annealed and annealed austenitic 18/10 chromium-nickel-molybdenum steels. III. Pitting and stress corrosion cracking behaviour in aqueous solutions of NaCl and MgCl₂) (in German) *Werkst. Korros.* 27 (1976) 7, p. 479
- [161] Diebold, A.; Weingerl, H.
Eigenschaften des schweißbaren, hoch korrosionsbeständigen Stahles X2CrNiMoN 25 22
(Properties of the weldable, highly corrosion resistant steel X2CrNiMoN 25 22) (in German) *Werkst. Korros.* 25 (1974) 3, p. 175
- [162] Grundmann, R.; Gümpel, P.; Ladwein, Th.
Eigenschaftsprofil des neuentwickelten Stahls X 2 CrNiMnMoN 23 17 6 4 (Properties of the newly developed steel X 2 CrNiMnMoN 23 17 6 4) (in German) *Werkst. Korros.* 41 (1990) 1, p. 19
- [163] Bock, H. E.; Kohl, H.; Bäumel, A.; Rockel, M. B.
Korrosionsverhalten eines seewasserbeständigen, nichtmagnetisierbaren Chrom-Nickel-Molybdän-Stahles hoher Festigkeit (Corrosion behaviour of a seawater resistant, non-magnetizable chromium-nickel-molybdenum steel of high strength) (in German) *Arch. Eisenhüttenwes.* 44 (1973) 11, p. 877
- [164] Oldfield, J. W.
Crevice corrosion resistance of stainless steels in marine environments. The influence of nitrogen, manganese, and sulphur
Mater. Performance 27 (1988) 7, p. 57
- [165] Lennartz, G.; Kiesheyer, H.
Korrosionsverhalten eines seewasserbeständigen, nicht magnetisierbaren Chrom-Nickel-Molybdän-Stahls hoher Festigkeit (Corrosion behaviour of a seawater resistant, non-magnetizable chromium-nickel-molybdenum steel of high strength) (in German) *Arch. Eisenhüttenwes.* 43 (1972) 8, p. 639
- [166] Holthe, R.; Bardal, E.; Gartland, P. O.
Time dependence of cathodic properties of materials in seawater
Mater. Performance 28 (1989) 6, p. 16
- [167] Eden, A.
Recent advances in the use of stainless steel for offshore and seawater applications
Anticorros. Methods Mater. 26 (1979) 11, p. 7–13

- [168] Kohl, H.
Inter- and transcrystalline stress corrosion cracking austenitic Mn- and CrNi steels in seawater
Werkst. Korros. 23 (1972) 11, p. 984
- [169] Bäuml, A.; Bachmann, F.
Verhalten austenitischer Manganstähle in Meerwasser
(behaviour of austenitic manganese steels in seawater) (in German)
Arch. Eisenhüttenwes. 43 (1972) 8, p. 631
- [170] Gallagher, P.; Nieuwhof, A.; Tausk, R. J. M.
Experiences with seawater chlorination on copper alloys and stainless steels
Working party report on marine corrosion of stainless steels: chlorination and microbial effects
EFC Publication No. 10
The Institute of Materials, London, 1993, p. 73-91
- [171] Scotto, V.; DiCinito, R.; Marcenero, G.
The influence of marine aerobic microbial films on stainless steel corrosion behaviour
Corros. Sci. 25 (1985), p. 185
- [172] Gartland, P. P.
Aspects of testing stainless steels for seawater application
Working party report on marine corrosion of stainless steels: chlorination and microbial effects
- [173] Larsson, B.; Gripenberg, H.; Mellström, R.
Special stainless steels for topside equipment on offshore platforms
Stainless Steel '84 (Proc. Conf.), Göteborg (Schweden), September 1984, p. 452
The Institute of Metals, London (GB), 1985
- [174] Bernhardsson, S.; Mellstrom, R.
Performance of a highly alloyed stainless steel in marine environments
Anticorros. Methods Mater. 32 (1985) 4, p. 7
- [175] Nordin, S.; Wallén, B.; Eriksson, G.
Optimization of high-pressure piping in reverse osmosis plants
acom (1985) 3, p. 6
- [176] Wallén, B.
A stainless steel for seawater service
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981), p. 31-44
- [177] Baroux, B.; Maitrepierre, P.; Decléty, P.
The behaviour of Ugin NSCD in seawater
Adv. Stainless Steels Seawater Appl., Proc. Symp. (1981), p. 103-112
- [178] Malik, A. U.; Siddiqi, N. A.; Andijani, N.
Corrosion behaviour of some highly alloyed stainless steels in seawater
Desalination 97 (1994) 1-3, p. 189-197
- [179] Hack, H. P.
Crevice corrosion behaviour of molybdenum-containing stainless steels in seawater
Mater. Performance 22 (1983) 6, p. 24-30
- [180] Streicher, M. A.
Analysis of crevice corrosion data from two seawater exposure tests on stainless alloys
Mater. Performance 22 (1983) 5, p. 37-50
- [181] Johnsen, R.
North sea experience with the use of stainless steels in seawater applications
Working party report on marine corrosion of stainless steels: chlorination and microbial effects
EFC Publication No. 10, The Institute of Materials, London, 1993
- [182] Altpeter, E.
Ni-Legierungen in strömendem Meerwasser
(Ni alloys in flowing seawater) (in German)
Ergebnisse des Forschungs- und Entwicklungsprogramms "Korrosion und Korrosionsschutz"
Werkst. Korros. 43 (1992) 10, p. 505
- [183] Altpeter, E.; Jasner, M.
Resistance to localized corrosion of stainless steels and nickel-base alloys in hot seawater – experience from the German North Sea
Corrosion 93, Paper No. 93499 (Proc. Conf.)
NACE (Houston/Texas), 1993

- [184] Jasner, M.; Herda, W. R.
Crevice corrosion behaviour of high-alloyed austenitic steels and nickel-base alloys in seawater with and without addition of chlorine
EUROCORR, European Corrosion meeting, Volume 2 (1994), p. 143-154
Chameleon Press, London
- [185] Franz, F.; Heitz, E.; Herbsleb, G.; Schwenk, W.
Strömungsabhängigkeit der Lochkorrosion eines CrNi-Stahles in NaCl-Lösung
(Flow-dependence of the pitting corrosion of a CrNi steel in NaCl solution) (in German)
Werkst. Korros. 24 (1973) 2, p. 97-105
- [186] Herbsleb, G.
Das Korrosionsverhalten passivierbarer nichtrostender Stähle in Wasser unter reduzierenden Bedingungen bei gleichzeitiger abrasiver Beanspruchung
(The corrosion behaviour of passivable stainless steels in water under reducing conditions with simultaneous abrasive demand) (in German)
GWF-Wasser/-Abwasser 123 (1982) 7, p. 343-355
- [187] DIN 50917-2 (02/1987)
Korrosion der Metalle; Naturversuche; Naturversuche in Meerwasser
DIN EN ISO 11306 (04/1998)
(Corrosion of metals and alloys – Guidelines for exposing and evaluating metals and alloys in surface sea water
Beuth Verlag GmbH, Berlin
- [188] Anonymous
Werkstoffe für Meerwasseranlagen
(Materials for seawater plants)
(in German)
International Nickel Deutschland GmbH, Düsseldorf
- [189] LaQue, F. L.
Corrosion by sea water. behaviour of metals and alloys in sea water
in: H. H. Uhlig "Corrosion Handbook", 6. ed., p. 383-430
John Wiley & Sons, Inc., New York, 1958
- [190] Friend, W. Z.
Nickel
in: LaQue, F. L.; Copson, H. R. "Corrosion resistance of metals and alloys", 2. edition, p. 467-513
Reinhold Publishing Corporation, New York, 1963
- [191] Kahn, D. K.; Mukherjee, K. P.; Banerjee, T.
N.M.L. Tech. J. 8 (1966) November, p. 17
- [192] Southwell, C. R. et al.
Naval Research Lab. Rep. NRL 6592, October 1967, p. 14
- [193] Beccaria, A. M.; Fiordiponti, P.; Mattogno, G.
The effect of hydrostatic pressure on the corrosion of nickel in slightly alkaline solutions containing Cl⁻ ions
Corros. Sci. 29 (1989) 4, p. 403
- [194] Niederberger, R. B.; Ferrara, R. J.; Plummer, F. A.
Corrosion of nickel alloys in quiet and low velocity sea water
Mater. Protection Performance 9 (1970) 8, p. 18
- [195] Miska, K. H.
Most non-ferrous metals and alloys weather well
Mater. Eng. 80 (1974) p. 64
- [196] DIN 17743 (09/2002)
Nickel-Knetlegierungen mit Kupfer – Zusammensetzung
(Wrought nickel alloys with copper – Chemical composition) (in German)
Beuth Verlag GmbH, Berlin
- [197] DIN 17730 (07/1971)
Nickel- und Nickel-Kupfer-Gußlegierungen; Gußstücke
(Nickel and nickel-copper alloys; castings) (in German)
Beuth Verlag GmbH, Berlin
- [198] Vreeland, D. C.; Bedford, S. T.
Effects of cathodic protection on crevice corrosion in seawater
Mater. Protection Performance 9 (1970) 8, p. 31
- [199] Stern, G.; Bayles, B. J.; Chukumerije, O. H.
Choosing materials for desalting by distillation
Chem. Eng. 87 (1980) 19, p. 171

- [200] Bom, P. R.
Selection of alloys for multi-stage flash-distillation plant
Marine Corrosion Conference, Biarritz, June 1969, report 5
- [201] Songa, T.; Careri, G.
The problem of materials in sea water desalination plants
Metallurgia Italiana (1967) 3, p. 181
- [202] Thomas, E. D.; Lucas, K. E.; Peterson, M. H.; Christian, D. K.
Effects of electrolytic chlorination on marine materials
Mater. Performance 27 (1988) 7, p. 36
- [203] Efrid, K. D.
Failure of Monel® Ni-Cu-Al alloy K-500 bolts in seawater
Mater. Performance 24 (1985) 4, p. 37
- [204] Maylor, J. B.
Corrosion resistance of high nickel alloys in sea water
Anitcorros. Methods Mater. 25 (1978) 7, p. 3–9
- [205] Lennox jr., T. J.; Peterson, M. H.; Billow, C. W.
Corrosion resistance and response to cathodic protection of advanced alloys in sea water
Mater. Performance 22 (1983) June, p. 49–55
- [206] v. Baeckmann, W.; Schwenk, W.; Prinz, W.
Handbuch des kathodischen Korrosionsschutzes, 3. ed.
(Handbook of the cathodic corrosion protection) (in German)
Verlag Chemie, Weinheim, 1989
- [207] Vassilev, K. I.; Petrov, M. D.; Krasteva, V. Z.
Über den Einfluß des Gefüges von Zinklegierungen auf die Schutzfähigkeit von Zinkanoden in Seewasser
(On the influence of structures of zinc alloys on the protection ability of zinc anodes in seawater) (in German)
Werkst. Korros. 25 (1974) 8, p. 587
- [208] Kurr, G. W.
Zinc anodes – underground uses for cathodic protection and grounding
Mater. Performance 18 (1979) 4, p. 34
- [209] Jensen, F. O.; Rygg, A.; Setre, O.
Testing of zinc anodes for offshore buried pipelines at elevated temperatures
Mater. Performance 17 (1978) 9, p. 9–15
- [210] Houghton, C. J.; Ashworth, V.
The performance of commercial zinc and aluminum anodes in hot sea-bed mud
Mater. Performance 21 (1982) 7, p. 20–30
- [211] Haney, E. G.
Zinc sacrificial anode behaviour at elevated temperatures
Mater. Performance 25 (1986) 4, p. 31–34
- [212] Ashworth, V.; Googan, C. G.; Scantlebury, J. D.
Intergranular dissolution of zinc alloy sacrificial anodes in seawater at elevated temperatures
Br. Corros. J. 14 (1979) 1, p. 46
- [213] ASTM B418-95a
Standard specification for cast and forged galvanic zinc anodes
ASTM American Society for Testing and Materials, West Conshohocken (PA/USA)
- [214] ASTM B428-93
Standard test method for angle of twist in rectangular and square copper and copper alloy tube
ASTM American Society for Testing and Materials, West Conshohocken (PA/USA)
- [215] Friehe, W.; Schwenk, W.
Korrosionsverhalten feuer- und spritzverzinkter Stahlbleche mit und ohne Schutzanstrich auf dem Seewasserversuchsstand des VDEh in Helgoland
(Corrosion behaviour of hot-dip galvanised and zinc sprayed sheet steels with and without protective coatings on the VDEh station for seawater tests on Helgoland) (in German)
Stahl Eisen 92 (1972) 21, p. 1030–1035
- [216] Friehe, W.; Schwenk, W.
Korrosionsverhalten von Stahlblechen mit unterschiedlichen Beschichtungssystemen in Meerwasser
(Corrosion behaviour of sheet steel with different coating systems in seawater) (in German)
Stahl Eisen 100 (1980) 13, p. 696–703

Waste Water (Municipal)

Authors: G. Heim, K. Reeh / Editor: R. Bender

Waste Water (Municipal) – Survey Table

The evaluation of the corrosion behaviour of the individual materials is based on practical experience and conditions described in the text. Only those materials have been taken into account which usually come into contact with waste water.

Material	Behaviour*
Unalloyed and low-alloy steels/cast steel	⊕ to –
Unalloyed cast iron and low-alloy cast iron	+ to –
High-alloy cast iron, silicon cast iron	
Structural steels with up to 12% chromium	
Ferritic chromium steels with more than 12% chromium	+ to –
Ferritic-austenitic steels with more than 12% chromium	+ to –
Austenitic CrNi steels	+ to –
Austenitic CrNiMo(N) steels	+ to –
Austenitic CrNiMoCu(N)-steels	+ to –
Special iron-based alloys	
Nickel	
Nickel-chromium alloys	
Nickel-chromium-iron alloys (without Mo)	
Nickel-chromium-molybdenum alloys	
Nickel-copper alloys	
Nickel-molybdenum alloys	
Other nickel alloys	
Zinc, cadmium and their alloys	+ to –

* + resistant/ ⊕ fairly resistant/ – unsuitable. Where no indication of corrosion resistance is made, experimental data are not available.

Introduction

Waste water is defined as drainage water which has been changed by utilisation and all that which flows into a sewerage system [1].

Types of waste water include:

- sanitary sewage
- storm water
- infiltrating water
- combined water
- cooling water.

The behaviour of materials in waste water systems is influenced by the composition of the water, the construction and the operating conditions, such as the temperature and flow rate.

In selecting materials it must be taken into account that e.g. in the case of operating faults, there may be unintentional release of harmful substances in different amounts and concentrations into the sewerage system.

Construction components of estate drainage systems within buildings, such as pipes, fittings, and pipe couplings for the connection, transporting, and collection pipelines must be suitable for a maximum waste water temperature of 368 K (95 °C) at an ambient temperature of 283 K (10 °C). The corresponding usability is checked in a system test under cyclic and continuous loading conditions [2].

For underground waste water sewers and pipelines, the pipes, fittings, and pipe connections must be suitable for diameters

- up to DN 350 for water temperatures of 318 K (45 °C)
- up to DN 400 for water temperatures of 308 K (35 °C)

at an ambient temperature of 283 K (10 °C) [2]. If process waste water has a higher temperature, then it must be cooled before it is discharged into the public waste water system.

In the case of plastic pipes, for example, the waste water temperature is decisive for the choice of material and its service life. For other materials, an increased attack of the material must be assumed at higher temperatures.

In components installed underground, particularly gravity-flow sewers, the temperature of both the waste water and the air space has a marked influence on the biogenic corrosion reactions occurring on the sewer walls above the level of the water.

To maintain aerobic conditions and to avoid the formation of deposits, the flow conditions (flow rate and gradient) are particularly important in waste water pipelines. Therefore, for the different types of pipes used for estate drainage, minimum gradients which depend on the individual nominal diameter are specified in [3].

– *Behaviour of materials* –

During transport of mixtures of water and solids, as is usual in waste water sewers and pipelines, abrasion occurs in the region of the bottom of the pipe as a result of the action of the solids in the waste water. This abrasion depends on the

- pipe material
- pipe diameter
- flow rate
- density, grain size and strength of the material.

Particularly in steep and bent sections, abrasion must be expected. Very different testing procedures have been proposed to determine the abrasion behaviour, e.g. Böhm's disc, sand-blast test, and the Bauch test. The most widely used test is the so-called Darmstadt procedure of Kirschmer [4].

In spite of careful planning and execution, maintenance of the pipelines cannot be avoided. It is not always possible to select the cross-section and the gradient of the pipes so that the flow rates are always sufficient under the changing flow conditions to avoid the formation of deposits and their subsequent removal by cleaning.

Nowadays, high-pressure flushing is used almost exclusively for the cleaning of waste water pipelines. This cleaning process serves to remove any deposits and blockages, and is also a preparatory measure for pipeline inspections and, if necessary, for repairs.

– *Corrosion behaviour* –

In waste water installations, the components are loaded by the waste water on the inside (e.g. pipes) as well as on the outside (e.g. air-inlet pipes, scrapers). The functioning of metallic pipes is influenced by local attack (shallow pit and pitting corrosion). Uniform surface corrosion generally plays a secondary role. A site particularly susceptible to local corrosion is the area close to an electrically conducting contact of different metals (contact corrosion).

A macroelement arises if metals with different corrosion potentials are in metallic and electrolytic contact with one another. Therefore, the following protective measures are recommended:

- use of materials with similar corrosion potentials
- galvanic separation of the structures with differing corrosion potentials or
- cathodic protection.

This can be realised most simply in new installations by galvanic separation using insulating intermediate layers, insulating flanges or insulating components [5].

Many metals are susceptible to microbiologically induced corrosion. Damage has been observed of unalloyed steels as well as high-alloy CrNi steels. Damage is also known for copper and copper alloys as well as aluminium. Titanium is less susceptible to microbiologically induced corrosion; however, it offers favourable conditions for biofouling [6].

Unalloyed steels and cast steel

Unalloyed steels without coatings or protective films are widely used for the reinforcement of concrete buildings [7]. Their required mechanical strengths are specified in DIN 1045 [8]. Common designations are "concrete steel I–IV" with minimum yield strengths of 220 to 500 N/mm² (special reinforced concrete) and tensile strengths of 340 to 550 N/mm².

In addition to a circular cross-section (round steel), the reinforcing steels can have special shapes, e.g. twisted, knotted, ribbed, in order to produce a special adhesion effect.

Constructional steel textiles and steel mats used to reinforce concrete consist of steel rods laid at right-angles to one another with various separations and cross-sections. They are joined together by welds which are electrically conducting. These steels, along with the concrete steels of groups II to IV, require a general approval by the highest building supervision office of the relevant federal state (building department approval). This prescribed approval must be taken into account for the use of pre-stressed concrete elements, e.g. round basins or septic towers. The corresponding details are given in the standard DIN 1045 [8].

Mainly steel St 37 is used for steel constructions in the different facilities in waste water treatment plants. This collective term is used for the steels St 37.0 (UNS K02501, DIN Mat. No. 1.0254), St 37-2 (UNS K02401, 1.0037) and St 37-3 (UNS K02501, 1.0116) according to DIN EN 10025 [9].

The electrochemical behaviour of the unalloyed steel must be taken into account in steel constructions. Since concrete has a strongly alkaline reaction, sub-microscopic thin films of iron oxides are formed on the surface of the steel. This leads to the unalloyed steel in concrete becoming electrochemically more noble, i.e. it behaves as a practically resistant material. Therefore, it can be used as a cathode in an electrochemical cell [10].

In reinforced concrete basins of waste water treatment plants, there are extensive steel mats which act as cathodes with a large surface area. If these steel mats, which are in the waste water, are in electrical contact with components of unalloyed steel, it is possible that an electrochemical cell is formed by contact corrosion [11].

A metallic conducting connection can be produced during building e.g. by the unintentional contact between the steel reinforcement and an iron bracket. On the other hand, a metallic conducting connection can be produced if all metallic components have to be in electrical contact with each other for reasons of electrical protection against human contact [12]. According to the area rule, coated steel components are strongly susceptible to the anodic dissolution of iron as pitting corrosion, particularly where there is a small defect in the coating [11]. This susceptibility can be estimated by the ratio of areas of the cathodic surface S_c (steel and concrete) to the anodic surface (S_a) (steel in waste water). For $S_c:S_a = 100:1$; pitting corrosion rates in the order of 1 mm/a (40 mpy) can be expected [13].

Contact corrosion is also possible if unalloyed steel is in contact with other materials which also act as cathodes, e.g. stainless steels. The area ratio $S_c:S_a$ is also decisive in this case; however, corrosion only occurs if, e.g. large area cathodes of stain-

less steel are present. For cathodes with smaller surface areas, e.g. stainless steel screws, contact corrosion is not expected.

As a protective measure against the electrochemical cell formation described above, it is recommended to install a “local cathodic corrosion protection” (see Figure 1) [14, 15].

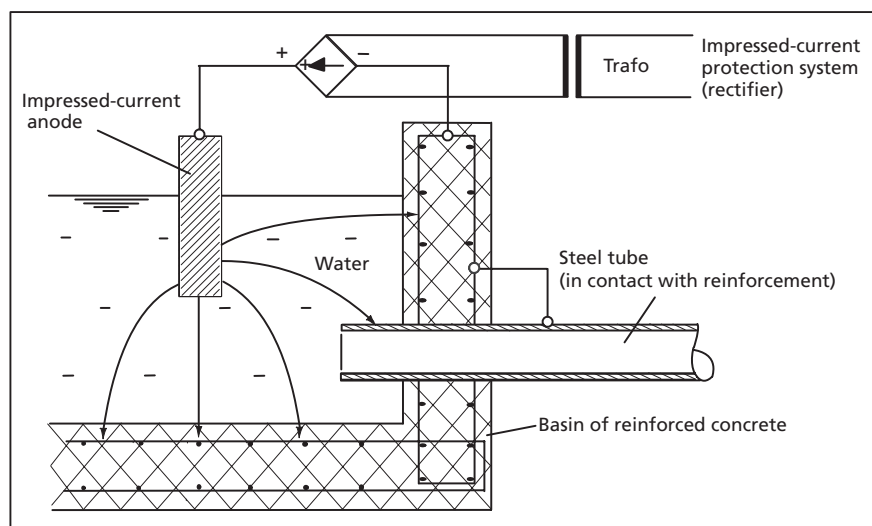


Figure 1: Local cathodic corrosion protection in a clarification basin [14]

If there is a gap between two components of unalloyed steel, then there is a possibility of crevice corrosion. For example, this can be the case for screwed connections. In principle, crevice corrosion is an aeration cell which results from a difference between the oxygen concentration in the crevice (low oxygen content) and that outside the crevice (higher oxygen content). This type of corrosion only occurs at critical crevice widths [16]. If the width of the crevice lies markedly above or below the critical value, there is no corrosive attack. This also explains the practical observation that corrosive attack does not occur in every crevice [13].

Another example for a possible aeration cell occurs with suction scrapers made of unalloyed steel in the clarification basin. In this case, the difference in aeration arises from the oxygen deficiency in the bottom deposit and the relatively high oxygen content in the waste water [17].

A further large application area of unalloyed steels are steel components which are used in connection with protective measures.

Unalloyed cast iron

Cast-iron sewer components for the drainage of buildings and estates or for the drainage of traffic areas include the following types of castings: drains for cellars, floors, bathrooms, balconies, rainwater, courtyards, flat roofs, as well as cleaning stoppers, cut-off devices against backpressure, sliding gates, waste water pumps, separators for light liquids (petrol traps, heating oil traps), heating oil barriers, fat separators, potato starch separators as well as covers and caps of e.g. courtyard drains, drainage gutters, bridge drains and manhole steps.

Some of these are the so-called BEGU constructions (cast concrete).

Coating of cast-iron sewer components is not necessary for reasons of corrosion protection. A surface treatment, e.g. for optical reasons, is optional for the manufacturer. This statement is now included in a number of standards for cast articles used in sewer systems. Surface treatment is carried out exclusively for cosmetic reasons; in the past, these have been thin coatings. Some castings are also epoxidised or enamelled.

Sanitary equipment, e.g. cast-iron bath tubs, is usually enamelled. Cast-iron drain pipes with sleeveless couplings (SML) and nominal diameters DN 50 to DN 300 in overall lengths of up to 3 m are standardised in DIN 19522, Part 1 [18]. They can be used to replace the previously standard cast-iron drainpipes with sleeves (GA) (which are still common) because since the outer diameters are the same.

Bridge pipelines are usually made of cast-iron drainpipes up to DN 600 and overall lengths of up to 6 m. The pipes consist of cast iron with lamellar graphite inclusions according to DIN EN 1561 (grade at least EN-GJL-150 (0.6015, GG-15), i.e. an iron-carbon alloy whose carbon is finely dispersed in the metallic matrix as lamellae) [19]. This particular microstructure gives the material very high damping properties. Even without special insulation, cast-iron drainpipes are robust, have a long service life and are quiet during operation. Additionally, according to its building material classification A 1 (flammable), no particular fire-protective wrapping is necessary. Table 1 summarises the properties of the material [19].

Material characteristics and properties	
Density:	approx. 7.2 kg/dm ³
Tensile strength:	≥ 150 N/mm ² for fittings ≥ 180 N/mm ² for pipes
Compressive strength:	approx. 3 to 4 times the value of the tensile strength
Shear strength:	1.1 to 1.6 times the value of the tensile strength
Circular compressive strength/pipe flattening resistance:	≥ 300 N/mm ²
Modulus of elasticity:	8 × 10 ⁴ to 12 × 10 ⁴ N/·mm ²

Table 1: Material characteristics and properties of cast-iron drainpipes [19]

Table 1: Continued

Material characteristics and properties	
Poisson no.:	~ 0.3
Longitudinal coefficient of expansion:	0.0105 mm/mK (between 273 and 373 K) (0 and 100 °C)
Thermal conductivity:	50–60 W/mK (at 293 K (20 °C))
Thermal resistance, without significant alteration of the mechanical properties:	up to 673 K (400 °C)
Chemical resistance:	pH 2 to 12 for domestic use of the pipeline

Table 1: Material characteristics and properties of cast-iron drainpipes [19]

For these pipes there is an extensive range of fittings and rubber-sealed couplings with stainless steel joiners made of 1.4510 (cf. UNS S43035) and sealing rings of EPDM (ethylene-propylene-diene rubber). These are resistant to ageing and also resistant to boiling water. The special principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), apply to the pipe couplings.

SML pipes and fittings are supplied with a red-brown ground coat which contains synthetic iron oxide pigments [18]. The ground coat is applied to the inside and outside of the fittings by dipping and to the pipes by spraying. The pipes are coated on the inside with a durable pitch-epoxide resin coating which offers additional protection against chemical and mechanical influences, and its smooth surface improves the flow behaviour in the pipes.

If necessary, the external ground coat of the pipes and fittings can be covered with commercially available paints and coating systems used for steel constructions.

In agreement with the technical delivery conditions specified in DIN 19522, Part 2, the phosphorus content of the cast iron must lie below 0.9 mass% [18].

A special type of sleeveless cast-iron drainpipes are the so-called EML drainpipes which are supplied with a internal enamel coating that is very resistant to acids and alkaline solutions.

In general, sealing collars made of EPDM are supplied with the couplings. They can be used between approximately –223 K (50 °C) and + 393 K (120 °C), depending on the medium being carried. These collars are resistant to a wide range of different media and substances under normal conditions.

For special requirements in which the EPDM seals are not resistant, special sealing collars of NBR (based on nitrile rubber) are used. Sealing collars made of fluorinated rubber are also possible; however, they are very expensive.

Ductile sewer pipes are standardised in DIN EN 598 for gravity-flow sewers and forced-flow pipelines pressurised up to 6 bar (600 kPa) in the nominal diameters DN 100 to DN 2000 [20]. They are used for combined, sanitary or storm water pipe-

lines in local canalisation systems, in free terrain, in wooded areas, in rivers, on steep slopes, and in groundwater-protected areas. The material characteristics are listed in Table 2 [21].

Material characteristics and properties	
Tensile strength:	min. 400 N/mm ²
0.2% yield strength:	min. 300 N/mm ²
Ductile yield:	min. 7%
Bursting strength:	min. 300 N/mm ²
Crushing strength	min. 550 N/mm ²
Longitudinal bending strength	min. 420 N/mm ²
Hardness	max. 250 HB 5/750
Modulus of elasticity:	170 kN/mm ²
Longitudinal elongation	10 ⁻⁵ m/m · K
Ductility of the alumina cement mortar lining	≤ 4%

Table 2: Material characteristics and properties of ductile sewer pipes [21]

The pipes are made with the bell-and-spigot coupling system Tyton® in overall lengths of 6 m. They are generally coated on the outside with a spray galvanised coating and top coat according to DIN 30674, Part 3 [20] and have an internal lining of aluminous cement mortar according to DIN 2614 [22]. The pipes are supplemented with special fittings, such as e.g. tapping saddle pieces 45° or 90° or shaft couplings with Tyton® bell-and-spigot joints to ensure that all the pipeline components are permanently leakproof. This prevents the infiltration of surrounding water into the pipe or leakage of the medium flowing through it into the ground.

To check the suitability of the sewer pipes for their use as a one-pipe system for waste water pipelines in drinking-water protected areas, an expert's report was commissioned [23]. Table 3 summarises the results of this report. Ductile sewer pipes are particularly suitable for the repetitive tests specified in the guidelines [24] with water or air or vacuum tests [25].

The vacuum testing of ductile sewer pipes has been newly developed for this. In contrast to the water overpressure test procedure, this new test method has the advantage that it can be carried out in a few hours, it doesn't require large amounts of test water and the test itself is especially enhanced.

Requirements	Evaluation
Observance of the standards and regulatory works as well as special ordinances	The waste water pipe under examination is made of ductile cast iron and is manufactured according to DIN EN 598. The bell-and-spigot coupling system Tyton® corresponds to DIN 28603.
High safety factor against the expected and calculated, external and internal, static and dynamic loads High reserve safety factor or insensitivity towards not planned or not calculated additional external and internal loads	The high work capacity of ductile iron, the large longitudinal displacement, the experimental uptake of shear loads as well as a water pressure of 10 bar confirm the large safety factor against external and internal loads. For this reason, it is generally sufficient to install Tyton® shaft couplings with simple joints in buildings.
As few pipe connections as possible using long pipes, with a simple and safe assembly.	The pipe overall length is 6 m.
No ports to the pipes. Availability of all necessary accessories (complete system)	There is a complete system available that allows e.g. pressure-sealed shafts with ductile shaft pipes which have ports only in the pipe shafts
External and internal corrosion resistance of the pipe material itself and the sealing material or the external and/or internal corrosion protection	External corrosion protection according to DIN 30674, Part 3 or Part 1, 2 or 5. Internal corrosion protection with cement mortar lining according to DIN 2614 or with a special lining.
Permanently leakproof pipe materials, pipe connections and ports in the shafts with respect to waste water and gases for both internal and external overpressure as well as a vacuum	Ductile cast-iron pipes and their couplings withstand a test pressure of more than 10 bar and thus exceed the pressure of 2.4 bar for pressure-less waste water pipes by several times. Also for special applications in which the pipe coupling must remain permanently leakproof, even in case of bending and longitudinal displacement as well as decentring (areas with ground subsidence etc.) the ductile cast-iron pipe system withstands a test pressure of 10 bar without a pressure drop. Likewise, the system remains gastight for an internal gas overpressure of 1.13 bar and a vacuum of 0.5 bar.
Wear resistance	The wear resistance of the cast-iron pipework was verified using the a "tilted gutter test"

Table 3: Ductile cast-iron pipeline system for the transportation of waste water in drinking-water protection zones II [23]

Table 3: Continued

Requirements	Evaluation
Thermal resistance	The thermal resistance specified in DIN EN 476 of 318 K (45 °C) for nominal diameters up to DN 350 and 308 K (35 °C) for nominal diameters greater than DN 400 was fulfilled by the ductile cast-iron pipe.
Tangential bending ability of the pipe couplings	The tangential bending ability of the pipe coupling system Tyton [®] was verified according to DIN 4060 and also with a test pressure of 10 bar.
Axial displacement in the pipe couplings	The leakproofness during longitudinal displacement of 80 mm in the pipe coupling was verified in a test using an internal water pressure of 10 bar.
Resistance to plant roots	The resistance to plant roots was verified in a shear test based on DIN 4060.
Permanent compatibility between the materials used in the pipes, fittings, seals and mountings	Permanent compatibility between the materials used in the pipes, fittings and seals was attained by observance of DIN 4060.
Maintenance suitability	Investigations with respect to the influence of high-pressure water sprays on the cement mortar lining of the ductile cast-iron pipes showed that there was no damage caused by commonly used nozzle heads and flushing pressures up to 170 bar.

Table 3: Ductile cast-iron pipeline system for the transportation of waste water in drinking-water protection zones II [23]

The differential pressure test is used for the vacuum test and is also used to test gas pipelines for leaks. In this test, the leakproofness of the sewer pipeline is compared with the absolute leakproofness of a heat-insulated control bottle (reference vessel). This is carried out with digital differential pressure measuring equipment. The pre-requisite for this is an absolutely leakproof pipe system. Both the pipe material and the couplings must be gastight.

The test section must be sealed off from the start and end shafts by sealing cushions. These are inserted into smooth pipes with an internal coating of epoxy resin. The same applies to the sealing of house connection pipelines in inspection shafts as well as road drains with adaptor pipes. After sealing off, the pipeline is evacuated by means of a vacuum pump that works on the principle of the water jet and is connected to a compressor.

In waste water sewers and pipelines in water-protection zone II, leakproof testing must be carried out at certain intervals during operation, at least every five years. Shorter intervals may be necessary, depending on the type and loading of the sewers and pipelines [24].

In water-protection zone III, leakproof tests should be carried out according to need, generally every ten years.

Ferritic chromium steels with more than 12% chromium

Ferritic austenitic steels with more than 12% chromium

Austenitic CrNi steels

Austenitic CrNiMo(N) steels

Austenitic CrNiMoCu(N)-steels

Within the class of stainless steels, ferritic chromium steels as well as austenitic chromium-nickel steels, with and without additional molybdenum, can be used as passivable materials in waste water installations. Table 4 lists the most frequently used chromium-nickel steels, which are also listed in DIN EN 1124-1 [26].

Designation			Chemical composition, %					Pitting index	Pitting potential U_{H^+} , mV
			C	Cr	Ni	Mo	Others		
SAE 304	UNS S30400	1.4301	≤ 0.07	17–19	8–11	–	–	18	+ 250
SAE 316 L	UNS S31603	1.4435	≤ 0.03	16–18.5	11–14	2.0–2.5	–	25	+ 600
SAE 316 Ti	UNS S31635	1.4571	≤ 0.08	16–18.5	10.5–14	2.0–2.5	5xC ≤Ti ≤0.5	25	+ 600
SAE 317 LMN	UNS S31726	1.4439	≤ 0.04	16.5–18.5	12.5–14.5	4.0–5.0	N 0.12–0.20	32	+ 1200

Table 4: Stainless steels used in waste water facilities [27]

The following considerations must be taken into account if stainless steels are to be used:

- water composition
- processing
- operating conditions.

The materials are primarily selected with regards to the corrosive loading by the waste water, particularly with respect to the amount of chloride ions. These are able

to locally penetrate the passivating layer on the stainless steels in very small regions, stabilise anodes and thus lead to pitting. Reference [28] gives information on the maximum permissible chloride content for a waste water with a pH of 7. From the information given in Table 5, it can be seen that the resistance of stainless steels to pitting corrosion increases with increasing molybdenum content. This statement is confirmed, in principle, by the diagram given in Figure 2. The pitting potential U_P on the abscissa is a criterion for the resistance to pitting corrosion, i.e. the more positive this potential is, the more resistant is the stainless steel against pitting corrosion [27]. Pitting corrosion can only occur if the redox potential of the waste water is more positive than the pitting potential.

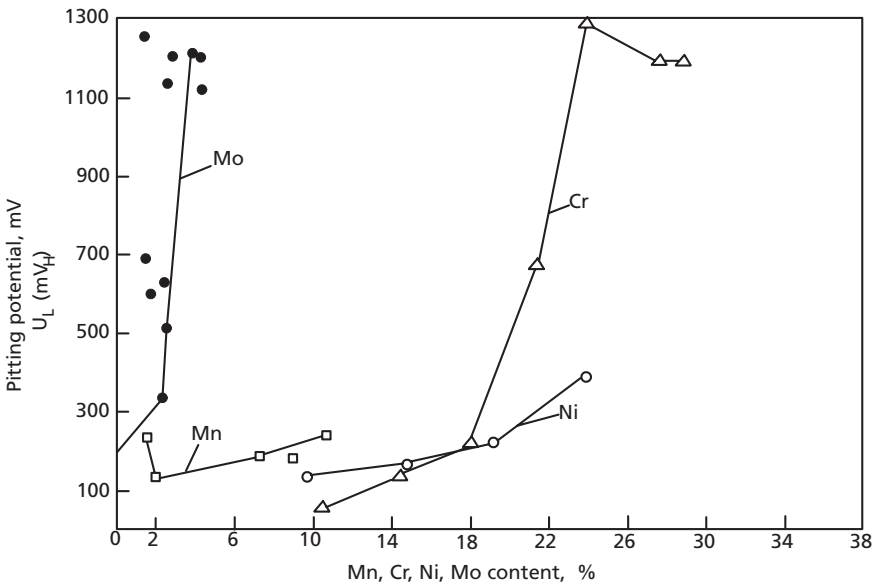


Figure 2: Influence of the alloying elements manganese, chromium, nickel and molybdenum on the pitting potentials of austenitic CrNi steels in 3 % NaCl solution [27]

DIN-Mat. No.	Designation	Chemical composition**, %				Resistance at pH 7 max. Cl content, g/l		Temperature K (°C)
		Cr	Ni	Mo	C	Pitting corrosion	Crevice corrosion	
1.4301*	SAE 304*	18	8	–	< 0.07	0.2	0.02	298 (25)
1.4306	SAE 304 L	18	8	–	< 0.03	0.2	0.02	298 (25)

*Attention: In the sensitised state, these steels have an increased susceptibility to pitting corrosion and a strongly reduced resistance to intergranular stress corrosion cracking.
 ** balance Fe

Table 5: Maximum chloride contents for pitting and crevice corrosion of stainless steels [28, 29]

Table 5: Continued

DIN-Mat. No.	Designation	Chemical composition**, %				Resistance at pH 7 max. Cl content, g/l		Temperature K (°C)
		Cr	Ni	Mo	C	Pitting corrosion	Crevice corrosion	
1.4401*	SAE 316*	18	10	2	< 0.07	1	0.2	308 (35)
1.4404	SAE 316 L	18	10	2	< 0.03	1	0.2	308 (35)
1.4436*	SAE 316*	18	12	3	< 0.07	5	1	308 (35)
1.4435	SAE 316 L	18	12	3	< 0.03	5	1	308 (35)
1.4439	SAE 317 LMN	17	13	4.5	< 0.03	10	5	334 (70)
1.4539	SAE 904 L	20	25	4.5	< 0.03	10	5	353 (80)

*Attention: In the sensitised state, these steels have an increased susceptibility to pitting corrosion and a strongly reduced resistance to intergranular stress corrosion cracking.

** balance Fe

Table 5: Maximum chloride contents for pitting and crevice corrosion of stainless steels [28, 29]

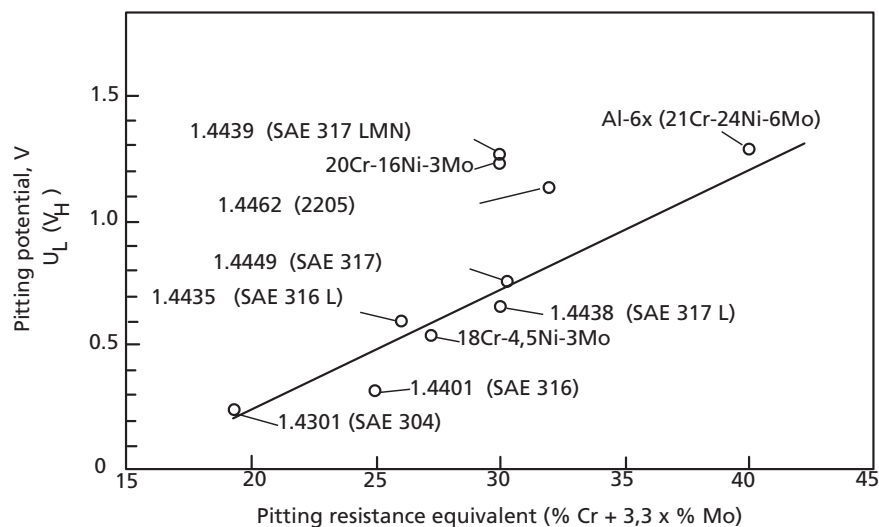


Figure 3: Dependence of the pitting potentials of austenitic CrNi steels in 1 mol/l NaCl solutions on the pitting resistance equivalent (PRE) of chromium and molybdenum [27].

Furthermore, it can be seen from Figure 2 that both manganese as well as nickel have very little influence on the pitting potential. The presence of chromium only has a favourable effect on the pitting potential when the steel contains more than 18

mass% Cr. This determination of the influence of chromium and molybdenum was the reason for the introduction of the so-called pitting resistance equivalent (PRE = % Cr + 3.3 % Mo). The larger the pitting resistance equivalent is, the more positive is the pitting potential U_p , as can be seen from Figure 3 and the corresponding values in Table 4 [27]. Generally, the N content is also included in the pitting resistance equivalent and is taken into consideration with a factor of 30.

There is a close relationship between crevice corrosion and pitting corrosion. Crevice corrosion only occurs in waste waters that contain chloride ions, and is dependent on the conditions in the crevice. Crevice widths of more than 0.5 mm are generally not critical; however, the crevice depth must also be taken into account [30]. Crevices between stainless steels and insulating materials, e.g. plastics, are particularly susceptible to crevice corrosion. Experience shows that the most important potential for crevice corrosion, the critical potential U_c , is clearly more negative than the pitting potential U_p , as shown in Figure 4 [31]. Thus, for example, for a chloride concentration of 1 g/l, these potentials are $U_c = +0.10$ V and $U_p = +0.45$ V. Crevice corrosion between stainless steel and stainless steel was also observed; however the risk of corrosive attack is only to be expected at very high chloride concentrations [27]. For the use of the materials listed in Table 4, only a very low probability of corrosion is to be expected if there are crevices in the components [32].

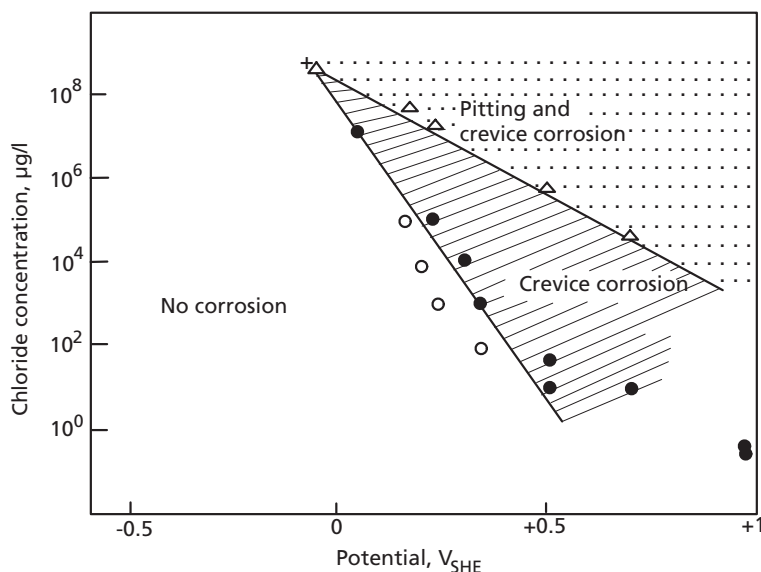


Figure 4: Resistance diagram of steel SAE 304 L (cf. 1.4306, X2CrNi19-11) towards pitting and crevice corrosion in neutral, chloride-containing waters at 298 K (25 °C) [31]

●, ○ = crevice corrosion potential

△ = pitting potential

+ = threshold potential

In most cases it is sufficient to use steels with 18 % Cr, 10–12 % Ni and a molybdenum content of 2 to 3 %. CrNi steels without additional molybdenum do not ex-

hibit sufficient resistance to crevice corrosion in waste waters with chloride contents of approx. 70 mg/l [5].

The data on pitting corrosion assumes that the stainless steel component has a smooth surface. However, if there are deposits or films on these surfaces that remain in place, then there may be a concentration of chloride ions at the sites of these deposits. At these sites, the pitting potential U_p is more negative than the pitting potential outside the deposits. Therefore, in the presence of deposits, pitting corrosion attack can occur even if the chloride content of the waste water is not at a critical level. With respect to the deposits caused by operation, the flow rate of the waste water is of great importance. The greater the flow rate, the less is the likelihood of the formation of deposits and thus also the risk of pitting corrosion. Surfaces with low flow rates can thus be susceptible to corrosion.

Adhering deposits can form at the three-phase boundary air/material/waste water. These deposits lead to the enrichment of chloride ions at this site. Pitting corrosion is not only favoured by deposits and films, but also by coarse mechanical damage of the surface, e.g. by scratches or by too coarse grinding.

A further important influential factor for pitting and crevice corrosion is the possible presence of oxidising agents (e.g. ozone) and anions (e.g. hydroxide and sulphate ions) in the waste water. The presence of these substances in the waste water can shift the potentials U_p and U_C in a positive direction. This results in an increased susceptibility towards pitting and crevice corrosion [27, 31].

In the selection of materials, the possibility of intergranular corrosion must also be taken into account. This type of corrosion is selective and is based, for example, on the precipitation of chromium-rich carbides on the grain boundaries (e.g. by welding). The chromium depletion can lower the corrosion resistance so that the grains disintegrate. This modification of the material is known as sensitisation [30]. Thus, for example, steel no. 1.4301 (Table 4) can be sensitised and, according to [32], the use of this material is not recommended.

Steels can be stabilised against intergranular corrosion e.g. by the use of steels with a low carbon content, as in material no. 1.4435 (Table 4). Another possibility is alloying with titanium or niobium which have a great affinity for carbon and thus prevent the formation of chromium carbides, as in e.g. material 1.4571 (SAE 316 Ti, Table 4).

Steels with 18 % Cr, 10–12 % Ni and carbon contents < 0.03 % or those stabilised with titanium are recommend for welded constructions [5].

Stress corrosion cracking and corrosion fatigue are only rarely observed in waste water installations [33]. These types of corrosion are only to be expected in materials listed in Table 4 only at temperatures above 323 K (50 °C).

Stainless steel components are preferentially joined by welding. During welding, oxide films and scales are produced on the surfaces and they very greatly reduce the resistance towards pitting corrosion [32]. Therefore, inert-gas-shielded arc welding is recommended to prevent the formation of oxide films and scales. It must be ensured that there is a sufficient supply and correct control of the inert gas. For example, during welding at construction sites it must be ensured that the position of the inert gas bell is not disturbed by the wind [34].

The permissibility of the different tarnishes which are produced during welding are discussed in [35]. According to this, straw yellow to dark blue tarnishes are harmless, whilst the lighter tarnishes with a film thickness of up to 50 nm are close to the limit of permissibility. Pitting corrosion must be expected in chloride-containing waste waters for brown to brown-black and particularly black films of macroscopic thickness. It is recommended to remove all tarnishes, regardless of colour. The films and layers that lead to corrosion must be removed by shot peening, careful grinding (grain size $>100\ \mu\text{m}$) or by pickling. The components can be treated by the manufacturer in pickling baths of nitric acid/hydrofluoric acid. Pickling pastes must be used at the construction site. The pickling agents must not contain any hydrochloric acid [32].

There are a number of possible welding defects, e.g. drips, root crevices that have not been properly welded, offset edges, open pores, welding splashes, residual slag on the base material and the welds. These defects underline the importance of correct and careful execution of the welding [35].

In the case of rubber-sealed joints, the amount of chlorides that can be extracted by water must not exceed 0.05% otherwise there is a risk of pitting or crevice corrosion. Brazed joints, independent of the braze, are no longer permitted for stainless steels because of attack by knife-line corrosion [32].

Clamped couplings made of stainless steel with elastomer seals are used for sleeveless drainpipes of cast iron and fibre cement. According to the principles of construction and inspection from the Deutsches Institut für Bautechnik (German Institute of Building Technology), the following requirements apply to the materials of the elements used to clamp cast-iron pipes [36]: the clamping straps/sleeves must be made of stainless steel according to DIN EN 10028-7, which is resistant to intergranular corrosion, even in the welded state. Therefore, in the case of austenitic steels, all grades are permissible, while only the two materials 1.4510 (SAE 439, X3CrTi17) and 1.4511 (X3CrNb17), are permissible in the case of ferritic and martensitic steels. For clamping collars made of stainless steel for fibre cement pipes which are to be welded, only steels may be used that are resistant to intergranular corrosion (1.4510 and 1.4511).

In waste water installations, the mixed construction i.e. the installation of components made of different materials, cannot be avoided. The risk of corrosion in mixed constructions is also discussed in [37].

Stainless steels are electrochemically noble materials in the passive state, i.e. they can form cathodes in electrochemical cells. Information with regards to this is given in Section "Unalloyed steels".

Corrosion damage which has been ascribed to acid attack has recently been observed in stainless steel sludge tanks in waste water treatment plants. The regions where corrosion occurred were in contact with sewer gas. The CrNi steels 18 10–12 with 2–3% molybdenum used here proved to have insufficient resistance. Therefore, the use of more highly alloyed stainless steels with increased resistance to acids is worthwhile in this case [5].

According to [38], thick-walled CrNiMo rolled-steel pumps are to be favoured for use as components in waste water installations over those made of plastic or grey cast iron as they are resistant to corrosion and biocorrosion.

Zinc

Zinc is widely used as a coating on unalloyed steel components in waste water installations. The zinc coating is generally applied using the hot-dip galvanisation process [39]. Spray galvanisation and electrogalvanisation only play a secondary role in this range of applications.

Hot-dip galvanised steel components are used in sewer technology as drain gratings, covers and as dirt pans for balconies, roofs, and cellars in road and estate drainage. It is also used as buckets for drains in roads [40]. A zinc layer of at least 400 g/m^2 is required for these components [41].

A large area of application are hot-dip galvanised steel drainpipes and fittings for estate drainage. According to DIN EN 1123-1 [41], these pipes can be used with and without coating. The hot-dip coating must have a smooth, perfectly adhesive and uniform layer with a minimum amount of 400 g/m^2 on average; the individual value must not be less than 350 g/m^2 .

For waste water with a normal level of aggressiveness, a service life of e.g. 20 years is calculated for a hot-dip galvanised pipeline with a coating thickness of $100 \mu\text{m}$ and a 1 mm thick wall of the steel pipe. This is based on a corrosion rate of the hot-dip coating of approx. 5 to $10 \mu\text{m/a}$ (without excessive abrasion) and of the steel of $100 \mu\text{m/a}$ (without the normal erosion or cavitation loading) [37].

The combination of hot-dip galvanisation and coating is a synergetic system, i.e. the overall protective effect is greater than the sum of the protective effects of the individual components of the system [42]. This system is defined as a duplex system.

For hot-dip galvanised components (holders, supports, handrails etc.) in waste water treatment plants that lie above the level of the waste water, it can be expected that there is an increase in the protective effect by the duplex system by approximately 50 to 200%, i.e. a four-fold protective effect, compared to the protective effect of the individual system components [43].

However, below the level of the water, hot-dip galvanised components are only regarded as resistant in exceptional cases [43]. This behaviour is attributed to the numerous waste water parameters [39]. The existing good practical experience is therefore often difficult to transfer to other systems and can only be generalised in a limited manner. This applies e.g. to the good experience with hot-dip galvanised components described in various publications [44–46].

Corrosion damage of hot-dip galvanised components in oxygen-poor waste waters with pH values between approximately 3.5 and 5.0 is reported in [47]. The reason for the damage is attributed to the low oxygen content under the layers of dirt and sewer slime. Because the oxygen content is too low, the conditions for the formation of protective layers of basic zinc carbonates deteriorate.

A coating of hot-dip galvanised components with plastics based on tar pitch or epoxy resins is recommended in [39]. It is expressly stated that the coating thicknesses should lie above 500 to $800 \mu\text{m}$. Before the coating is applied to the hot-dip galvanised surfaces they should be treated by means of the irradiation process known as “sweeping” to obtain good adhesion [48]. For the coating of hot-dip galva-

nised surfaces, only certain plastics can be used whose suitability must be verified according to the AGK Worksheet B 1 [49].

Bibliography

- [1] DIN 4045 (08/2003)
Abwassertechnik, Grundbegriffe
(Waste water engineering – Vocabulary)
(in German)
Beuth Verlag GmbH, Berlin
- [2] DIN EN 476 (04/2011)
General requirements for components
used in drains and sewers
Beuth Verlag GmbH, Berlin
- [3] DIN EN 12056-1 (01/2001)
Gravity drainage systems inside
buildings –Part 1: General and
performance requirements
Beuth Verlag GmbH, Berlin
- [4] ATV work report AG 1.5.3.
Abriebfragen
(Questions of abrasion) (in German)
Korrespondenz Abwasser 37 (1990) 2
- [5] Bindschedler, D.
Korrosionsschutz in
Abwasserreinigungsanlagen
(Corrosion protection in waste water
treatment plants) (in German)
gwa 73 (1993) 10, p. 808
- [6] Weber, J.; Knopf, K.
Mikrobielle Werkstoff zerstörung –
Simulation, Schadensfälle und
Gegenmaßnahmen: Metallische
Werkstoffe Überblick
(Microbial deterioration of materials –
simulation, case histories and
countermeasures: Metallic materials –
Overview) (in German)
Werkst. Korros. 45 (1994) 2, p. 73
- [7] Anonymous
Entwurf und Bau von Kanalisationen und
Abwasserpumpwerken
(Draft and construction of canalization
and sewage pumping stations)
(in German)
Lehr- und Handbuch der
Abwassertechnik, 3. ed., Volume 11
Verlag W. Ernst und Sohn, Berlin,
Munich, 1982
- [8] DIN 1045-1 (08/2008)
Concrete, reinforced and prestressed
concrete structures –
Part 1: Design and construction
Beuth Verlag GmbH, Berlin
- [9] DIN EN 10025 (04/2011)
Warmgewalzte Erzeugnisse aus
unlegierten Baustählen; Technische
Lieferbedingungen
(Hot-rolled unalloyed structural steel
products; technical delivery conditions)
Beuth Verlag GmbH, Berlin
- [10] Heim, G.
Korrosionsschutz von unlegierten
Eisenwerkstoffen
(Corrosion protection of unalloyed
ferrous materials) (in German)
Schriftenreihe Siedlungswasserwirtschaft
Bochum, vol. 1 (1 982) p. 37
- [11] DIN 50919 (05/2015)
Korrosion der Metalle.
Korrosionsuntersuchungen der
Bimetallkorrosion in Elektrolytlösungen
(Corrosion of metal; investigations of
galvanic corrosion in electrolytic
solutions) (in German)
Beuth Verlag GmbH, Berlin
- [12] Bindschedler, D.
Makroelementbildung in
Abwasserreinigungsanlagen – Ursache
und Schutzmaßnahmen
(Formation of macro elements in sewage
treatment works – causes and protective
measures) (in German)
Association report no. 380 (1988), p. 4
Verband Schweizerischer
Abwasserfachleute, Zürich
- [13] Heim, G.
Korrosionsverhalten von
Erderwerkstoffen
(Corrosion behaviour of grounding
materials)
Elektrizitätswirtschaft 81 (1982) 25,
offprint no. 3475, p. 875
- [14] Anonymous
Richtlinien zum Korrosionsschutz in
Abwasserreinigungsanlagen und
Kanalisationen
(Guidelines for the corrosion protection
in sewage treatment works and
canalization works) (in German), 7. draft
1990, p. 156
Korrosionskommission, Zürich

- [15] TRBF 522
Richtlinie für den lokalen kathodischen Korrosionsschutz (LKS) von unterirdischen Tankanlagen und Rohrleitungen aus metallischen Werkstoffen (LKS-Richtlinie) (Guideline for the local cathodic corrosion protection of buried fuel storage depots and pipes of metallic materials) (in German), edition March 1988
Carl Heymanns Verlag KG, Köln, Berlin
- [16] Gräfen, H.
Berücksichtigung der Korrosion bei der konstruktiven Gestaltung von Chemieapparaten
(Consideration of the corrosion at the constructional design of chemical apparatus) (in German)
Werkst. Korros. 23 (1972) 4, p. 247
- [17] Müller, R. O.
Korrosionsprobleme in Abwasseranlagen – Grundlagen, Beispiele, Maßnahmen (Corrosion problems in waste water treatment plants) (in German)
Association report no. 381 (1988) p. 14
Verband Schweizerischer Abwasserfachleute, Zürich
- [18] DIN 19522-1 (12/2010)
Cast iron drainage pipes and fittings without socket (SML)
Beuth Verlag GmbH, Berlin
- [19] DIN EN 1561 (08/1997)
Gießereiwesen – Gußeisen mit Lamellengraphit (in German)
DIN EN 1561 (01/2012)
Founding – Grey cast irons
Beuth Verlag GmbH, Berlin
- [20] DIN 30 674-3 (03/2001)
Umhüllung von Rohren aus duktilem Gußeisen – Teil 3: Zink-Überzug mit Deckbeschichtung
(Sheathing ductile cast iron pipes – Part 3: Zinc coating with protective sheathing) (in German)
Beuth Verlag GmbH, Berlin
- [21] DIN EN 598 (10/2009)
Ductile iron pipes, fittings, accessories and their joints for sewerage applications – Requirements and test methods
Beuth Verlag GmbH, Berlin
- [22] DIN 2614 (02/1990)
Zementmörtelauskleidung für Gußrohre, Stahlrohre und Formstücke – Verfahren, Anforderungen, Prüfungen (in German)
DIN EN 10298 (12/2005)
Steel tubes and fittings for onshore and offshore pipelines – Internal lining with cement mortar; German version
Beuth Verlag GmbH, Berlin
- [23] Stein, D.; Brune, P.; Bockermann, K.
Gutachterliche Stellungnahme: Das duktile Gußrohrsystem für den Abwassertransport in der Trinkwasserschutzzone II
(Drafting of an expert's report: The ductile cast iron pipe system for the sewage transport in the protection area for drinking water) (in German)
Buderus Gußrohrtechnik (1991), p. 101
- [24] ATV-Worksheet 142
Abwasserkanäle und -leitungen in Wassergewinnungsgebieten
(Drains and sewers in areas of drinking water extraction) (in German), October 1992
Abwassertechnische Vereinigung, St. Augustin
- [25] Hein, H.; Walter, G.
Unterdruckprüfungen in Abwassersystemen im Grundwasser und im innerstädtischen Bereich
(Vacuum testings in sewage systems in ground water and in the urban area) (in German)
FGR 26 Gussrohr-Technik (1991) April, p. 35
- [26] DIN EN 1124-1 (12/2004)
Rohre und Formstücke aus längsnahtgeschweißtem, nichtrostendem Stahlrohr mit Steckmuffe für Abwasserleitungen – Teil 1: Anforderungen, Prüfungen, Güteüberwachung
(Pipes and fittings of longitudinally welded stainless steel pipes with spigot and socket for waste water systems – Part 1: Requirements, testing, quality control)
Beuth Verlag GmbH, Berlin

- [27] Gräfen, H.; v. Baeckmann, W. G.; Föhl, J.; Herbsleb, G.; Huppatz, W.; Kuron, D.; Rother, H.-J.; Rüdinger, K.
Eigenschaften und Anwendungen nichtrostender Stähle und korrosionsbeständiger Nickellegierungen (Properties and applications of stainless steels and corrosion resistant nickel alloys) (in German)
Die Praxis des Korrosionsschutzes. Kontakt & Studium, vol. 64, p. 37 expert verlag, Grafenau, 1981
- [28] Anonymous
Richtlinien zum Korrosionsschutz in Abwasserreinigungsanlagen und Kanalisationswerken (Guidelines for the corrosion protection in clarification plants and canalization works) (in German), 7. draft 1990, p. 94 Korrosionkommission, Zürich
- [29] Bindschedler, D.; Bruhin, J.; Ineichen, H.; Lier, F.; Lüscher, H. J.; Lunk, P.; Lütolf, R.; Morgenthaler, P.; Müller, R.; Peter, G.; Stalder, F.; Theiler, F.; Votapek, E.
Richtlinien zum Korrosionsschutz in Abwasserreinigungsanlagen und Kanalisationswerken (Guidelines for the corrosion protection in clarification plants and sewer plants) (in German), C 6 d, 7. draft of 25.09.1990 Schweizerischer Elektrotechnischer Verein, Zürich
- [30] DIN 50930-4 (02/1993)
Korrosion der Metalle; Korrosion metallischer Werkstoffe im Innern von Rohrleitungen, Behältern und Apparaten bei Korrosionsbelastung durch Wässer; Beurteilung der Korrosionswahrscheinlichkeit nichtrostender Stähle (in German)
DIN EN 12502-4 (03/2005)
Protection of metallic materials against corrosion – Guidance on the assessment of corrosion likelihood in water distribution and storage systems – Part 4: Influencing factors for stainless steels Beuth Verlag GmbH, Berlin
- [31] Scheidegger, R.; Müller, R. O.
Loch- und Spaltkorrosion von Chrom- und Chromnickestählen in chloridhaltigen Lösungen (Pitting and crevice corrosion of stainless steels in chloride solutions) (in German) Werkst. Korros. 31 (1980) 5, p. 387
- [32] Müller, R. O.
Korrosionsprobleme in Abwasseranlagen – Grundlagen, Beispiele, Maßnahmen (Corrosion problems in waste water treatment plants) (in German), Association report no. 381 (1988), p. 19 Verband Schweizerischer Abwasserfachleute, Zürich
- [33] Haendel, H.
Werkstoffe in der Abwassertechnik (Materials in sewage engineering) (in German)
Special event no. F-40-207-045-7 “Korrosion in Abwasserkanälen”, February 1987
Haus der Technik e.V., Essen
- [34] Huber, H.
Edelstahl rostfrei, ein Werkstoff für die Wasserversorgung Brunnenbau, Bau von Wasserwerken (Stainless steel, a material for water supply, well construction, construction of water works) (in German)
Rohrleitungsbau (bbr) (1 983) 5
- [35] Anonymous
Schweißverbindungen (Welded connections) (in German)
Schriftenreihe Siedlungswasserwirtschaft Bochum, vol. 1 (1982) p. 104
- [36] Anonymous
Bau- und Prüfgrundsätze für Spannverbindungen mit Elastomerdichtungen für Abwasserrohre nach DIN 19522 (Principles for construction and for testing of tensioned joints with elastomeric seals for sewer and drain pipes according to DIN 19522) (in German), version November 1990 Institut für Bautechnik, Berlin
- [37] Rickenbacher, F.
Korrosionsrisiken bei Mischkonstruktionen (Corrosion risks with mixed constructions) (in German)
gwa 73 (1993) 1 0, p. 803

- [38] Berdelle-Hilge, Ph.
Mikrobielle Werkstoff zerstörung –
Biofilm und Biofouling: Anforderungen
an biokorrosionsfeste Pumpen
(Microbial deterioration of materials –
biofilm and biofouling: Requisition to
biocorrosion resistant pumps)
(in German)
Werkst. Korros. 45 (1994) 1, p. 68
- [39] Data sheet 400
Korrosionsverhalten von feuerverzinktem
Stahl
(Corrosion behaviour of hot-dip
galvanised steel) (in German), 4. ed.,
1983
Beratungsstelle für Stahlverwendung,
Düsseldorf
- [40] DIN 4052-4 (05/2006)
Betonteile und Eimer für Straßenabläufe,
Eimer
(Concrete elements and buckets for road
gullies; buckets) (in German)
Beuth Verlag GmbH, Berlin
- [41] DIN EN 1123-1 (03/1999)
Rohre und Formstücke aus
längsnahtgeschweißtem feuerverzinktem
Stahlrohr mit Steckmuffe für
Abwasserleitungen – Teil 1:
Anforderungen, Prüfungen,
Güteüberwachung
DIN EN 1123-1 (12/2004)
Pipes and fittings of longitudinally
welded hot-dip galvanised steel pipes
with spigot and socket for waste water
systems –Part 1: Requirements, testing,
quality control
Beuth Verlag GmbH, Berlin
- [42] Data sheet 329
Feuerverzinkung + Beschichtung =
Duplex-System
(Hot-dip galvanising + coating = duplex
system) (in German), 6. ed., 1981
Beratungsstelle Stahlverwendung,
Düsseldorf
- [43] Anonymous
Verzinkungen
(Galvanisation) (in German)
Schriftenreihe Siedlungswasserwirtschaft
Bochum, vol. 1 (1982), p. 98
- [44] Albrecht, D.
Aspekte der Oberflächenbehandlung von
Stahlteilen beim Bau und Betrieb von
Abwasserreinigungsanlagen
(Aspects of surface treatment of steel
components at the construction and
operation of waste water treatment
plants) (in German)
Verzinken 3 (1974) 1, p. 12
- [45] Kraak, L. A.
Einsatz der Feuerverzinkung bei den
Stahlwasserbauten der Niederländischen
Wassergenossenschaft
(Use of hot-dip galvanising of the
hydraulic steelwork of the Dutch water
cooperative)
Verzinken 5 (1976) 1, p. 16
- [46] Schröder, F.
Zukunftssicherer Korrosionsschutz im
Klärwerk Bonn – Bad Godesberg
(Future-proof corrosion protection in the
waste water treatment plant Bonn – Bad
Godesberg) (in German)
Verzinken 5 (1976) 11, p. 1 8
- [47] Schröder, F.
Zukunftssicherer Korrosionsschutz im
Klärwerk Bonn – Bad Godesberg
(Future-proof corrosion protection in the
waste water treatment plant Bonn – Bad
Godesberg) (in German)
Verzinken 5 (1976) 11, p. 1 8
- [48] ATV-date sheet M 263
Empfehlungen zum Korrosionsschutz
von Stahlteilen in
Abwasserbehandlungsanlagen durch
Beschichtungen und Überzüge
(Recommendations for the corrosion
protection of steel components)
(in German), September 1991
Abwassertechnische Vereinigung,
St. Augustin
- [49] AGK-Arbeitsblatt B 1
Prüfung von Duplexsystemen zum
Korrosionsschutz von
Stahlkonstruktionen durch
Feuerverzinken und Beschichten
(Testing of duplex systems for the
corrosion protection of steel
constructions by hot-dip galvanising and
coating) (in German), January 1985
Werkst. Korros. 38 (1987) 3, p. 135

Waste Water (Industrial)

Authors: E. Heitz, G. Subat / Editor: R. Bender

Introduction

Waste waters are classified according to their source into domestic, commercial, and industrial waste waters and contaminated storm water runoff. Liquids that have seeped and have been collected from landfill facilities (leachates, landfill leachates) are also regarded as waste water. If these waste waters are combined, they are known as municipal waste water [1].

In contrast to municipal waste water, the type and concentration of the pollutants in commercial and industrial waste waters can vary greatly, depending on their origin.

Industrial waste waters contain non-recyclable materials from chemical, thermal, and mechanical processes and may contain a wide variety of corrosive agents, depending on their origin. The concentrations of these agents must comply with the legally stipulated values before they can be discharged into waste water treatment plants or sewers. This is achieved by means of a wide range of treatment processes that are very specific to the particular branch or industry and the respective process engineering.

Although modern processing techniques that have integrated environmental protection aim to minimise waste, they still produce aqueous solutions containing high levels of contaminants that have to be treated chemically, thermally, physically, or biologically.

In the diverse waste water treatment processes, the typically high concentrations of aggressive compounds and the frequently high temperatures necessitate the use of highly corrosion-resistant materials. This means that a design with standard materials is no longer suitable.

A very useful description and assessment of the various methods and their variants that are used in practice for industrial waste water treatment are compiled in [2]. A comprehensive evaluation of the physical and chemical methods reported in the specialist literature is given in [3] with a total of 382 references.

Comprehensive overviews and information on the origin and types of waste water produced by the different commercial and industrial facilities as well as the appropriate treatment process are given in [4–6].

Reference [7] gives a detailed description of the basic principles for the treatment of industrial waste waters and also discusses the legal aspects, problems regarding environmental protection, and the various technical processes. In addition to an overview on industrial waste waters, evaluation criteria, and the possibilities of reducing or avoiding waste water are also addressed. The chemical, physical, and biological processes for waste water treatment and the elimination of waste water contaminants are described in detail.

Unalloyed steels and low-alloy steels/cast steel

The corrosion rates of these materials in almost neutral waste waters are chiefly determined by the concentration of oxygen and by its transport to the surface of the material. However, in addition to uniform surface attack, which must be taken into account by increasing the wall thickness, there may be increased local attack in the form of shallow pit corrosion and pitting corrosion due to the formation of aeration cells. The use of unalloyed and low-alloy steels as well as cast iron and cast steel is generally not recommended if there are no additional corrosion protection measures, e.g. with coatings, linings, or cathodic protection.

In air-saturated deionised water with low ozone concentrations and at room temperature, unalloyed steel exhibits a corrosion rate that is several times higher than that in ozone-free water. This must be taken into account, if appropriate, in waste water treatment processes that use ozone.

Pipes made of unalloyed and low-alloy steels are frequently used for waste water pipelines, which are usually installed underground. The corrosion rates of these materials in almost neutral waste waters are chiefly determined by the concentration of dissolved oxygen and by its transport to the steel surface. Uniform corrosion rates are usually in the range of 0.1 to 0.2 mm/a (3.94 to 7.85 mpy). There may be increased local attack owing to the formation of aeration cells, e.g. underneath deposits, and if there are differing oxygen concentrations in the medium. Without corrosion protection, these steel grades are thus not sufficiently resistant to the flowing medium nor to the gas atmosphere above the level of the liquid. Therefore, pipes made of these steels as well as the frequently used pipes of ductile cast iron can only be used if they have sufficient corrosion protection [1]. Unalloyed steels are not attacked by dry H_2S at room temperature. There have been several reports of heavy corrosion of covers of biological settling tanks after longer operating times. These tanks are exposed to high H_2S concentrations and high humidity levels.

The structural steel St 38 (cf. SAE 1015, 1.0037), grey cast iron, austenitic CrNi steels, aluminium, and polymer materials were tested in the laboratory for their suitability in a waste water treatment plant under simulated operating conditions, such as in collecting tanks for mixed waste water (buffer tanks), in the neutralisation stage, in primary biological stage and in the final biological stage. The industrial waste waters from various points with differing compositions are stored in buffer tanks at an average temperature of 314 K (41 °C). In the neutralisation stage, the waste waters at approx. 313 K (40 °C) are adjusted to pH 6–7. In the main biological treatment stage, the mixed water, neutralised or at pH 5, is subjected to bacterial degradation at a temperature between 303 K (30 °C) and 313 K (40 °C) with excess oxygen and strong turbulence from recirculating pumps. This increases the pH value to pH 7–8. The subsequent treatment is carried out in the final biological stage at 303 K (30 °C). The resulting corrosion rates for samples of unalloyed steel and grey cast iron are given in Table 1 [8].

According to these results, St 38 (cf. SAE 1015) or grey cast iron can only be used in the final biological stage under the given conditions. The likewise tested austenitic CrNi steels were resistant under all experimental conditions, whereas all tested aluminium samples exhibited strong pitting corrosion.

Plant	Test duration days	Corrosion rate mm/a (mpy)	
		unalloyed steel St 38 SAE 1015	Grey cast iron
Buffer tank	140	2.68 (105.5)	5.90
Neutralisation stage		0.76 (29.92)	0.32
Main biological treatment stage	180 to 260	0.89 (35.04)	0.38
Final biological treatment stage	260	0.02 (0.70)	0.02

Table 1: Corrosion rates of unalloyed steel and grey cast iron in plants used for waste water treatment [8]

The corrosion behaviour of unalloyed C steel USt 42-2 (1.0040, JIS SS 400), low-alloy steel 34CrMo4 (1.7220, JIS SCM 435) and 36NiCr10 (1.5736, JIS SNC 631), CrNi steel SAE 304 (1.4301, X5CrNi18-10), 13 % chromium steel SAE 403 (1.4000, X6Cr13), 17 % chromium steel SAE 430 (1.4016, X6Cr17), copper Cu-PHC (CW020A, SE-Cu, 2.0070) and a CuZn alloy CuZn40 (CW509L, 2.0360) in contact with ozone-containing water was investigated with respect to ozone, which has been used more frequently in recent years [9]. The chemical composition of the materials is given in Table 2.

Material	DIN-Mat. No.	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
USt 42-2 (JIS SS 400)	1.0040	0.18	0.05	0.80	0.007	0.005	–	–	–	balance
34CrMo4 (JIS SCM 435)	1.7220	0.34	0.19	0.71	0.012	0.006	–	1.09	0.19	balance
36NiCr10 (JIS SNC 631)	1.5736	0.30	0.32	0.57	0.014	0.006	2.64	0.75	–	balance
SAE 304 X5CrNi18-10	1.4301	0.06	0.40	0.75	0.031	0.004	9.07	18.22	–	balance
SAE 430 X6Cr17	1.4016	0.07	0.52	0.41	0.031	0.007	0.30	16.61	–	balance

Table 2: Composition of the investigated materials (%) [9]

Table 2: Continued

Material	DIN-Mat. No.	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
SAE 403 X6Cr13	1.4000	0.07	0.36	0.32	0.022	0.002	0.24	12.57	–	balance
		Cu	Zn	Fe	Pb					
CuZn40 (CW509L)	2.0360	61.41	38.57	0.006	0.016					
Cu-PHC (CW020A, SE-Cu)	2.0070	99.95	–	–	–					

Table 2: Composition of the investigated materials (%) [9]

The ozone concentration in the deionised water was varied between 0 and 7.1 mg/l, and the corrosion rate was determined in static, fast-flowing, and slow-flowing media (Table 3). The corrosion rate of unalloyed steel USt 42-2 (1.0040) in pure, air-saturated water at room temperature with a very low concentration of dissolved ozone, determined under static conditions and with a slow flow rate, was several times higher than that obtained in ozone-free water. According to the generally accepted evaluation rules, resistance can only be expected for higher flow rates. In practice, however, this favourable behaviour is not significant because the investigation showed that the corrosion potential was immediately shifted from the positive range to the negative range when the ozone feed diminished. Once the corrosion process had started, the potential could not be shifted back into the noble range, even if ozone was added.

Water flow rate	None		Low flow rate, 5–10 cm/s		High flow rate, 1.7 m/s	
Ozone concentration, mg/l	2.1	0	2.1	0	2.1	0
Material	Corrosion rate, mm/a (mpy)					
Unalloyed steel USt 42-2 (1.0040)	0.18 (7.09)	0.07 (2.76)	0.68 (26.77)	0.11 (4.33)	0.003 (0.12)	0.003 (0.12)
Low-alloy steel 34CrMo4 (1.7220)	0.14 (5.51)	0.05 (1.97)	0.17 (6.69)	0.06 (2.36)	0.01 (0.39)	0.002 (0.08)
Low-alloy steel 36NiCr10 (1.5736)	0.12 (4.71)	0.04 (1.57)	0.15 (5.91)	0.05 (1.97)	0.015 (0.59)	0.001 (0.04)

Table 3: Corrosion rates of the metals listed in Table 2 in air-saturated water with and without ozone at room temperature and with differing flow rates [9]

Table 3: Continued

<i>Water flow rate</i>	<i>None</i>		<i>Low flow rate, 5–10 cm/s</i>		<i>High flow rate, 1.7 m/s</i>	
<i>Ozone concentration, mg/l</i>	<i>2.1</i>	<i>0</i>	<i>2.1</i>	<i>0</i>	<i>2.1</i>	<i>0</i>
<i>Material</i>	<i>Corrosion rate, mm/a (mpy)</i>					
CrNi steel SAE 403 (1.4301, X5CrNi18-10)	< 0.001 (< 0.04)	< 0.001 (0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	–	–
13 %-Cr steel SAE 304 (1.4000, X6Cr13)	< 0.001 (< 0.04)	< 0.001 (0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)
17 %-Cr steel SAE 430 (1.4016, X6Cr17)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)	< 0.001 (< 0.04)
Copper SE-Cu (CW020A, 2.0070)	0.02 (0.79)	0.002 (0.08)	0.02 (0.79)	0.003 (0.12)	0.03 (1.18)	0.004 (0.16)
Brass CuZn40 (CW509L, 2.0360)	0.02 (0.79)	0.003 (0.12)	0.03 (1.18)	0.003 (0.12)	0.05 (1.97)	0.01 (0.39)

Table 3: Corrosion rates of the metals listed in Table 2 in air-saturated water with and without ozone at room temperature and with differing flow rates [9]

From the experience with ozone treatment of cooling waters reported in [10], it can be assumed that a negative influence on the corrosion of low-alloy steels is not expected for ozone concentrations of 0.1 mg/l. However, the use of high-alloy steels is recommended for pipelines carrying ozone-rich water.

Reference [11] describes the influence of sulphate-reducing bacteria on the corrosion of unalloyed steels in detail. Certain prerequisites are linked to the formation of a biofilm. These are essentially the concentrations of dissolved oxygen and dissolved Fe^{2+} ions as well as the physical and chemical properties of the resulting iron sulphides. Locally occurring anaerobic conditions on metal surfaces in industrial waste water systems encourage the formation of biofilms that contain sulphate-reducing bacteria. Even low concentrations of Fe^{2+} ions in the presence of sulphate-reducing bacteria lead to the breakdown of protective layers, and the corrosion rate increases proportionally to the concentration of iron ions (Figure 1). The corrosion rate of unalloyed steels in industrial waste water systems is not directly determined by the activity of sulphate-reducing bacteria, but indirectly by the properties of the adhering Fe^{2+} sulphides produced as corrosion products [11].

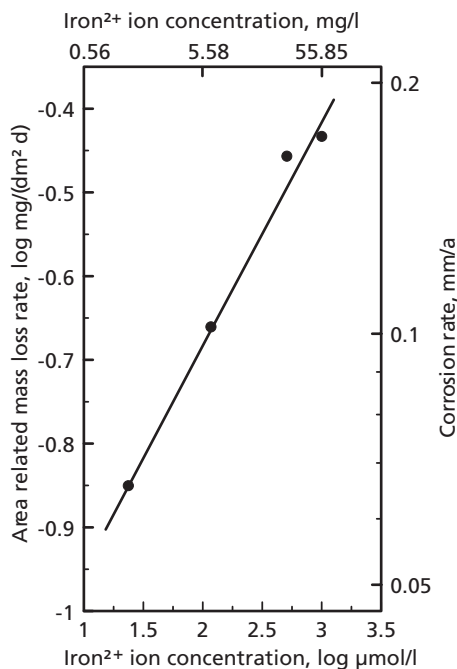


Figure 1: Corrosion rate of unalloyed steels depending on the Fe^{2+} concentration in water and on the presence of sulphate-reducing bacteria [11]

Corrosion damage to several components made of low-alloy steels and cast iron in the waste water treatment plant of a petroleum refinery were also caused by the action of sulphate-reducing bacteria. To prevent further damage, the pipelines were either replaced by those made of glass-fiber-reinforced polyester resin or they were lined with sulphate-resistant concrete [12].

Unalloyed cast iron and low-alloy cast iron

High-alloy cast iron

Silicon cast iron

Unalloyed cast iron (grey cast iron) exhibits similar behaviour to unalloyed steel in waste water treatment plants. Waste water pumps made of grey cast iron (GG 22, GG 25, 0.6025) have a rough surface that is an ideal substrate for adhesive biofilms that can cause biocorrosion. Biocorrosion cannot be completely excluded on polished cast parts containing spheroidal graphite and silicon as well as on high-alloy CrNiMo cast pumps. The corrosion properties of hard chromium-molybdenum cast iron G-X 250 CrMo 15 3 (cf. G-X 300 CrMo 15 3, 0.9635) are comparable to those of unalloyed cast iron; however, the former is a superior material for immersion

pumps owing to its better resistance to abrasive wear. Ferritic-austenitic CrNiMo cast steel G-X 3 CrNiMoCuN 24 6 (cf. DIN-Mat. No. 1.4517) is a superior pump material compared to other cast materials, particularly if the pumped medium is a chemical waste water containing chloride and large quantities of abrasive solids and also has a widely fluctuating pH value.

The results of corrosion tests described in Section “Unalloyed and low-alloy steels” that were carried out in a biological industrial waste water treatment plant on samples of grey cast iron are given in Table 1.

These showed, as expected, that unalloyed cast iron behaves similarly to unalloyed steel [8].

Immersed motor pumps made of grey cast iron have been used for many years in waste water applications; however, for reasons of weight and improved corrosion resistance, they have recently been replaced by pumps made of CrNiMo stainless steels [13].

Waste water pumps made of grey cast iron (EN-GJL-250, 0.6025) have surface roughnesses between 12 and 50 μm (R_a , arithmetic mean roughness) and are thus ideal substrates for adhesive biofilms. Biocorrosion is accelerated on these materials, in contrast to polishable spherical graphite cast iron and cast ferrosilicon. Bronze pumps have improved mean roughness values of approx. 10 μm R_a , and pumps made of cast high-alloy CrNiMo can be polished to values of 5 μm R_a . However, the formation of cavities with a risk of biocorrosion cannot be excluded in this case [14].

Unalloyed cast iron grades (e.g. EN-GJL-250) are mainly recommended for less aggressive waste waters in the pH range of ≥ 6 with low concentrations of abrasive solid particles (less than 1 g/l) [15]. Pipes made of grey cast iron usually have corrosion protection coatings on the inner and outer surfaces [1]. The withdrawn standard DIN 19690 specified a bitumen-based coating for the external corrosion protection. The new DIN EN 598 [16] stipulates that the standard external protection of the pipes must consist of a zinc coating plus top coat as well as an epoxy resin coating in the region of the male ends and the inner surfaces of the sockets. DIN 19690 stipulates a cement-bonded mortar lining for the inner corrosion protection [17].

Hard chromium-molybdenum-alloyed cast iron G-X 250 CrMo 15 3 (Norihard® NH 15 3, cf. G-X 300 CrMo 15 3, 0.9635) has a predominantly martensitic microstructure with chromium carbide inclusions. It is characterised by a high wear resistance and relatively good toughness. The hardness and abrasion resistance of this material is only superseded by the pure metal oxides and metal carbides (hard metals). However, compared to these materials, it has the advantage that it can be soft-annealed by heat treatment after casting so that it can be machined. It has a corrosion resistance comparable to unalloyed cast iron. However, as a material for submersible pumps, it is superior to the latter material because it has a better resistance to abrasive wear. Under comparable operating conditions, it has a 10- to 15-fold longer service life than grey cast iron and a 5- to 10-fold longer service life than wear-resistant special cast iron. Application areas include the transport of lime milk, sludges in alumina production, sinter waters from steelworks, and ash/water suspensions in power stations [18].

Materials	Chemical composition mass%							Mechanical properties (approximate values)						
	C	Si	Mn	P _{max}	S _{max}	Cr	Ni	Mo	Cu	Tensile strength R _m N/mm ²	Yield strength R _{p0.2} N/mm ²	Elongation at failure A ₅ %	Impact toughness A ₁ DVM J	Hardness HB 30
EN-GJL-250, 0.6025	3.3	1.95	0.7	0.10	0.08					309				180–240
EN-GJS-400-15, 0.7040	3.7	2.2	0.4	0.04	0.01					420	283	24		180–220
Norihard® NH 15 3 cf. G-X 300 CrMo 15 3, 0.9635	2.6	0.7	0.6			15		2.6		600				750–1000 ¹⁾
1.4408, CF-8M GX5CrNiMo19-11-2	0.07	2.0	1.5			18.5	10	2.2		440	185	20	68	130–200
Noridur® 9.4460 cf. GX2CrNiMoCuN25- 6-3-3, 1.4517	0.04	1.5	1.5			25.5	6.0	2.5	3.0	690	485	25	80	200–260

¹⁾ HV 50

Table 4: Material data for selected pump materials [18]

The high-alloy ferritic-austenitic CrNiMo cast steel G-X 3 CrNiMoCuN 24 6 with a ferrite/austenite ratio of 50:50 (Noridur® 9.4460, cf. GX2CrNiMoCuN25-6-3-3, 1.4517) is suitable as a pump material owing to its good resistance to simultaneous hydroabrasive wear and chemical attack. Its high chromium and molybdenum contents make it superior to the conventional austenitic CrNi and CrNiMo cast steel grades, particularly if, for example, there are strong fluctuations in the pH value and high chloride concentrations in chemical waste waters that also contain large quantities of abrasive solids [15, 18–21]. Table 4 gives the relevant material data for the various cast materials and Table 5 gives information on their applications [18].

Materials	Comments on applications
EN-GJL-250, 0.6025	Standard material for waste waters containing chemicals that are not aggressive; without abrasive solids
EN-GJS-400-15, 0.7040	For waste waters containing chemicals that are not aggressive; without abrasive solids when pressurised components are subjected to pressure surges or if there is a risk of frost damage
Norihard® NH 15 3 cf. G-X 300 CrMo 15 3, 0.9635	For waste waters containing chemicals that are not aggressive but with large quantities of abrasive solids
1.4408, CF-8M GX5CrNiMo19-11-2	For waste waters containing chemicals that are not aggressive up to pH values of ≥ 4.0 and chloride concentrations of < 100 mg/l
Noridur® 9.4460 cf. GX2CrNiMoCuN25-6-3-3, 1.4517	For chemical waste waters with extremely low pH values and high chloride concentrations; also for low concentrations of abrasive solids

Table 5: Comments on applications for selected pump materials [18]

Pipes made of ductile cast iron i.e. cast iron with spheroidal graphite according to DIN EN 1593 [22] are used extensively in communal and industrial waste water disposal systems. The technical terms of delivery DIN EN 598 [16] contain information on the material parameters, on their joints, as well as on the testing and quality control of pipes. Some material parameters are given in Table 6.

Material parameters	
Tensile strength	$\geq 400 \text{ N/mm}^2$
0.2 % Yield strength	$\geq 300 \text{ N/mm}^2$
Elongation at failure	$\geq 7 \%$ (pipes)
Hardness	$\leq 250 \text{ HB } 5/750$
Modulus of elasticity	170 kN/mm^2
Bursting strength	$\geq 300 \text{ N/mm}^2$
Hoop strength	$\geq 550 \text{ N/mm}^2$
Longitudinal bending strength	$\geq 420 \text{ N/mm}^2$

Table 6: Material data for pipes made of ductile cast iron according to DIN EN 598 [16, 24]

Pipes made of ductile cast iron are supplied with push-in joints according to DIN 28603 [23]. These joints have a sealing ring made of natural or synthetic rubber. The pipes are used in waste water applications with a standard protection consisting of an internal cement mortar lining and an external spray-coating of zinc with an additional bitumen-based coating. The cement mortar lining not only provides passive protection because it separates the metal surface from the media, but it also provides active protection by absorbing lime out of the mortar so that the phase on the surface of the metal has a pH value greater than 12 in which the cast iron is virtually passive [24].

Ferritic chromium steels with $< 13 \%$ Cr

Ferritic chromium steels with $\geq 13 \%$ Cr

High-alloy multiphase steels

Ferritic/pearlitic-martensitic steels

Ferritic-austenitic steels/duplex steels

Although ferritic chromium steels exposed to chloride-containing waters exhibit good resistance to chloride-induced stress corrosion cracking, they are rarely used owing to the problems associated with their processing. Ferritic-austenitic steels have proven suitable in waste water facilities because of their good resistance to pitting and stress corrosion cracking, even under critical conditions.

In a biological sewage treatment plant, components made of ferritic stainless chromium steel SAE 409 (1.4512, X2CrTi12) that were partially immersed in the waste water exhibited strong corrosion, particularly at the weld seams. The incoming industrial waste water contained between 1100–3080 mg/l chloride during the observation period. A microbiological analysis also showed high levels of sulphate-

reducing bacteria. The selected material with a chromium content of only 12 % was not suitable for this application [25].

Table 3 [9] also gives the results of exposure tests in ozone-containing water for the 13 % chromium steel SAE 403 (1.4000, X6Cr13) and the 17 % chromium steel SAE 430 (1.4016, X6Cr17) (composition in Table 2). Both materials were resistant under the given test conditions. In contrast, the low-alloy chromium steel 34CrMo4 (UNS G41300, 1.7220) is not resistant in ozone-containing water.

Most of the waste waters from oil refinery plants arise from stripping of acidic waste gases that are produced by distillation or gas production. In this process, the H₂S and CO₂ components are absorbed by a counterflow of amine solutions (monoethanolamine (MEA) or diethanolamine (DEA)). The absorption solution is recycled after thermal removal of the acidic gases. The heat exchangers used in this process are subjected to the conditions given as an example in Table 7.

<i>Untreated water, piping Treated water, outer wall</i>		
H ₂ S	5,000 ppm	4 ppm
Mercaptans	90 ppm	15 ppm
Thiosulphate	–	25 ppm
Cl [–]	10–30 ppm	–
pH	7	9–11
Temperature	inlet: 303 K (30 °C) outlet: 373 K (100 °C)	inlet: 423 K (150 °C) outlet: 333 K (60 °C)
Pressure	1.0 MPa	1.0 MPa

Table 7: Corrosion conditions in heat exchangers exposed to waste waters from oil refining for components made of ferritic-austenitic steel (duplex steel) UNS S31500 (3RE60, 1.4417) [26, 27]

Heat exchangers made of duplex steel UNS S31500 (18 Cr, 5 Ni, 3 Mo, cf. 3RE60, 1.4417) have been used without problems for more than 10 years. In previous trials, the ferritic 17 % chromium steel SAE 430 (1.4016, X6Cr17) and also the austenitic chromium-nickel-molybdenum steel SAE 316 (1.4401, X5CrNiMo17-12-2) failed due to stress corrosion cracking less than six months after commissioning. The duplex steel UNS S31500 has been used successfully for almost seven years as a head condenser in a DEA scrubber. The gas in contact with the pipes contained hydrogen sulphide, water, carbon dioxide, ammonia, as well as traces of DEA, oxygen, and acetonitrile. The temperature was 368–378 K (95–105 °C). The outer wall was in contact with brackish water containing 1000–1200 ppm Cl[–] [26, 27].

In general, for the selection of materials to be used in conditions where there is a risk of stress corrosion cracking, it is advisable to short-list duplex steels because these exhibit better resistance than austenitic chromium-nickel steels [28].

Ferritic, austenitic, or ferritic-austenitic cast alloys are used in preference as materials for pumps in scrubber circuits of flue gas desulphurisation plants (FGD

plants). The chemical compositions of some typical high-alloy pump materials are given in Table 8 [29]. The pumped media are strongly corrosive owing to their low pH values and high salt concentrations. Also the entrained solids cause hydroabrasive wear of pump parts, such as impellers or wear plates, that are exposed to fast-flowing media. Table 9 gives the essential parameters to which the material is exposed along with values of a typical FGD scrubbing solution. Furthermore, Sheet 4 of the ATV Notice H 706 discusses waste waters from flue gas scrubbers in detail [30].

Material		C	Si	Mn	Cr	Ni	Mo	Cu	other
GX5CrNiMo19-11-2, 1.4408	Norinox [®]	≤ 0.14	≤ 1.5	≤ 1.5	19.0	11.0	2.3		
EN-GJN-HV 600, 0.9650	Noriloy [®] NL 25 2	1.7	1.0	1.0	25.0		2.0		
GX3CrNiMoCu 24-6-2-3, 1.4593	Noridur [®]	≤ 0.04	≤ 1.5	≤ 1.5	25.0	6.0	2.4	3.1	N
GX3CrNiMoCuN 24-6-5, 1.4573, SAE 316 Ti	Noriclor [®] NL 24 6	≤ 0.04	≤ 1.0	≤ 1.0	24.0	6.0	5.0	2.0	N

Table 8: Approximate analysis values of some high-alloy cast steel grades used for pump construction (mass%, balance Fe) [29]

Parameters and contents	Unit	Usual range	Extreme values
pH value		4–8	< 1–12
Chloride concentration	g/l	5–80	100
Sulphate concentration	g/l	1–4	6
Nitrate concentration	g/l	0.2–1.0	1.5
Other salts	mg/l	< 0.5	
Solids content	mass%	10–25	60
Density	g/cm ³	1.02–1.15	1.5

Table 9: Essential parameters of scrubbing solutions in flue gas desulphurisation plants that operate with the calcium carbonate scrubbing process [29]

Under critical conditions, these materials also exhibit damage due to abrasion or corrosion. For example, in a FGD scrubbing suspension with the following data

- pH value: 3.5–5.5
- chloride concentration: approx. 70,000 mg/l
- solids content: > 200 g/l

the wear plate of a pump made of EN-GJN-HV 600 exhibited strong abrasive wear after 8800 operating hours. Noticeably improved service lives were attained under these conditions by the use of GX3CrNiMoCu 24-6-2-3 with a wear plate protected with by a weld-cladding with the hard alloy Stellite[®] H6 or by a SiC ceramic coating [29].

Austenitic CrNi steels

Austenitic CrNiMo(N) steels

Austenitic CrNiMoCu(N) steels

The molybdenum-free austenitic steels are susceptible to crevice corrosion at chloride concentrations greater than approx. 20 mg/l and to pitting corrosion at concentrations above approx. 200 mg/l. Austenitic steels containing 18 % Cr, 10–12 % Ni and 2–3 % Mo have proven suitable in waste water treatment plants and are frequently used. They have sufficient resistance to pitting corrosion at moderate temperatures (up to approx. 308 K (35 °C)) in neutral to weakly acidic waters and chloride concentrations up to approx. 1000 mg/l. However, they may exhibit crevice corrosion at chloride concentrations above 200 mg/l. At higher temperatures, higher chloride concentrations, and lower pH values, as in e.g. evaporator units for waste waters from flue gas desulphurisation units, sewage sludge drying, and for landfill leachates, steels containing high Mo contents must be used. These include 1.4439 (SAE 317 LMN, X2CrNiMoN17-13-5), 1.4539 (SAE 904 L, X1NiCrMoCuN25-20-5), 1.4529 (UNS N08926, X1NiCrMoCuN25-20-7), and 1.4562 (UNS N08031, X1NiCrMoCu32-28-7). Nickel-based alloys should be used in strongly acidic solutions and in solutions with a high redox potential.

Stainless steels must be processed and machined correctly so as not to interfere with the homogeneous formation of the protective oxide layer. The surface finish has a significant influence on the corrosion resistance. The greatest resistance is attained with a clean and metallically bright surface that is also free of cracks and crevice like phenomena. This is particularly important if the parts are welded. Tarnishing and other surface defects, such as weld splashes and slag residues, undercuts, incomplete welding of the root and pores, as well as metal abrasion, deposits, and extraneous rust must be carefully removed. Crevices and stresses must also be avoided in the design.

In addition to ferritic-austenitic steels (duplex steels), austenitic CrNiMo steels can also be used in waste water treatment plants. These steels are sufficiently passive in most waste waters so that uniform surface corrosion can be practically neglected; however, under critical conditions, they can exhibit local corrosive attack in the form of pitting corrosion, crevice corrosion, or stress corrosion cracking. The decisive evaluation criteria for their possible application with respect to the media are:

- the chloride concentration
- the pH value
- the temperature
- the redox potential

Pitting corrosion only occurs when the potential of the steel in the medium is more positive than the pitting corrosion potential. For longer exposures, the corrosion potential of the steel shifts in the direction of the redox potential, however, it

does not exceed this potential. Pitting corrosion cannot occur if the pitting corrosion potential is more positive than the redox potential of the system. In the inverse case, if the pitting corrosion potential is more negative than the redox potential, there is always a risk of pitting corrosion.

The risk of pitting corrosion thus increases if the pitting corrosion potential is shifted to more negative values, e.g. in the event of

- an increasing chloride concentration
- a decreasing pH value
- a higher temperature

Higher redox potentials, i.e. high concentrations of oxidising agents, increase the risk of pitting corrosion in that they shift the resting potential of the steel in the direction of the pitting corrosion potential.

The resistance to pitting corrosion increases as the pitting corrosion potential becomes increasingly positive. As the contents of chromium and molybdenum increase, the pitting corrosion potential of stainless steels is shifted to more positive values, i.e. the resistance to pitting corrosion is increased, whereby the effect of molybdenum is approximately three times greater than that of chromium.

This allows the pitting corrosion resistance to be estimated from the composition of the steel. The differing efficiencies of the alloying elements is taken into account in the **pitting resistance equivalent (PRE)**.

$$\text{PRE} = \text{mass\% Cr} + 3.3 \times \text{mass\% Mo}$$

The pitting corrosion resistance of the steels increases as the value of the pitting resistance equivalent increases.

Correctly selected materials made of CrNiMo stainless steels have proven suitable in various components of sewage treatment plants, including aerated and buried sewage sludge and digester gas tanks. The few problematic cases to date have been limited to two types of damage, which, however, are not limited to waste water treatment plants, but are generally applicable:

- spots of extraneous rust due to incomplete final cleaning
- crevice corrosion due to deposits that were not removed by routine cleaning
- processing faults

These problems can be avoided by final checks before commissioning the plant and sufficiently high flow rates during operation.

Table 10 gives a selection of DIN and European standards for stainless steels [31].

DIN 17440 [32]	Stainless steels; Technical terms of delivery for sheets, hot-rolled strip, rolled wire, drawn wires, bars, forgings, and semi-finished products
DIN EN 10028-7 [33]	Stainless steels; Technical terms of delivery for cold-rolled strips and split strips as well as sheets cut from them
DIN 17455 [34]	Welded circular tubes made of stainless steels for general quality requirements; Technical terms of delivery
DIN 17456 [35]	Seamless circular tubes made of austenitic stainless steels for general quality requirements; Technical terms of delivery
DIN EN 10217-7 [36]	Welded circular tubes made of austenitic stainless steels for enhanced quality requirements; Technical terms of delivery
DIN 17458 [37]	Seamless circular tubes made of austenitic stainless steels for enhanced quality requirements; Technical terms of delivery
DIN EN 1124-3 [38]	Pipes and fittings of longitudinally welded stainless steel pipes with spigot and socket joints for waste water pipelines – Part 3: System X; Dimensions
SEW 400 [39]	Stainless steels for rolling and forging
DIN EN 10088-1 [40]	List of stainless steels, chemical composition and physical properties
DIN EN 10088-2 [41]	Technical terms of delivery for sheet and strip steel for general purposes
DIN EN 10088-3 [42]	Technical terms of delivery for semifinished products, bars, rolled wire, and sections for general purposes
Applicable to pressure vessels:	
DIN EN 10028-7 [33]	Flat products, bars
DIN EN 10225-5 [43]	Forgings

Table 10: DIN and DIN EN standards for stainless steels [31]

Nowadays, austenitic steels with chromium contents of 18 %, nickel contents of 10–12 % and molybdenum contents of 2–3 % are generally used in preference in waste water treatment plants. Steels that do not contain molybdenum are generally not sufficiently crevice corrosion resistant to the chloride concentrations of approx. 70 mg/l that are typical in waste waters. Repeatedly observed corrosion damage of the gas zone in sludge tanks are attributed to the influence of high concentrations of organic acids. Under these conditions, preference should be given to the use of more highly alloyed metallic materials with an enhanced resistance to acids by alloying with copper, e.g. SAE 904 L (X1NiCrMoCuN25-20-5, 1.4539) or UNS N08926 (X1NiCrMoCuN25-20-7, 1.4529) [44]. Table 11 gives the critical values for the chloride ion concentrations in pure, neutral water for a few commercially available steels with respect to avoiding pitting and crevice corrosion. The critical concentrations decrease with decreasing pH values and increasing temperatures [45].

Alloy	Contents of key alloying components					Max. chloride concentration g/l		Max. temperature K (°C)
	% C	% Cr	% Ni	% Mo	Other	PC	CC	
SAE 304 1.4301 X5CrNi18-10	max. 0.07	18	10	–		0.2	0.02	298 (25)
SAE 304 L 1.4306 X2CrNi19-11	max. 0.03	19	11	–		0.2	0.02	298 (25)
SAE 321 1.4541 X6CrNiTi18-10	max. 0.08	18	10	–	Ti	0.2	0.02	298 (25)
SAE 316 1.4401 X5CrNiMo17-12-2	max. 0.07	17	12	2		1.0	0.2	308 (35)
SAE 316 L 1.4404 X2CrNiMo17-12-2	max. 0.03	17	13	2		1.0	0.2	308 (35)
SAE 316 Ti 1.4571 X6CrNiMoTi17-12-2	max. 0.08	17	12	2	Ti	1.0	0.2	308 (35)
SAE 316 1.4436 X3CrNiMo17-13-3	max. 0.07	17	13	3		5.0	1.0	308 (35)
SAE 316 L 1.4435 X2CrNiMo18-14-3	max. 0.03	18	14	3		5.0	1.0	308 (35)
SAE 317 LMN 1.4439 X2CrNiMoN17-13-5	max. 0.03	17	13	5	N	10.0	5.0	343 (70)
SAE 904 L 1.4539 X1NiCrMoCuN25-20-5	max. 0.03	20	25	5	Cu, N	10.0	5.0	353 (80)
UNS N08926 1.4529 X1NiCrMoCuN25-20-7	max. 0.02	20	25	6	Cu, N	10.0	5.0	353 (80)

PC: pitting corrosion, CC: crevice corrosion

Table 11: Critical concentrations of chloride ions in neutral waters to avoid pitting or crevice corrosion of stainless steels [45]

Figure 2 gives an example of a flow diagram of a waste water treatment plant with the essential components. Table 12 gives the associated operating conditions and the behaviour of the austenitic steel grades CrNi18-8 (type SAE 304, comparable to 1.4301) and CrNiMo18-8-2 (type SAE 316, comparable to 1.4401, 1.4436) for the respective conditions [46].

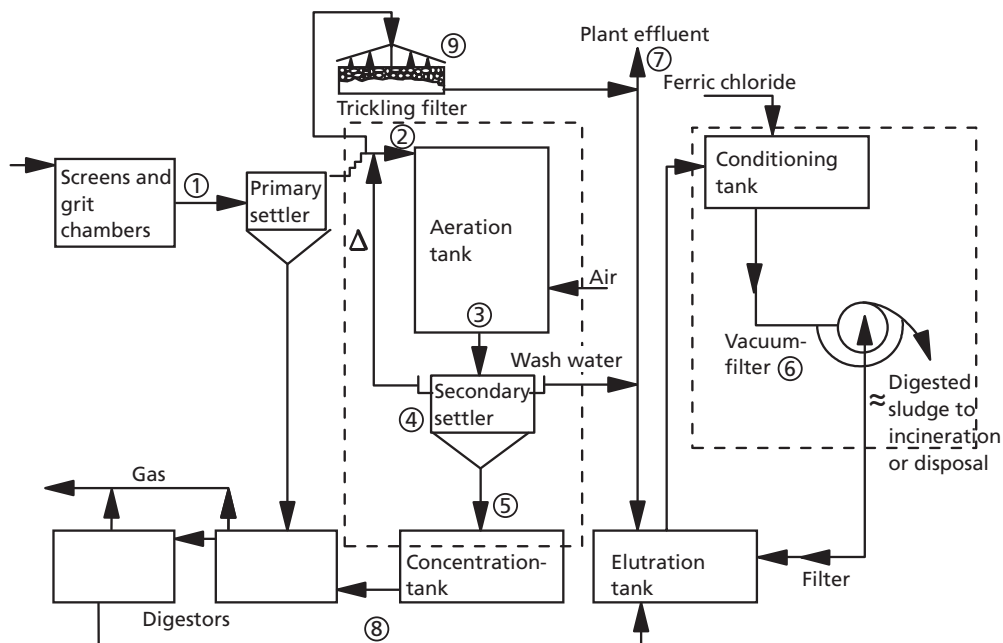


Figure 2: Typical flow diagram of a waste water treatment plant [46]

The corrosion rates for uniform surface corrosion are always less than 0.002 mm/a (0.08 mpy), so that this type of corrosion can be neglected. However, for molybdenum-free steel grades, there is a risk of crevice corrosion in most cases. Both types of steel are also insensitive to damp gases containing H_2S that occur in some parts of the plant. Damp chlorine vapors, which arise if there is insufficient ventilation in the vicinity of chlorine storage tanks, can also lead to pitting corrosion of the 316-type steels at locations where such vapors can collect.

Austenitic steels are sufficiently corrosion-resistant for chlorine concentrations below 3 mg/l, which usually occur if the waste water is chlorinated. The molybdenum-free grades are susceptible to crevice corrosion if they are in continuous contact with waters with a residual chlorine concentration of 3–5 mg/l. Austenitic steels are not suitable in chlorine discharge systems in which the chlorine concentration may reach several hundreds of mg/l.

Iron(III) chloride, which is frequently added as a flocculant to treatment tanks, can lead to pitting corrosion and crevice corrosion of both types of steel.

Plant section ¹⁾	Flow rate	Component	Type 304 ³⁾	Type 316 ³⁾
1		untreated raw water BOD ²⁾ : 175–300 ppm O ₂ : 140 ppm; solids: 220–550 ppm	< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
2	0.6–0.9 m/s	70 % waste water 30 % activated sludge + H ₂ S	< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
3	vigorous	70 % waste water 30 % activated sludge	< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
4	weak	activated sludge some outflow	< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
5	fairly high		< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
6	0.3 m/s no aeration	active sludge FeCl ₃ addition (250–300 ppm)	< 0.002 mm/a (< 0.08mpy) CC + PC	< 0.002 mm/a (< 0.08mpy) CC
7	0.6 m/s moderate aeration		< 0.002 mm/a (< 0.08mpy) PC	< 0.002 mm/a (< 0.08mpy) CC
8	1.2–1.5 m/s intensive aeration	high concentrations of chloride and solids possible	< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC
9	high aeration		< 0.002 mm/a (< 0.08mpy) CC	< 0.002 mm/a (< 0.08mpy) CC

1) Numbering from Figure 2, 2) BOD: Biological Oxygen Demand, 3) Corrosion rate, CC: crevice corrosion, PC: pitting corrosion

Table 12 Operating conditions in the plant sections shown in Figure 2 and corrosion behaviour of austenitic CrNi and CrNiMo steels
(temperature range: 293–298 K (20–25 °C); pH range: 7.4–7.7) [46]

Wet oxidation is a process to oxidise organic waste materials as an alternative to incineration. It is carried out at high temperatures (up to approx. 603 K (330 °C)) and high pressures (up to approx. 250 bar) in aqueous media. This process is used for the treatment of sewage sludge and industrial waste water. The chloride concentration of the waste water is the decisive criterion for the selection of materials for plant components, such as reactors, heat exchangers, high-pressure pumps, and air compressors. Austenitic CrNiMo stainless steels can be used for chloride-free or low-chloride waste waters containing less than 300–400 mg/l chloride. Only special alloys, such as Hastelloy[®] C-276 alloy (cf. 2.4819, NiMo16Cr15W) or Inconel[®] alloy 625 (2.4856, NiCr22Mo9Nb) are suitable for chloride concentrations of 1000 mg/l and

temperatures of approx. 423 K (200 °C). Titanium has proven suitable at higher concentrations [47].

Reference [48] reports on practical experience with respect to the corrosion behaviour of austenitic steels, nickel alloys, and titanium in more than 30 plants used for the wet oxidation of sewage sludge over a period of more than 5 years. It also gives the results of investigations in autoclaves and in a pilot plant under comparable conditions. The investigated materials are given in Table 13. The investigations were carried out in autoclaves on welded U-bend samples and in the pilot plant on pipe samples and on bend samples. The results of these investigations are given in Table 14.

The austenitic steels alloy SAE 304 (1.4301, X5CrNi18-10) and alloy SAE 316 (1.4401, X5CrNiMo17-12-2) were only resistant to stress corrosion cracking in sludges with chloride concentrations of less than 300–400 mg/l and also at temperatures up to 561 K (288 °C). Stress corrosion cracking of steel SAE 316 was observed after 48 hours of exposure to a chloride concentration of 1000 g/l. For information on the behaviour of nickel alloys in these investigations, see corresponding Sections.

Material		Ni	Fe	Cr	Mo	C_{max.}	Other
Hastelloy [®] alloy C-276	2.4819 NiMo16Cr15W	balance	5	16	16	0.015	Co _{max.} 2.5, W 3.5
Inconel [®] alloy 625	2.4856 NiCr22Mo9Nb	balance	max. 5	22	9	0.010	(Nb + Ta) 3.5
Hastelloy [®] alloy G	2.4618 NiCr22Mo6Cu	balance	20	22	6.5	0.015	Cu 2.0, Co _{max.} 2.5, (Nb + Ta) 2.0
28Cr-4Mo	cf. UNS S44700 29-4	max. 0.15	balance	28	4	0.01	(C + N) _{max.} 0.025
28Cr-4Mo-2Ni	cf. UNS S44800 29-4-2	2	balance	28	4	0.01	(C + N) _{max.} 0.025
Incoloy [®] 825	2.4858 NiCr21Mo	42	balance	21	3	0.025	Cu 2
Carpenter [®] 20Cb-3	2.4660 NiCr20CuMo	37	balance	20	2.5	0.05	Cu 3.5, Mn _{max.} 2.0, Nb _{max.} 1.0
Sandvik [®] 2RN65		24	balance	17.5	4.7	0.02	Mn 1.8
E-Brite [®] 26-1		max. 0.5	balance	26	1.0	0.06	
Sandvik [®] 3RE60	1.4417 X 2 CrNiMoSi 19 5	4.7	balance	18.5	2.7	0.03	Si 1.65, Mn _{max.} 2.0

Table 13: Composition (approximate, mean, or maximum % values) of the materials investigated under conditions of wet oxidation of sewage sludge [48]

Table 13: Continued

Material		Ni	Fe	Cr	Mo	C_{max.}	Other
SAE 316	1.4401 X5CrNiMo17-11-2	12	balance	17	2.5	0.08	Mn _{max.} 2.0, Si _{max.} 1.0
SAE 304	1.4301 X5CrNi18-10	9	balance	18		0.08	Mn _{max.} 2.0, Si _{max.} 1.0
Titanium			balance				Ti 99.5

Table 13: Composition (approximate, mean, or maximum % values) of the materials investigated under conditions of wet oxidation of sewage sludge [48]

Material	DIN-Mat. No.	Autoclave experiments 477 K (204 °C)			Pilot plant 450 K (177 °C)
		Chloride concentration			
		600 mg/l	1000 mg/l	3000 mg/l	1000 mg/l
Titanium		0	0	0	0
Hastelloy [®] alloy C-276	2.4819 NiMo16Cr15W	0	0	PC	0
Inconel [®] alloy 625	2.4856 NiCr22Mo9Nb	0	0	PC	0
Hastelloy [®] alloy G	2.4618 NiCr22Mo6Cu	0	PC; CC	PC;CC	–
28Cr-4Mo	cf. UNS S44700 29-4	0	PC; CC	PC;CC	PC
28Cr-4Mo-2Ni	cf. UNS S44800 29-4-2	0	PC; CC	PC;CC	–
Incoloy [®] 825	2.4858 NiCr21Mo	PC; CC	PC; CC	PC; CC	PC
Carpenter [®] 20Cb-3	2.4660 NiCr20CuMo	PC; CC	PC; CC	PC; CC	PC
Sandvik [®] 2RN65		–	PC;CC; SCC	PC;CC; SCC	PC;SCC
E-Brite [®] 26-1		PC; CC	PC; CC	PC; CC	PC
Sandvik [®] 3RE60	1.4417 X 2 CrNiMoSi 19 5	PC; CC	PC;CC; SCC	PC;CC; SCC	PC;SCC
SAE 316	1.4436 X3CrNiMo17-13-3	PC;CC; SCC	PC;CC; SCC	–	PC;CC; SCC

0 = No corrosion, PC = pitting corrosion, CC = crevice corrosion, SCC = stress corrosion cracking

Table 14: Results of corrosion tests of the materials listed in Table 13 [48]

Pipe-in-pipe heat exchangers made of four different alloys were tested in a wet oxidation unit for sewage sludge over a period of 1600 h under the following operating conditions.

Temperature	294–466 K (21–193 °C)
pH	5.1
Chloride concentration	250–500 ppm
Sludge composition	
COD (Chemical Oxygen Demand)	26.1 g/l
Total volatile acids	0.6 g/l
NH ₃ , total	0.06 g/l
N, total	0.31 g/l
P, total	0.10 g/l
Solids, total	22.0 g/l
Volatile substances	14.4 g/l
Sulphur, total	0.17 g/l
Alkalinity calculated as CaCO ₃	0.24 g/l
Soluble chlorides	0.51 g/l

Table 15: Experimental conditions in a wet oxidation unit for sewage sludge [49]

The investigated materials were stainless steel SAE 316 L (1.4401, X5CrNiMo17-12-2) and the nickel alloys Incoloy® 825 (2.4858, NiCr21Mo), Hastelloy® alloy G (2.4618, NiCr22Mo6Cu) and Hastelloy® alloy C-276 (DIN-Mat. No. 2.4819, NiMo16Cr15W). The dismantled heat exchangers were examined after completion of the test. Depending on the operating conditions and the alloy, some of them exhibited pitting corrosion as well as crevice corrosion and stress corrosion cracking. All the investigated materials exhibited uniform surface corrosion rates of 0.03–0.06 mm/a (1.18–2.36 mpy). Table 16 gives the limiting temperatures of the materials with respect to local corrosion for these test conditions [49].

Material	Limiting temperature
Alloy 316 L 1.4401, X5CrNiMo17-12-2	366 K (93 °C)
Incoloy® 825 2.4858, NiCr21Mo	395 K (122 °C)
Hastelloy® alloy G 2.4618, NiCr22Mo6Cu	395 K (122 °C)
Hastelloy® alloy C-276 2.4819, NiMo16Cr15W	466 K (193 °C) ¹⁾

¹⁾ Final temperature of the test

Table 16: Limiting temperatures for the occurrence of local corrosion in a wet oxidation unit for sewage sludge [49]

A study was carried out with a large number of individual and mixed waste waters in test plants at pressures of 150–200 bar, temperatures of 543–603 K (270–330 °C) and with variations of the chloride, sulphate, and phosphate concentrations, the pH values as well as the COD values (Chemical Oxygen Demand). The following metallic materials were examined in this study with regard to their suitability in wet oxidation plants for industrial waste waters: chromium-nickel-molybdenum steel 1.4571 (X6CrNiMoTi17-12-2), titanium, tantalum, and nickel. None of the investigated materials was resistant at acidic pHs. At pH values > 7, titanium and tantalum were resistant, even in the presence of low fluoride concentrations and chloride concentrations of up to 100 g/l [50].

The standard stainless steels of type SAE 300 series (cf. SAE 304, 1.4301, X5CrNi18-10; SAE 321, 1.4541, X6CrNiTi18-10; SAE 316, 1.4401, X5CrNiMo17-12-2; SAE 316 Ti, 1.4571, X6CrNiMoTi17-12-2) exhibited sufficient resistance to damp hydrogen sulphide and to waters containing low concentrations of sulphuric acid. They are used in biological waste water plants for pipelines to extract odorous gases as well as for aeration screens and ladders [51].

The chromium-nickel steel SAE 304 (1.4301, X5CrNi18-10) is resistant to ozone-containing water (Table 3).

Austenitic chromium-nickel steels have proven suitable in all sections (collecting tanks for various industrial waste waters, treatment tanks) in a biological sewage treatment plant [8].

References [52] and [53] point out that the oxidic passive layer on stainless steels only develops its full effectiveness if the material has been properly processed. If this work is not carried out properly, it may result in damage at a lower corrosive load than the expected nominal resistance. Table 17 lists the processing steps that can have a negative effect on the corrosion resistance of the materials [52]. Figure 3 shows the influence of **tarnishes**, which may be produced during welding, on the pitting potential of the austenitic steel 1.4571 (SAE 316 Ti, X6CrNiMoTi17-12-2).

Tarnishes must be completely removed by pickling with nitric acid/hydrofluoric acid [52].

Reference [54] gives a general discussion of the effect of tarnishing on the pitting corrosion of austenitic steels. With respect to this, the author emphasises the common practice of removing all tarnishing to prevent any pitting corrosion. It is now considered standard practice to avoid tarnishing. If tarnishing cannot be prevented, the materials must be pickled. If there are places where it is not possible to check for tarnishing and thus its presence cannot be reliably excluded, the materials must be pickled.

Factors influencing corrosion	Production step causing corrosion
Chemical composition	melting welding, weld filler, welding parameters
Microstructure	hot and cold forming, heat treatment
Precipitations • intermetallic phases • nonmetallic compounds	heat treatment welding, welding parameters
Gaps	constructive design flanges, sleeves, seals, weldments
Superficial contaminants • Inclusions of foreign metals • Notches • Oxide layers	mechanical processing and machining; shaping, cutting, grinding, peening, welding
Surface roughness	surface treatment peening, grinding, pickling
State of stress	welding, construction, production, assembly

Table 17: Possible influences of the material during production [52]

It is just as important that the construction has been properly executed for the particular material taking account of the specific strength and elasticity values, careful assembly, as well as parting and joining techniques during assembly [52, 53].

The immersion motor pumps that were made of chromium-nickel-molybdenum steel SAE 316, 1.4401 (X5CrNiMo17-12-2) were compared to those made of cast iron. In addition to a better corrosion resistance, the CrNiMo steel pumps also have the advantage of a smooth and poreless surface and can thus be cleaned more easily if used in waste water treatment tanks [13].

CrNiMo pumps made of rolled, thick walled material that have a poreless and void-less surface have considerable advantages with respect to their susceptibility to biocorrosion owing to their lower roughness, which can be as low as approx. 1 µm Ra after a corresponding surface finishing [55–57].

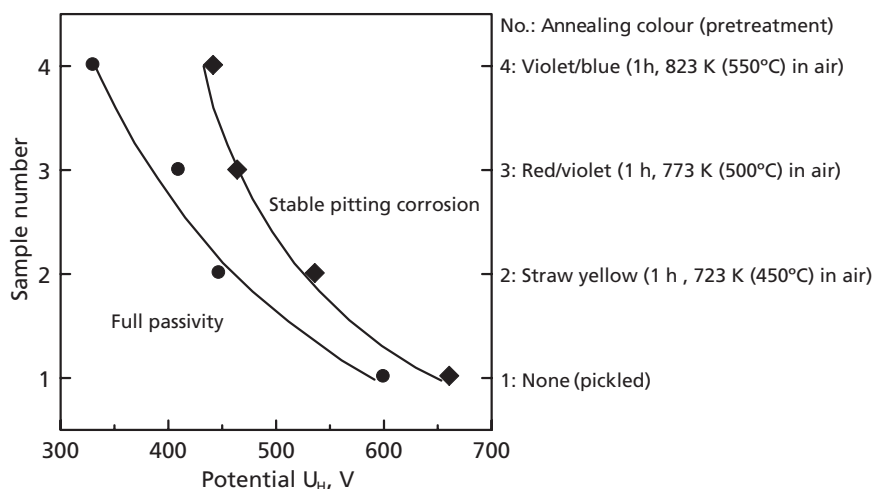


Figure 3: Influence of tarnishing on the pitting corrosion potential of steel 1.4571 (X6CrNiMoTi17-12-2); 0.01 M NaCl, 303 K (30 °C) [52]

The austenitic chromium-nickel-molybdenum steel UNS N08904 (1.4539, X1NiCrMoCu25-20-5) has proven suitable as a material for the head cooler of stripper units used in waste water treatment plants of refineries [26]. The operating parameters are summarised in Table 18.

	<i>Inner surface of the pipe</i>	<i>Outer surface of the pipe</i>
Medium	cooling water with 2 % chlorides	stripped acidic water
Temperature	323 K (50 °C)	403 K (130 °C)
Pressure	0.5 MPa	1.0 MPa

Table 18: Operating parameters of UNS N08904 (1.4539, X1NiCrMoCu25-20-5) in a stripping unit [26]

The chromium-nickel-molybdenum steels 1.4571 (SAE 316 Ti, X6CrNiMoTi17-12-2) and particularly 1.4435 (SAE 316 L, X2CrNiMo18-14-3) are resistant to crevice corrosion, which can occur under the operating conditions in a digester if steels with lower alloy contents are used. The importance of the correct constructive design as well as the elimination of welding tarnishes by pickling is discussed [58].

The raw waters produced in waste water treatment plants or seawater desalination plants that operate on the principle of reverse osmosis must also be treated. Suitable materials for the pipelines must have good corrosion resistance to chlorides and other aggressive ingredients in the media as well as good strength properties to be able to withstand the pressures occurring during the reverse osmosis process. The requirements demanded by some of the operating conditions are fulfilled

by the austenitic chromium-nickel steel X1NiCrMoCuN25-20-7 (DIN-Mat. No. 1.4529) which contains 6–7 % molybdenum [59].

Filters made of stainless steel of grade CrNi18-10 exhibited pitting corrosion due to contact corrosion with the activated carbon that is used for waste water treatment. Activated carbon is electrochemically more noble than steel. Suitable countermeasures include modification of the filter design and more frequent cleaning of the filters. The chemical composition of the steels for the outer and the inner pipes are given in Table 19 [60].

	<i>Outer pipe</i>	<i>Inner pipe</i>
C	0.06	0.06
Si	0.57	0.76
Mn	1.76	1.04
P	0.038	0.030
Cr	18.74	18.38
Ni	11.03	8.51
Mo	0.39	0.13

Table 19: Chemical composition of the corroded pipes [60]

For small evaporator units, e.g. those used to concentrate emulsions for drilling, cutting, grinding, and deep-drawing, as well as process solutions and rinsing baths used for surface treatments during electroplating, pickling, anodising, phosphating, EPS coating, and painting, the austenitic chromium-nickel-molybdenum steel 1.4571 (SAE 316 Ti, X6CrNiMoTi17-12-2) is used for components exposed to dirty water and distillates, such as evaporators and heat exchangers [61].

According to the Federal Water Resources Act (Wasserhaushaltsgesetz, 17th BImSchV), from 1996 onwards, all waste waters must be treated, including those from flue gas desulphurisation plants (FGD), from the drying of activated sludge, as well as landfill leachates. Because of the higher levels of pollutants, particularly heavy metals in waste waters, the stipulations given in the approvals must be taken into account for the construction of new thermal waste recycling plants. Such waste waters are treated in waste water evaporator units. Salt concentrations of up to 60 % may arise that crystallise to give a disposable or a reusable salt as the end product. The very high chloride concentrations and temperatures up to approx. 393 K (120 °C) require a high corrosion resistance of the metallic construction materials in the waste water evaporator units [62]. Stainless steels soon exhibit pitting corrosion, crevice corrosion, and stress corrosion cracking, so that preference is given to nickel alloys. An average FGD waste water analysis is given in Table 20 [63]. The samples were analysed after a two-stage concentration process and after concentration in the thin-film evaporator in the final stage. The waste water is evaporated at almost neu-

tral pH values. The suitability of the metal materials for components in evaporator units are given in Table 21 [63].

<i>Main components</i>	<i>Initial concentration (%)</i>	<i>Concentrated to 1:6 after 2-stage evaporation (%)</i>	<i>Concentrated to 1:8 after the thin-film evaporator (%)</i>
Anions:			
Chloride	4.50	27.00	36.00
Fluoride	0.006	0.036	0.048
Bromide	0.01	0.06	0.08
Iodide	0.005	0.03	0.04
Sulphate	0.14	0.84	1.12
Nitrate	0.10	0.60	0.80
Cations:			
Calcium	1.80	10.80	14.40
Potassium	0.03	0.18	0.24
Sodium	0.18	1.08	1.44
Magnesium	0.40	2.40	3.20
Aluminium	0.015	0.09	0.12
Sum of the heavy metals	0.008	0.05	0.066
Silicic acid	0.015	0.09	0.12
DOC	0.003	0.018	0.02

DOC = dissolved organic carbon

Table 20: Average waste water analysis values from a flue gas desulphurisation unit [63]

<i>Material</i>	<i>Standard abbreviations</i>			<i>Composition, approx. values (%)</i>					
	<i>DIN-Mat. No.</i>	<i>Alloy</i>	<i>UNS</i>	<i>Ni</i>	<i>Cr</i>	<i>Fe</i>	<i>Mo</i>	<i>other</i>	
X1NiCrMoCuN25-20-7 (Cronifer® 1925 hMo)	1.4529	926	N08926	25	21	balance	6.5	Cu 0.9; N 0.2	
X1NiCrMoCu32-28-7 (Nicrofer® 3127 hMo)	1.4562	31	N08031	31	27	balance	6.5	Cu 1.2; N 0.2	
NiCr22Mo9Nb (Nicrofer® 6020 hMo)	2.4856	625	N06625	62	22	2	9	Nb 3.5	
NiMo16Cr15W (Nicrofer® 5716 hMoW)	2.4819	C-276	N10276	57	16	6	16	W 3.8	
NiCr23Mo16Al (Nicrofer® 5923 hMo)	2.4605	59	N06059	59	23	1	16	–	

Table 21: Stainless steels and nickel-based alloys for environmental engineering [63]

The materials listed in Table 21 were investigated by simulating laboratory tests under operating conditions and exposure tests in waste water evaporator units of flue gas desulphurisation plants and waste incineration plants [64]. It was confirmed that only an approximate resistance can be estimated for the metallic materials in these plant sections. Precise material resistance data can only be determined for actual plants. The mass losses determined for alloy C-276 and alloy 59 after an exposure time of 9 months was only 0.053 mm/a (2.09 mpy) and 0.045 mm/a (1.77 mpy), respectively, with respect to the term of exposure. Therefore, they do not have technical significance. This results in the following proposal for materials for pipelines and tanks of waste water evaporator units of flue gas desulphurisation plants

- for the 1st evaporation stage: X1NiCrMoCu32-28-7, 1.4562 (Nicrofer® 3127 hMo, alloy 31)
- for the 2nd evaporation stage: NiCr23Mo16Al, 2.4605 (Nicrofer® 5923 hMo, alloy 59)
possibly also : NiMo16Cr15W, 2.4819 (Nicrofer® 5716 hMoW, alloy C-276)

The high-alloy austenitic steel 1.4529 (X1NiCrMoCuN25-20-7) and the nickel alloy Inconel® alloy 625 (NiCr22Mo9Nb, 2.4856) are not sufficiently resistant for the third concentration stage of waste waters from flue gas desulphurisation plants using thin-film evaporators. Alloy C-4 (NiMo16Cr16Ti, 2.4610) is not always sufficiently resistant. Laboratory tests indicated that the most resistant material is alloy 59 (NiCr23Mo16Al, 2.4605). However, in this case, the pH value must not drop below pH 5 and the redox potential must not increase into the transpassive dissolution range of this NiCrMo alloy. In addition, the design must avoid crevices as far as possible [62-65].

Austenitic steels for the evaporation of problematic leachates from special waste landfills were not sufficiently resistant to pitting corrosion when exposed to chloride concentrations of up to 6 g/l at the given temperatures [66].

Tanks for vehicles used to recover materials that are hazardous to water and waste media after accidents at sea or on land must be qualified with respect to the resistance of the tank materials. Statements on the resistance of tank materials to hazardous materials are given in the following regulations:

- List from the Bundesanstalt für Materialforschung und -prüfung (BAM, German Federal Institute for Materials Research and Testing): Requirements for tanks used to transport hazardous goods [67]
- Ordinance on the transport of hazardous goods on roads (Gefahrgutverordnung Straße – GGVS) [68]
- DIN 6601 [69]: Resistance of materials of steel tanks against liquids, (positive list of liquids)

On the basis of the evaluated literature data, X1NiCrMoCuN25-20-7 (1.4529, cf. UNS N08926) has been qualified for the transport of more than 1000 media [70].

In a Russian study of construction materials to test for their suitability for industrial waste water plants in which the samples were exposed for 8 h/d with stirring to the waste water media [Table 22], only the steel 06ChN28MDT (22–25 % Cr, 26–29

% Ni, 2.5–3 % Mo, 2.3–3.5 % Cu) proved to be resistant in acidic waste water (Medium 1) with a corrosion rate of 0.002 mm/a (0.08 mpy). The steels from Table 23 were also resistant in neutralised waste water (Medium 2) [71].

	Medium 1 acidic waste water	Medium 2 waste water neutralised with NaOH and lime milk
pH	0.95–2.7	7.1
Cl ⁻	3.2–10.3 g/l	3.7 g/l
NO ₃ ⁻	0.13 g/l	0.05 g/l
NH ₄ ⁺	0.26 g/l	0.08 g/l
SO ₄ ²⁻		7.4 g/l
Br ⁻		0.2 g/l
Nitro compounds	0.008–0.300 g/l	
Amino compounds	0.17–0.40 g/l	
Phenolic compounds	0.007–0.028 g/l	

Table 22: Analysis of the waste water [71]

Grade (Russian)	Analysis	Abbreviation
06ChN28MDT	0.06 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.020 S, 22–25 Cr, 2.5–3.5 Cu, 2.5–3.0 Mo, 26–29 Ni, 0.5–0.9Ti	–
12Ch13	0.09–0.15 C, 0.80 Si, 0.80 Mn, 0.030 P, 0.025 S, 12–14 Cr, 0.30 Cu, 0.60 Ni, 0.20 Ti	1.4006, X12Cr13, SAE 410
08Ch17T	0.08 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.025 S, 16–18 Cr, 0.30 Cu, 0.60 Ni	1.4510, X3CrTi17
15Ch25T	0.15 C, 1.0 Si, 0.80 Mn, 0.035 P, 0.025 S, 24–27 Cr, 0.30 Cu, 1.0 Si	–
08Ch22N6T	0.08 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.025 S, 21–23 Cr, 0.30 Cu, 0.30 Mo, 5.30–6.30 Ni, 0.20 W	–
12Ch18N10T	0.12 C, 0.80 Si, 2.0 Mn, 0.035 P, 0.020 S, 17–19 Cr, 0.30 Cu, 0.50 Mo, 9–11 Ni, 0.20 W	1.4541, SAE 321, X6CrNiTi18-10
08Ch21N6M2T	0.08 C, 0.80 Si, 2.0 Mn, 0.035 P, 0.025 S, 20–22 Cr, 0.30 Cu, 1.80–2.50 Mo, 5.5–6.5 Ni, 0.20–0.40 Ti, 0.20 W	
10Ch17N13M2T	0.10 C, 0.80 Si, 2.00 Mn, 0.035 P, 0.020 S, 16–18 Cr, 0.30 Cu, 2.00–3.00 Mo, 12–14 Ni, 0.20 W	1.4571, SAE 316 Ti, X6CrNiMoTi17-12-2
06ChN28MDT	0.06 C, 0.80 Si, 0.80 Mn, 0.035 P, 0.020 S, 22–25 Cr, 26–29 Ni, 2.5–3 Mo, 2.5–3.5 Cu, 0.5–0.9 Ti	

Table 23: List of Russian steel grades that are resistant to neutralised waste water (Medium 2 from Table 22) [71]

Nickel-chromium alloys

Nickel-chromium-iron alloys (without Mo)

Nickel-chromium-molybdenum alloys

Nickel-copper alloys

Nickel-based alloys of the Hastelloy® group (alloy C-4, NiMo16Cr16Ti, 2.4610, alloy C-276, NiMo16Cr15W, 2.4819) and Inconel® 625 (NiCr22Mo9Nb, 2.4856) have proven resistant to chloride concentrations of approx. 1000 mg/l and temperatures of approx. 573 K (300 °C) in wet oxidation units for sewage sludge and waste water.

NiCrMo alloys with high molybdenum contents can be used in waste water evaporator units of FGD plants. Their resistance decreases in the following order: 59 (NiCr23Mo16Al, 2.4605), alloy C-22 (NiCr21Mo14W, 2.4602), and alloy C-276 (NiMo16Cr15W, 2.4819).

The nickel-copper Monel® 400 (NiCu 30 Fe, 2.4360) can be used in evaporator/crystallisation units for FGD waste waters at 363 K (90 °C) and pH values from pH 8–10. It exhibits a corrosion rate of 0.04 mm/a.

Investigations of the suitability of nickel alloys Hastelloy® alloy C-276 (2.4819, NiMo16Cr15W), Incoloy® 825 (2.4858, NiCr21Mo) and Hastelloy® alloy G (2.4618, NiCr22Mo6Cu) as materials for heat exchanger pipes in a wet oxidation unit for sewage sludge are reported in [49]. The experimental conditions in the wet oxidation plant for sewage sludge are given in Table 15. Hastelloy® alloy C-276 was resistant up to the final testing temperature of 466 K (193 °C), Incoloy® 825 and Hastelloy® alloy G were resistant up to 395 K (122 °C).

The evaluations of the behaviour of various metallic materials from more than 30 plants used to treat sewage sludges with the wet oxidation process after more than 5 years and supplementary test results showed that Hastelloy® alloy C-276 (2.4819, NiMo16Cr15W) and Inconel® alloy 625 (2.4856, NiCr22Mo9Nb) are resistant under the corresponding operating conditions with up to 1000 mg/l chloride. Both alloys exhibited signs of attack when exposed to 3000 mg/l Cl⁻ ions. Hastelloy® alloy G can only be used up to approx. 600 mg/l Cl⁻. The remaining alloys (see Table 13) exhibited noticeably lower operating limits (Table 14) [48].

Reference [72] summarises the results of intensified SCC tests of various nickel-based materials under conditions simulating wet oxidation (Table 24). The test solution had the following composition:

- 3,000 ppm acetic acid
- 7,500 ppm oxygen
- 2,500 ppm carbon dioxide
- 1,000 ppm chloride
- 5 ppm fluoride

The test was carried out on C-ring samples at a temperature of 565 K (292 °C) and a pressure of 107 bar. Only Hastelloy® alloy C-276 did not show any stress corrosion

cracking and pitting corrosion. The other materials reacted in the following order of decreasing resistance:

Inconel[®] alloy 625

Hastelloy[®] alloy G

E-Brite[®] 26-1

Carpenter[®] 20 Cb-3

Wet oxidation units are used to treat waste waters and sludges that contain contaminants which are difficult to biodegrade and which are frequently produced in the chemical industry. They are treated at temperatures up to 603 K (330 °C) and pressures up to 250 bar. The following materials are proposed for concentrations of 1000 mg/l chloride and temperatures of 573 K (300 °C): nickel-chromium-molybdenum alloys of the Hastelloy[®]-C group (C-4, NiMo16Cr16Ti, 2.4610; C-276, 2.4819, NiMo16Cr15W; C-22, NiCr21Mo14W, 2.4602) and Inconel[®] alloy 625 (2.4856, NiCr22Mo9Nb). Titanium has proven suitable for higher chloride concentrations, whereas Hastelloy[®] C exhibited considerable pitting corrosion in a waste water containing 80 g/l NaCl at 493 K (220 °C). Comparisons of economic viability have been carried out for processes based on adsorption, biological treatment, and incineration, whose range of applications depend on the COD value (Chemical Oxygen Demand) of the waste water [47].

The desulphurisation of flue gases in coal-fired power plants is usually carried out with wet processes. This scrubbing process uses suspensions of lime milk or limestone to remove sulphur dioxide as well as all other water-soluble components in the flue gases, e.g. halogen hydric acids. In the evaporation process used to treat these scrubbing fluids from flue gas desulphurisation plants in coal-fired power plants and waste incineration plants, the aqueous phase that has been separated from the solids contains high concentrations of soluble salts, mainly calcium chloride (see Table 20) [63]. Table 25 summarises results from extensive laboratory investigations in simulated test solutions. These results, which have been confirmed by exposure tests, indicate that only NiCrMo alloys with molybdenum contents greater than 14 % can be used for the highest exposure levels. These include alloy C-22 (DIN-Mat. No. 2.4602, NiCr21Mo14W), alloy C-276 (DIN-Mat. No. 2.4819, NiMo16Cr15W), alloy C-4 (DIN-Mat. No. 2.4610, NiMo16Cr16Ti) [65]. Subsequent laboratory investigations of alloy 59 (DIN-Mat. No. 2.4605; NiCr23Mo16Al) showed it to be the most resistant material. However, it must be ensured that the pH value does not drop below pH 5, if possible, and that the redox potential cannot increase into the transpassive dissolution range. Crevices must be avoided [62, 63, 65].

Materials		SCC in the liquid phase fractured samples, tested samples, test duration	Corrosion rate (max.) mm/a (mpy)		Susceptibility to pitting corrosion ¹⁾	
Alloy	Abbreviation		Vapor phase	Liquid phase	Vapor phase	Liquid phase
C-276	2.4819, UNS N10276 NiMo16Cr15W	0	0.04 (1.57)	0.04 (1.57)	0	0
625	2.4856, UNS N06625 NiCr22Mo9Nb	0	0.06 (2.36)	0.6 (23.62)	1	2
G	2.4618, UNS N06007 NiCr22Mo6Cu	0	0.18 (7.09)	2.1 (82.68)	1	1
26-1	UNS S44626	3 of 10 in 281 h	0.33 (12.99)	0.71 (27.95)	2	3
20Cb-3	2.4660, UNS N08020 NiCr20CuMo	0	0.25 (9.84)	2.7 (106.3)	3	4
20Cb-3 pipe		1 of 10 in 440 h			3	4
825	2.4858, UNS N08825 NiCr21Mo	1 of 9 in 295 h	0.16 (6.3)	5.2 (204.72)	2	4
Nitronic® 50	1.3964 X2CrNiMnMoNb21-16-5-3	9 of 10 in 30 h	0.24 (9.45)	3.3 (129.92)	2	3
Nitronic® 10		8 of 10 in 16 h	0.66 (25.98)	4.5 (177.17)	2	3
Nitronic® 60	UNS S21800	9 of 10 in 11 h	2.6 (102.36)	5.2 (204.72)	3	1
Nitronic® 33		9 of 10 in 11 h	1.0 (39.37)	13.4 (527.56)	2	4
SAE 316 L	1.4404	10 of 10 in 12 h			3	3
SAE 304 L	1.4306	10 of 10 in 12 h			3	3

1) 0 = none, 1 = slight, 2 = medium, 3 = heavy, 4 = very heavy

Table 24: Results of intensified SCC tests on various nickel-based materials under conditions simulating wet oxidation [72]

Test solution	pH value	Redox potential		Materials				
		mV _{NHE}		UNS N08926 1.4529 X2NiCrMoCu25-20-6	UNS N06625 2.4856 NiCr22Mo9Nb	UNS N06022 2.4602 NiCr21Mo14W	UNS N10276 2.4819 NiMo16Cr15W	UNS N06455 2.4610 NiMo16Cr16Ti
500 g/l CaCl ₂ 30 g/l NaCl	9.4	445		pitting	pitting	pitting	pitting	pitting
200 g/l CaCl ₂ 30 g/l NaCl	8.7	525		pitting	pitting	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl	3.0 ¹⁾	635		pitting	pitting	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 100 mg/l Fe ³⁺	3.0 ¹⁾	615		pitting	pitting	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l Fe ³⁺	1.4	855		pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l Fe ³⁺ SO ₂ saturated	< 1	335		pitting	passive	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 100 mg/l F ⁻	3.0 ¹⁾	665		pitting	pitting	passive	passive	passive
200 g/l CaCl ₂ 30 g/l NaCl 1000 mg/l F ⁻	3.0 ¹⁾	635		pitting	pitting	passive	passive	passive

1) pH adjusted with HCl

Table 25: Results of electrochemical corrosion tests (holding time 48 h) with polarisation of the materials to the redox potential of the aerated test solution at 353 K (80 °C) [65]

Because of their lack of susceptibility to chloride-induced stress corrosion cracking, nickel-copper alloys are used in seawater desalination plants as pipes for evaporators or heat exchangers. An evaporator made of alloy 400 (NiCu 30 Fe, 2.4360) exhibited a corrosion rate of > 0.01 mm/a (> 0.4 mpy) after an exposure time of 225 days to a CaCl_2 concentration of up to 35 % and a temperature of 433 K (160 °C). The corrosion rate was 0.07 mm/a (2.76 mpy) for a NaCl solution saturated with water vapor and air at 366 K (93 °C) [73].

Alloy 400 (NiCu30Fe, 2.4360) was used in three stages of the evaporator/crystallisation unit for waste water from the absorption fluid of a flue gas desulphurisation plant at 364 K (91 °C) and a pH value of 8–10. A corrosion rate of 0.04 mm/a (1.57 mpy) was measured after an operating time of 4 years. The alloy was used because the previously fitted rubber-coated steel components required frequent repairs [74].

Zinc

The most commonly used method of coating steel parts with a metal layer is hot-dip galvanising. For this, the steel part is given a suitable surface treatment and is then dipped into a zinc melt. A zinc-iron alloy is formed first, and a zinc layer then grows on top. This produces a uniform, poreless, and firmly adhering corrosion protection coating. The good corrosion behaviour of zinc coatings is essentially determined by the dense and firmly adhering top layers produced in air. The thickness of the zinc coating is

- 50 μm to 150 μm for individually galvanised parts
- more than 60 μm for galvanised pipes
- 10 μm to 70 μm for strip galvanising

Examples for the use of hot-dip galvanised components for waste water engineering are described in [75, 76].

For the use of galvanised steel parts in sewage treatment plants, a differentiation is made between the above-water zone and zone in contact with the waste water. Much positive long-term experience has been made with galvanised components in the above-water zone, e.g. for brackets, supports, handrails, etc. An additional coating of the zinc layer is recommended (the so-called duplex process) [77]. An assessment of the corrosion protection effect in the zone in contact with the water is primarily based on the understanding of the chemical and physical criteria of the waste water and the type of processing during treatment. The following limiting values of the waste water must be observed for the use of hot-dip galvanised components without a coating:

- pH value 6.5 to 9.0 (temporarily 6.0 to 9.5).
- Chloride ion concentrations up to 300 mg/l (temporarily up to 1000 mg/l).
- The effects of other neutral salts are regarded as secondary; the electrical conductivity should not exceed 100 mS/cm.
- Maximum copper ion concentration of 0.064 mg/l. If the Cu concentration in the water exceeds this value, there is a risk of copper-induced corrosion.

Bibliography

- [1] DIN 4045 (08/2003)
Abwassertechnik – Grundbegriffe
(Sewage technology – basic ideas)
(in German)
Beuth Verlag GmbH, Berlin
- [2] Belhateche, D. H.
Choose appropriate waste water
treatment technologies
Chem. Eng. Progr. (1995) August,
p. 32–51
- [3] Peters, R.; Oresik, W. L.; Engelder, C. L.;
Gopalratnam, V. C.; Greenfield, J.
Physical and chemical methods
Journal WPCF 59 (1987) 6, p. 364–388
- [4] Abwassertechnologie (Sewage
technology)
Entstehung, Ableitung, Behandlung,
Analytik der Abwässer
(Emergence, derivative, treatment,
analysis of sewage) (in German)
Springer Verlag, Berlin, 2nd ed., 1994
- [5] Hartinger, L.
Handbuch der Abwasser- und
Recyclingtechnik für die
metallverarbeitende Industrie
(Handbook of sewage-recycling
techniques for the metalworking
industry) (in German)
Hanser Verlag, München, 1991
- [6] Bank, M.
Basiswissen Umwelttechnik: Wasser,
Boden, Abfall, Lärm, Umweltrecht,
3rd ed.
(Basic knowledge environment
engineering: water, soil, waste, noise,
environmental law) (in German)
Vogel Verlag, Würzburg, 1995
- [7] ATV – Handbook
Industrieabwasser – Grundlagen;
4th ed. 1999
(Industrial waste water – basics)
(in German)
Gesellschaft zur Förderung der
Abwassertechnik e. V., Hennef
- [8] Meißner, J.
Ergebnisse aus
Werkstoffuntersuchungen für die
Investitionsvorbereitung einer Anlage
zur biologischen
Industrieabwasserbehandlung
(Results from material tests for capital
expenditure planning of a biological
industrial waste water treatment plant)
(in German)
Chem.Techn. 31 (1979) 11, p. 574–567
- [9] Matsudaira, M.; Suzuki, M.; Sato, Y.
Technical Note: Dissolved ozone effect on
corrosion of metals in water
Mater. Performance. 20 (1981) 11,
p. 55–56
- [10] Wasel-Nielen, J.; Baresel, M.
Kühlwasserbehandlung mit Ozon in der
Hoechst AG im Vergleich zu anderen
mikrobiziden Verfahren
(Cooling water treatment with ozone by
Hoechst AG) (in German)
VGB Kraftwerktechn. 77 (1997) 2,
p. 130–134
- [11] Lee, W.; Lewandowski, Z.; Nielsen, P. H.;
Hamilton, W. A.
Role of sulphate-reducing bacteria in
corrosion of mild steel: a review
Biofouling (London) 8 (1995) 3,
p. 165–194
- [12] Assad, S.; Barakat, M. R.; Narain, S.;
Prasada, R.
Case histories of corrosion problems in a
waste water treatment plant
Mater. Perform. 24 (1985) 9, p.23–27
- [13] Arnswald, W.
Referat Nr. 5: Nichtrostende Stähle bei
Tauchmotorpumpen für Abwässer
(Paper no. 5: Stainless steels in
submersible motor-driven pumps for
sewage) (in German)
Specialized meeting “Nichtrostende
Stähle in der Abwasserbehandlung”,
Berlin, November 1995
Informationsstelle Edelstahl Rostfrei,
Düsseldorf; Nickel Development
Institute, London, Toronto; Institut für
Korrosionsschutz, Dresden

- [14] Tamm, G. U.
Referat Nr. 6.: Vermeidung von Biokorrosion bei Pumpen für Abwässer (Paper no. 6: Avoiding biocorrosion with pumps for sewage) (in German)
Specialized meeting "Nichtrostende Stähle in der Abwasserbehandlung", Berlin, November 1995
Informationsstelle Edelstahl Rostfrei, Düsseldorf; Nickel Development Institute, London, Toronto; Institut für Korrosionsschutz, Dresden
- [15] Kratzer, A.; Heumann, A.; Wittekindt, W.
Tauchmotorpumpen aus korrosions- und verschleissbeständigen Werkstoffen (Submersible motor pumps from corrosion and wear resistant materials) (in German)
Chemie-Technik 13 (1984) 12, p. 63
- [16] DIN EN 598 (05/2005)
Ductile iron pipes, fittings, accessories and their joints for sewerage applications – Requirements and test methods
Beuth Verlag GmbH, Berlin
- [17] Rummel, M.
Auswahlkriterien für Rohrwerkstoffe aus Sicht des Planers
(Criteria for the selection of materials for pipes as seen by a designer) (in German)
Abwassertechnik 48 (1997) 1, p. 21–24
- [18] Kratzer, A.
Werkstoffe für die Abwassertechnik (Materials for sewage technology) (in German)
Umwelt (Düsseldorf), 13 (1983) 5, p. 355–357
- [19] Schneider, U.; A.Ruhm
Tauchmotorpumpen: Allrounder für die Entsorgung und Aufbereitung (Submersible motor-driven pumps: Allrounder for disposal and treatment) (in German)
cav (1995) 12, p. 10
- [20] Anonymous
Verschleißfester Werkstoff für Abwasserpumpen (Wear-resistant material for waste water pumps) (in German)
Industrie-Anzeiger 101 (1979) 8, p. 15
- [21] Raab, P.
Tauchmotorpumpen für Abwasser und industrielle Flüssigkeiten (Submersible motor pump for waste water and industrial liquids) (in German)
wlb wasser, luft und betrieb (1983) 12, p. 15–17
- [22] DIN EN 1563/A2 (03/2005)
Founding – Spheroidal graphite cast irons
Beuth Verlag GmbH, Berlin
- [23] DIN 28603 (05/2002)
Ductile iron pipes and fittings – Push-in joints – Survey, sockets and gaskets
Beuth Verlag GmbH, Berlin
- [24] Zoeller, H.
Rohre aus duktilem Gußeisen in der Abwasserentsorgung (Ductile cast-iron pipes in waste-water disposal) (in German)
3R international 20 (1981) 5, p. 251–257
- [25] Zamandzadeh, M.; O'Connor, K.; Bavarian, B.
Case histories of corrosion problems in waste-water facilities
Mater. Performance 28 (1989) 9, p. 43–46
- [26] Martenson, C.; Supko, G. M.
Experiences with high-alloy stainless steels in the HPI
Hydrocarbon Processing 62 (1983) 1, p. 69–74
- [27] Berglund, G.; Wilhelmsson, P. H.; Martenson, C.
Specialty stainless steels increase refinery exchanger life
Hydrocarbon Processing 67 (1988) 1, p. 46–49
- [28] Forsen, O.; Aromaa, J.; Virtanen, J.
The effect of composition and microstructure on pitting and crevice corrosion of stainless steels in chloride environment
EUROCORR European Corrosion Meeting 3 (1994), p. 43
- [29] Hesse, P.
Beurteilung von Pumpenteilen aus Stahlwerkstoffen oder Keramik an Hand von Schadensanalysen (Evaluating pump parts from cast steel or ceramics by analyzing failures) (in German)
Maschinenmarkt 102 (1996) 32, p. 38–41

- [30] ATV worksheet H 706
Kraftwerke und
Energieversorgungsbetriebe
Blatt 4: Abwasser, das bei der Wäsche von
Rauchgasen aus Feuerungsanlagen
anfällt, December 1993
(Power stations and power supply
enterprises. Sheet 4: Waste water, which
results with the laundry of flue gases
from feuerungsanlagen) (in German)
Abwassertechnische Vereinigung e.V.,
Hennef
- [31] Strassburg, F. W.; Tuthill, A. H.
Paper no. 1.: Internationale Erfahrungen
mit nichtrostenden Stählen in der
Abwasserbehandlung
Fachveranstaltung "Nichtrostende Stähle
in der Abwasserbehandlung", Berlin,
November 1995
(International experiences with stainless
steel in waste water treatment
"Specialized meeting", "Rustproof steel in
the waste water treatment") (in German)
Informationsstelle Edelstahl Rostfrei,
Düsseldorf; Nickel Development
Institute, London, Toronto; Institut für
Korrosionsschutz, Dresden
- [32] DIN EN 10088-3 (09/2005)
Stainless steels –Part 3: Technical delivery
conditions for semi-finished products,
bars, rods, wire, sections and bright
products of corrosion resisting steels for
general purposes
Beuth Verlag GmbH, Berlin
- [33] DIN EN 10028-7 (06/2000)
Flat products made of steels for pressure
purposes – Part 7: Stainless steels
Beuth Verlag GmbH, Berlin
- [34] DIN EN 10296-2 (02/2006)
Welded circular steel tubes for
mechanical and general engineering
purposes –Technical delivery conditions –
Part 2: Stainless steel; German version
Beuth Verlag GmbH, Berlin
- [35] DIN EN 10297-2 (02/2006)
Seamless steel tubes for mechanical and
general engineering purposes –Technical
delivery conditions –Part 2: Stainless steel
Beuth Verlag GmbH, Berlin
- [36] DIN EN 10217-7 (01/2015)
Welded steel tubes for pressure purposes
– Technical delivery conditions – Part 7:
Stainless steel tubes (in German)
Beuth Verlag GmbH, Berlin
- [37] DIN 10216-5 (11/2004)
Seamless steel tubes for pressure
purposes –Technical delivery conditions –
Part 5: Stainless steel tubes
Beuth Verlag GmbH, Berlin
- [38] DIN EN 1124-3 (02/2009)
Pipes and fittings of longitudinally
welded stainless steel pipes with spigot
and socket for waste water systems –
Part 3: System X; dimensions
Beuth Verlag GmbH, Berlin
- [39] Worksheet
Stahl-Eisen-Werkstoffblatt SEW 400 (02/
1997)
Nichtrostende Walz- und Schmiedestähle
(Stainless rolled and forged steels)
(in German)
Verlag Stahleisen GmbH, Düsseldorf
- [40] DIN EN 10088-1 (12/2014)
Nichtrostende Stähle – Teil 1: Verzeichnis
der nichtrostenden Stähle
(Stainless steels – Part 1: List of stainless
steels) (in German)
Beuth Verlag GmbH, Berlin
- [41] DIN EN 10088-2 (12/2014)
Nichtrostende Stähle – Teil 2: Technische
Lieferbedingungen für Blech und Band
für allgemeine Verwendung
(Stainless steels – Part 2: Technical
delivery conditions for sheet/plate and
strip for general purposes) (in German)
Beuth Verlag GmbH, Berlin
- [42] DIN EN 10088-3 (12/2014)
Nichtrostende Stähle – Teil 3: Technische
Lieferbedingungen für Halbzeug, Stäbe,
Walzdraht und Profile für allgemeine
Verwendung
(Stainless steels – Part 3: Technical
delivery conditions for semi-finished
products, bars, rods and sections for
general purposes) (in German)
Beuth Verlag GmbH, Berlin
- [43] DIN EN 10222-5 (01/2013)
Steel forgings for pressure purposes –
Part 5: Martensitic, austenitic and
austenitic-ferritic stainless steels
(in German)
Beuth Verlag GmbH, Berlin

- [44] Bindschedler, D.
Korrosionsschutz in
Abwasserreinigungsanlagen
(Corrosion protection in waste water
treatment plants) (in German)
gwa 73 (1993) 10, p. 808–815
- [45] Guideline C6d, Ausgabe 1995
Richtlinien zum Korrosionsschutz in
Abwasseranlagen
(Guidelines for corrosion protection in
waste water treatment plants)
(in German)
Korrosionskommission der SGK, Zürich
- [46] Tuthill, A.H.
Guidelines for the use of Stainless Steel
in Municipal Waste Water Treatment
Plants
NIDI Nickel Development Institute,
Publication No. 10076 (1995)
- [47] Perkow, H.; Steiner, R.; Vollmüller, H.
Naßoxidation – Ein Beitrag zum Stand
der Technik
(Wet air oxidation – present-day
technology) (in German)
Chemie-Ingenieurtechnik 52 (1980) 12,
p. 943–951
- [48] Oettinger, T. P.; Fontana M. G.
Austenitic stainless steels and titanium
for wet air oxidation of sewage sludge
Mater. Performance 15 (1976) 1, p. 29–35
- [49] Harpaz, D.; Oettinger, T. P.
Space-age alloys solve sludge disposal
problem
WATER Engineering & Management 130
(1983) 13, p. 36, 38
- [50] Braden, R.; Schulz-Walz, A.
Naßoxidation von halogenhaltigen
Industrieabwässern
(Wet oxidation of halogen-containing
industrial waste waters) (in German)
Chem.-Ing.-Tech. 54 (1982) 7, p. 692–693
- [51] Rigdon, J. H.
Corrosion above the water surface in
waste water facilities
Mater. Performance 23 (1984) 2, p. 18–20
- [52] Riedel, G.
Referat Nr. 2: Korrosionsverhalten
nichtrostender Stähle – Beeinflussung
durch Faktoren der Herstellung,
konstruktive Gestaltung, Be- und
Verarbeitung
(Paper no. 2: Corrosion behaviour of
stainless steels – influence by factors of
the production, constructional
organization, and processing)
(in German)
Fachveranstaltung “Nichtrostende Stähle
in der Abwasserbehandlung”, Berlin,
November 1995
Informationsstelle Edelstahl Rostfrei,
Düsseldorf; Nickel Development
Institute, London, Toronto; Institut für
Korrosionsschutz, Dresden
- [53] Priller, R.
Referat Nr. 3: Innovative Anlagen aus
nichtrostendem Stahl für die Fest-
Flüssig-Trennung in der
Abwasserbehandlung
(Paper no. 3: Innovative plants from
rustproof steel for the fixed liquid
separation in the waste water treatment)
(in German)
Fachveranstaltung “Nichtrostende Stähle
in der Abwasserbehandlung”, Berlin,
November 1995
Informationsstelle Edelstahl Rostfrei,
Düsseldorf; Nickel Development
Institute, London, Toronto; Institut für
Korrosionsschutz, Dresden
- [54] Kuron, D.
Lochkorrosion nichtrostender Stähle
(Pitting corrosion of stainless steels)
(in German)
in: Gräfen, H.; Rahmel, A. “Korrosion
verstehen – Korrosionsschäden
vermeiden”, p. 60–65
Verlag Irene Kuron Bonn 1994
- [55] Berdelle-Hilge, Ph.
Mikrobielle Werkstoffzerstörung –
Biofilm und Biofouling: Anforderungen
an biokorrosionsfeste Pumpen
(Microbial deterioration of materials-
biofilm and biofouling: Requisition to
biocorrosion resistant pumps)
(in German)
Werkst. Korros. 45 (1994) 1, p. 68

- [56] Berdelle-Hilge, Ph.
Biokorrosion in und mit Pumpen
(Biocorrosion in and with pumps)
(in German)
Chemie-Technik, 22 (1993), 12, p.50–54
- [57] Berdelle-Hilge, Ph.
Biocorrosion in pumps and pumping
systems
World Pumps (1995) 342, p. 50–56
- [58] Huber, H.
Schutz vor Spaltkorrosion
(Protection from crevice corrosion)
(in German)
wlb wasser, luft und betrieB (1983) 6,
p. 30
- [59] Jasner, M.
Application of an austenitic nitrogen-
alloyed 6MO stainless steel for seawater
desalination (RO) and waste water
treatment
Desalination 84 (1991) 1–39, p. 335–348
- [60] Kumada, M.
A few examples of localized corrosion
problems and their countermeasures in
chemical plants
Boshoku Gijutsu 30 (1981) 6, p. 344–348
- [61] Company publication
Schmutzwasser-Eindampfanlagen für
geringe Durchsatzmengen
PROWADDEST 10 E, 20 E und 30 E
(Waste water evaporation plants for small
throughput quantities PROWADDEST 10
E, 20 E und 30 E) (in German)
KMU-Umweltschutz GmbH, Steinen-
Höllstein (1995)
- [62] Company publication
Thermische Abfallbehandlung.
Werkstoffe für das Entsorgen der
Abwässer
(Thermal waste treatment. Materials for
waste water disposal) (in German), print
no. N 552-95-06 (1995)
Krupp VDM GmbH, Werdohl
- [63] Kirchheiner, R.
Metallische Werkstoffe für die
Umweltechnik
(Metallic materials for environmental
engineering) (in German)
in: Gräfen, H.; Rahmel, A. “Korrosion
verstehen – Korrosionsschäden
vermeiden”, p. 307–321
Verlag Irene Kuron Bonn 1994
- [64] Riedel, G.
Erprobung metallischer
Werkstoffkonzepte für die
Abwassereindampfung von
Rauchgasreinigungsanlagen
(Testing of metallic material concepts for
the waste water evaporation of flue gas
purification plants) (in German)
Vortrag auf Lehrgang Nr. 20849 der
Technischen Akademie Esslingen,
Ostfildern, 15./16.04.1996
- [65] Altpeter, E.; Wallis, E.; Heubner, U.
Erprobung verschiedener metallischer
Legierungen für die
Abwasseraufbereitung hinter
Rauchgasentschwefelungsanlagen
(Evaluation of different metal alloys for
waste water treatment of flue gas
desulphurisation plants) (in German)
Werkst. Korros. 45 (1994) 10, p. 539–549
- [66] Amsoneit, N.
Eindampfen problematischer Deponie-
Sickerwässer
(Evaporation of problematic disposal site
percolating water) (in German)
Wasser, Luft und Betrieb 29 (1985) 10,
p. 63–66
- [67] BAM-list – Anforderungen an Tanks für
die Beförderung gefährlicher Güter
(Requirements at tanks for the transport
of dangerous goods) (in German)
Ed.: Bundesanstalt für Materialforschung
u. -prüfung, Berlin
Wirtschaftsvlg N.W., 4. Aufl. 1997
- [68] Busch, Hans J:
Gefahrgutverordnung Strasse – GGVS,
Mit Anlagen A und B der GGVS, des
ADR und alphabetischem Verzeichnis
gefährlicher Güter
(Order for dangerous goods – road –
GGVS, with annexe A and B of the
GGVS, the ADR and alphabetical listing
of dangerous goods) (in German)
Deutscher Bundes-Vlg, 8th revised edition
1997, 880 p.
- [69] DIN 6601 (04/2007)
Resistance of materials of steel tanks
against liquids (positiv-list of liquids)
(in German)
Beuth Verlag GmbH, Berlin

- [70] Werner, H.; Decking, H.; Schambach, L.
Qualifizierung von hochlegierten
Sonderedelstählen und
Nickelbasislegierungen für den Transport
von wassergefährdenden Stoffen und
Abfallmedien
(Qualification of high-alloy special
stainless steels and nickel base alloys for
the transportation of hazardous water
polluting substances and waste media)
(in German)
Werkst. Korros. 45 (1994) 12, p. 663–667
- [71] Kopylov, V. T.; Spiridonova, I. M.; Rudaya,
T. P.
Corrosion stability of construction
materials in industrial waste waters
Khim.Prom-st (Moscow) 20 (1988) 1,
p. 18–19 (in Russian)
Soviet Chemical Industry 20 (1988) 1,
p. 31–33
- [72] Russel, D.K.
Pick the right materials for wet oxidation
Chemical Engineering Progress 3 (1999)
p. 51–58
- [73] Brill, U. (Krupp VDM GmbH, Werdohl)
Special print for Krupp VDM GmbH
from “Korrosion und Korrosionsschutz”
E. Kunze Verlag Walter de Gruyter, Berlin
(1992)
- [74] Company publication
References: Waste Incineration –
Germany
Krupp VDM, D-04 / Issue: 124 – 05/93
(Nicrocorros® tubes) (1993), p. 21
- [75] Data sheet
Korrosionsverhalten von feuerverzinktem
Stahl, data sheet 400
(Corrosion behaviour of hot-dip
galvanised steel) (in German)
Stahl-Informations-Zentrum, Düsseldorf,
1990
- [76] Anonymous
Feuerverzinkter Stahl in Fluß- und
Meerwasser
(Hot-galvanised steel in river and sea
water) (in German)
Blech-Rohre-Profil 23 (1976), p. 191
- [77] Data sheet
Beschichtungen auf Zink und
verzinktem Stahl, data sheet no. 5
(Coatings on zinc and galvanised steel)
(in German)
Bundesausschuß Farbe und
Sachwertschutz, Frankfurt (1982)

Key to materials compositions

Table 1: Chemical compositions of alloys according to German and other standards

<i>German Standard</i>		<i>Materials Compositions</i>	<i>US-Standard</i>
<i>Mat.-No.</i>	<i>DIN-Design</i>	<i>Percent in Weight</i>	<i>SAE/ASTM/UNS</i>
0.6015	EN-JL1020	–	A 48 (25B)
0.6025	EN-JL1040	–	A 48 (40B)
0.6655	GGL-NiCuCr 15 6 2	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-13.5-17.5Ni-1.0-2.5Cr-5.5-7.5Cu	A 436 Type 1
0.6656	GGL-NiCuCr 15 6 3	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-13.5-17.5Ni-2.5-3.5Cr-5.5-7.5Cu	A 436 Type 1b
0.6660	GGL-NiCr 20 2	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-18.0-22.0Ni-1.0-2.5Cr	A 436 Type 2
0.6661	GGL-NiCr 20 3	Fe-max. 3.0C-1.0-2.8Si-0.5-1.5Mn-18.0-22.0Ni-2.5-3.5Cr	A 436 Type 2b
0.6667	GGL-NiSiCr 20 5 3	Fe-≤2.5C-3.5-5.5Si-0.5-1.5Mn-1.5-4.5Cr-18.0-22.0Ni	
0.6676	GGL-NiCr 30 3	Fe-max. 2.5C-1.0-2.8Si-0.5-0.8Mn-2.5-3.5Cr-28.0-32.0Ni	A 436 Type 3
0.6680	GGL-NiSiCr 30 5 5	Fe-≤2.5C-5.0-6.0Si-0.5-1.5Mn-4.5-5.5Cr-29.0-32.0Ni	A 436 Type 4
0.7040	EN-JS1030	–	A 536 (60-40-18)
0.7660	EN-GJSA-XNiCr20-2	Fe-≤3.0C-1.5-3.0Si-0.5-1.5Mn-≤0.080P-1.0-3.5Cr-≤0.50Cu-18.0-22.0Ni	A 439 Type D-2
0.7661	GGG-NiCr 20 3	Fe-≤3.0C-1.5-3.0Si-0.5-1.5Mn-≤0.080P-2.5-3.5Cr-18.0-22.0Ni	A 439 Type D-2B
0.7665	GGG-NiSiCr 20 5 2	Fe-≤3.0C-4.5-5.5Si-0.5-1.5Mn-≤0.080P-1.0-2.5Cr-18.0-22.0Ni	A 439 Type D-2C
0.7670	EN-GJSA-XNi22	Fe-≤3.0C-1.0-3.0Si-1.5-2.5Mn-≤0.080P-≤0.5Cr-≤0.5Cu-21.0-24.0Ni	A 439 Type D-2C
0.7679	GGG-NiSiCr 30 5 2	Fe-≤2.6C-4.0-6.0Si-0.5-1.5Mn-≤0.08P-29.0-32.0Ni	
0.7680	EN-GJSA-XNiSiCr30-5-5	Fe-≤2.6C-5.0-6.0Si-0.5-1.5Mn-≤0.080P-4.5-5.5Cr-≤0.5Cu-28.0-32.0Ni	A 439 Type D-4

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
0.7688	EN-GJSA-XNiSiCr35-5-2; GGG-NiSiCr 35 5 2	Fe-≤2.0C-4.0-6.0Si-0.5-1.5Mn-≤0.08P- 1.5-2.5Cr-≤0.5Cu-34.0-36.0Ni	A 439 (Type D-5S)
0.9625	EN-GJN-HV550	Fe-≤3.0-3.6C-≤0.080Si-≤0.080Mn-≤0.1P- ≤0.1S-1.5-3.0Cr-≤0.5Mo-3.0-5.5Ni	A 532 (IA NiCr-HC)
0.9635	EN-JN3029	Fe-max. 1.8-2.4C-1.0Si-0.5-1.5Mn-0.08P- 0.08S-14.0-18.0Cr-3.0Mo-2.0Ni	A 532
0.9640	EN-GJN-HV600(XCr14)	Fe-≤1.8-2.4C-≤1.0Si-≤0.5-1.5Mn-≤0.080P- ≤0.080S-14.0-18.0Cr-≤3.0Mo-≤2.0Ni	A 532
0.9650	EN-JN3049	Fe-max. 2.4-3.2C-1.0Si-0.5-1.5Mn-0.08P- 0.08S-23.0-28.0Cr-3.0Mo-2.0Ni	A 532
1.0030	St 00	Fe-≤0.30C-≤0.30Si-0.20-0.50Mn-≤0.08P- ≤0.05S	
1.0032	St 34-2; (S205GT)	Fe-≤0.15C-≤0.3Si2.0-0.5Mn-0.05P-0.05S- 0.007N	1010 (SAE)
1.0035	St 33; S 185		
1.0036	S235JRG1; USt 37-2; USt 37-2 G; (S235JRG1+CR)	Fe-≤0.17C-≤1.4Mn-≤0.0045P-≤0.045S- ≤0.007N	K02502 (UNS)
1.0037	St 37-2; S235JR	Fe-≤0.17C-≤0.3Si-≤1.4Mn-≤0.045P- ≤0.045S-≤0.009N	A 283; SAE 1015
1.0038	RSt 37-2; S235JR	Fe-≤0.17C-≤1.4Mn-≤0.045P-≤0.045S- ≤0.009N	UNS K02502
1.0040	USt 42-2	Fe-≤0.25C-≤0.2-0.5Mn-≤0.05P-≤0.05S- ≤0.007N	
1.0044	S275JR; St 44-2	Fe-≤0.21C-≤1.50Mn-≤0.045P-≤0.045S- ≤0.009N	UNS K03000 A 853 (1020) SAE 1020
1.0050	E295; St 50-2	Fe-≤0.045P-≤0.045S-≤0.009N	
1.0070	E360; St 70-2	Fe-≤0.045P-≤0.045S-≤0.009N	
1.0114	S235J0	Fe-≤0.17C-≤1.40Mn-≤0.040P-≤0.040S- ≤0.009N	
1.0116	S235J2G3; St 37-3 N	Fe-max. 0.17C-1.4Mn-0.035P-0.035S	UNS K02001
1.0120	S235JRC	Fe-≤0.17C-≤1.40Mn-≤0.045P-≤0.045S- ≤0.009N	
1.0204	UQSt 36	Fe-≤0.14C-≤0.25-0.50Mn-≤0.040P-0.040S	SAE 1008
1.0208	RSt 35-2; (C10G2)	Fe-0.06-0.12C-≤0.25Si-0.40-0.60Mn- ≤0.035P-≤0.035S-≤0.25Cu-≤0.012N	
1.0253	USt 37.0	Fe-≤0.2C-≤0.55Si-≤1.6Mn-≤0.04P-≤0.04S- ≤0.007N	
1.0254	P235TR1, St 37.0	Fe-max. 0.16C-0.35Si-1.2Mn-0.025P- 0.020S-0.30Cr-0.30Cu-0.08Mo-0.010Nb- 0.30Ni-0.04Ti-0.02V	UNS K02501
1.0256	St 44.0	Fe-≤0.21C-≤0.55Si-≤1.60Mn-≤0.040P- ≤0.040S-≤0.009N	A 106

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.0301	C10	Fe-≤0.07-0.13C-≤0.4Si-≤0.3-0.6Mn- ≤0.045P-≤0.045S	SAE 1010
1.0305	St 35.8	Fe-≤0.17C-≤0.10-0.35Si-≤0.40-0.80Mn- ≤0.040P-≤0.040S	UNS K01200
1.0308	E 235	Fe-≤0.17C-≤0.35Si-0.4Mn-≤0.05P-≤0.05S- ≤0.007N	SAE 1010
1.0309	DX55D	Fe-≤0.16C-0.17-0.40Si-0.35-0.65Mn- ≤0.05P-≤0.050S-≤0.30Cr-≤0.30Ni-≤0.30Cu	UNS K02501
1.0330	St 12; DC01 + ZN	Fe-≤0.12C-≤0.60Mn-≤0.045P-≤0.045S	A 366 (C)
1.0333	USt 13	Fe-≤0.08C-≤0.007N	
1.0336	USt 4	Fe-≤0.09C-≤0.25-0.50Mn-≤0.030P- ≤0.030S-≤0.007N	
1.0338	DC04; St 14	Fe-≤0.08C-≤0.40Mn-≤0.03P-≤0.030S	
1.0345	P235GH; H I	Fe-≤0.16C-≤0.35Si-≤0.40-1.20Mn-≤0.030P- ≤0.025S-0.02Al-≤0.30Cr-≤0.30Cu-≤0.08Mo- ≤0.010Nb-≤0.30Ni-≤0.03Ti-≤0.02V	A 285; A 414
1.0346	H220G1	Fe-≤0.04C-≤0.40Mn-≤0.03P-≤0.02S-≤0.01- 0.04Ti	UNS K02202 A 516 (55)(380)
1.0356	TTSt35 N	Fe-≤0.18C-≤0.13-0.45Si-≤0.55-0.98Mn- ≤0.035P-≤0.04S	UNS K03000 A 524 (I,II)
1.0375	TH57; T 57	Fe-≤0.1C-Traces Si-0.25-0.45Mn-≤0.04P- ≤0.04S-0.007N	
1.0401	C 15	Fe-≤0.12-0.18C-≤0.40Si-≤0.3-0.6Mn- ≤0.045P-≤0.045S	SAE 1015
1.0402	C 22	Fe-≤0.17-0.24C-≤0.4Si-≤0.4-0.7Mn- ≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1020
1.0405	St 45.8	Fe-≤0.21C-≤0.10-0.35Si-≤0.40-1.20Mn- ≤0.040P-≤0.040S	A 106
1.0408	St 45	Fe-≤0.25C-≤0.035Si-0.40Mn-≤0.050P- ≤0.050S	A 108; SAE 1020
1.0414	C20D; D 20-2	Fe-≤0.18-0.23C-≤0.30Si-≤0.3-0.6Mn- ≤0.035P-≤0.035S-≤0.01Al-≤0.2Cr-≤0.3Cu- ≤0.05Mo-≤0.25Ni	UNS G10200; SAE 1020
1.0425	P265GH; H II	Fe-≤0.20C-≤0.4Si-≤0.5-1.4Mn-≤0.030P- ≤0.025S-0.02Al-≤0.3Cr-≤0.3Cu-≤0.08Mo- ≤0.01Nb-≤0.3Ni-≤0.03Ti-≤0.02V	UNS K01701
1.0426	P280GH	Fe-≤0.08-0.20C-≤0.4Si-≤0.9-1.5Mn- ≤0.025P-≤0.015S-≤0.30Cr	A 662 (A)
1.0461	StE 255	Fe-≤0.18C-≤0.40Si-≤0.50-1.30Mn- ≤0.035P-≤0.030S-≥0.02Al-≤0.30Cr- ≤0.20Cu-≤0.08Mo-≤0.02N-≤0.03Nb-≤0.30Ni	UNS K02202 A 516 (55)(380)
1.0473	P355GH; 19 Mn 6	Fe-≤0.1-0.22C-≤0.6Si-≤1.0-1.7Mn-≤0.03P- ≤0.025S-≤0.30Cr-≤0.3Cu-≤0.08Mo-≤0.3Ni	A 299

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.0481	17 Mn 4; P 295 GH	Fe≤0.08-0.20C-≤0.4Si-≤0.90-1.50Mn- ≤0.030P-≤0.025S-0.02Al-≤0.30Cr-≤0.30Cu- ≤0.08Mo-≤0.010Nb-≤0.3Ni-≤0.03Ti-≤0.02V	A 414, 515
1.0482	19 Mn 5	Fe-≤0.17-0.22C-≤0.30-0.60Si- ≤1.00-1.30Mn-≤0.045P-≤0.045S-≤0.30Cr	UNS K12437; A 537
1.0490	S275N	Fe-≤0.18C-≤0.40Si-0.50-1.40Mn-≤0.035P- ≤0.030S-≥0.0200Al-≤0.30Cr-≤0.35Cu- ≤0.10Mo-≤0.015N-≤0.050Nb-≤0.30Ni- ≤0.03Ti-≤0.05V	UNS K03000
1.0501	C 35	Fe-≤0.32-0.39C-≤0.4Si-≤0.5-0.8Mn- ≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1035
1.0503	C 45	Fe-≤0.42-0.50C-≤0.4Si-≤0.5-0.8Mn- ≤0.045P-≤0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1045
1.0505	StE 315	Fe-≤0.18C-≤0.45Si-≤0.70-1.50Mn- ≤0.035P-≤0.030S-≤0.30Cr-0.020Al- ≤0.20Cu-≤0.020N-≤0.03Nb-≤0.08Mo-0.30Ni	A 573
1.0528	C 30	Fe-≤0.27-0.34C-≤0.4Si-≤0.5-0.8Mn- ≤0.045P-0.045S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1030
1.0540	C50	Fe-0.47-0.55C-≤0.40Si-0.60-0.90Mn- ≤0.045P-≤0.045S-≤0.40Cr-≤0.10Mo-≤0.40Ni	A 689 (1050) ASTM A 866 (1050) ASTM
1.0545	S355N	Fe-≤0.20C-≤0.50Si-≤0.90-1.65Mn- ≤0.035P-0.030S-0.02Al-≤0.30Cr-≤0.35Cu- ≤0.10Mo-≤0.015N-≤0.050Nb-≤0.50Ni- ≤0.03Ti-≤0.12V	UNS K12709
1.0553	S355J0	Fe-≤0.20C-≤0.55Si-≤1.60Mn-≤0.04P- ≤0.04S-≤0.009N	
1.0562	StE 355; P 355 N	Fe-≤0.20C-≤0.50Si-≤0.90-1.70Mn-≤0.03P- ≤0.025S-0.02Al-≤0.30Cu-≤0.30Cr-≤0.08Mo- ≤0.02N-≤0.05Nb-≤0.50Ni-0.03Ti	A 633 (C)
1.0564	N-80	Fe-≤0.030P-≤0.030S	—
1.0570	St 52-3 N; S 355 J2G3	Fe-≤0.20C-≤0.55Si-≤1.60Mn-≤0.035P- ≤0.035S	SAE 1024
1.0580	E 355	Fe-≤0.22C-≤0.55Si-≤1.60Mn-≤0.025P- ≤0.025S	A 513 (1024) (ASTM)
1.0589	GL-E 36	Fe-≤0.18C-≤0.50Si-0.90-1.60Mn-≤0.040P- ≤0.040S-≥0.0200Al-≤0.20Cr-≤0.35Cu- ≤0.08Mo-0.020-0.050Nb-≤0.40Ni-0.05-0.10V	UNS K11852
1.0601	C60	Fe-0.57-0.65C-≤0.40Si-0.60-0.90Mn- ≤0.045P-≤0.045S-≤0.40Cr-≤0.10Mo-≤0.40Ni	A 830 (1060) ASTM A 713 (1060) ASTM
1.0605	C 75	Fe-≤0.7-0.8C-≤0.15-0.35Si-≤0.6-0.8Mn- ≤0.045P-≤0.045S	SAE 1074
1.0616	C86D	Fe-≤0.83-0.88C-≤0.10-0.30Si- ≤0.50-0.80Mn-≤0.035P-≤0.035S-≤0.01Al- ≤0.15Cr-≤0.25Cu-≤0.05Mo-≤0.20Ni	SAE 1086

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.0619	GP240GH	Fe-≤0.18-0.23C-≤0.60Si-≤0.50-1.20Mn-≤0.03P-≤0.02S	A 216
1.0664	St 160/180	Fe-≤0.80C-≤0.20Si-≤0.70Mn-≤0.04P-≤0.04S	
1.0670	P-105	Fe-≤0.70C-≤0.03-0.30Si-1.0Mn-≤0.04P-≤0.04S-≤0.007N	—
1.0721	10S20	Fe-0.07-0.13C-≤0.40Si-0.70-1.10Mn-≤0.060P-0.150-0.250S	SAE 1109
1.0854	M125-35P	consult producer	
1.0912	46Mn7	Fe-≤0.42-0.50C-≤0.15-0.35Si-≤1.6-1.9Mn-≤0.05P-≤0.05S-≤0.007N	SAE 1345
1.1013	RFe 100	Fe-≤0.05C-≤0.10Si-≤0.20-0.35Mn-≤0.03P-≤0.035S-≤0.04-0.10Al	
1.1104	EStE 285; P275NL2	Fe-≤0.16C-≤0.4Si-≤0.5-1.5Mn-≤0.025P-≤0.015S-0.02Al-≤0.30Cr-≤0.30Cu-≤0.02N-≤0.5Ni	P275NL2
1.1106	P355NL2; EStE 355	Fe-≤0.18C-≤0.5Si-≤0.9-1.7Mn-≤0.025P-≤0.015S-≤0.3Cr-≤0.3Cu-≤0.3Mo-0.5Ni-≤0.02N	A 707
1.1121	C10E; Ck 10	Fe-≤0.07-0.13C-≤0.40Si-≤0.30-0.60Mn-≤0.035P-≤0.035S	SAE 1010
1.1127	36Mn6	Fe-≤0.34-0.42C-≤0.15-0.35Si-≤1.4-1.65Mn-≤0.035P-≤0.035S	
1.1136	G24Mn4	Fe-0.20-0.28C-0.30-0.60Si-0.90-1.20Mn-≤0.035P-≤0.035S	
1.1151	Ck 22; C22E	Fe-≤0.17-0.24C-≤0.4Si-≤0.4-0.7Mn-≤0.035P-≤0.035S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1023
1.1166	34Mn5	Fe-0.30-0.37C-0.15-0.30Si-1.20-1.50Mn-≤0.035P-≤0.035S	G15360 (UNS) A 711 (1536) (ASTM) 1536 (SAE)
1.1176	G36Mn5	Fe-≤0.32-0.40C-≤0.15-0.35Si-≤1.20-1.50Mn-≤0.035P-≤0.035S	UNS H10380; A 830; SAE 1038
1.1186	C40E; Ck 40	Fe-≤0.37-0.44C-≤0.4Si-≤0.5-0.8Mn-≤0.035P-≤0.035S-≤0.4Cr-≤0.1Mo-≤0.4Ni	SAE 1040
1.1191	C45E; Ck 45	Fe-≤0.42-0.50C-≤0.4Si-≤0.50-0.80Mn-≤0.035P-≤0.035S-≤0.40Cr-≤0.10Mo-≤0.4Ni	SAE 1045
1.1520	C70U	Fe-≤0.65-0.74C-≤0.10-0.30Si-≤0.10-0.35Mn-≤0.030P-≤0.030S	
1.1525	C80U; C80W1	Fe-≤0.75-0.85C-≤0.10-0.25Si-≤0.10-0.25Mn-≤0.020P-≤0.020S	SAE W 108
1.1545	C105U; C105W1	Fe-≤1.0-1.1C-≤0.10-0.25Si-≤0.10-0.25Mn-≤0.020P-≤0.020S	SAE W 110
1.1730	C45U; C45W	Fe-≤0.42-0.50C-≤0.15-0.40Si-≤0.60-0.80Mn-≤0.03P-≤0.03S	A 830 (1045); SAE 1045

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.2210	115CrV3	Fe-1.10-1.25C-0.15-0.30Si-0.20-0.40Mn- ≤0.030P-≤0.030S-0.50-0.80Cr-0.07-0.12V	L 2 SAE A 681 (L2) ASTM
1.2311	40CrMnMo7	Fe-0.35-0.45C-0.20-0.40Si-1.30-1.60Mn- ≤0.035P-≤0.035S-1.80-2.10Cr-0.15-0.25Mo	
1.2343	X37CrMoV5-1; X38CrMoV5-1	Fe-0.33-0.41C-0.80-1.20Si-0.25-0.50Mn- ≤0.030P-≤0.020S-4.80-5.50Cr-1.10-1.50Mo- 0.30-0.50V	H 11 SAE A 681 (H 11) ASTM T 20811 UNS
1.2344	X40CrMoV5-1	Fe-0.35-0.42C-0.80-1.20Si-0.25-0.50Mn- ≤0.030P-≤0.020S-4.80-5.50Cr-1.20-1.50Mo- 0.85-1.15V	H 13 SAE T 20813 UNS A 681 (H13) ASTM
1.2365	32CrMoV12-28 X32CrMoV33	Fe-≤0.28-0.35C-≤0.10-0.40Si- ≤0.15-0.45Mn-≤0.030P-≤0.030S- ≤2.70-3.20Cr-≤2.60-3.00Mo-≤0.40-0.70V	SAE H 10
1.2550	60WCrV8; 60WCrV7	Fe-0.55-0.65C-0.70-1.00Si-0.15-0.45Mn- ≤0.030P-≤0.030S-0.90-1.20Cr-0.10-0.20V- 1.70-2.20W	
1.2567	30WCrV17-2	Fe-0.25-0.35C-0.15-0.30Si-0.20-0.40Mn- ≤0.035P-≤0.035S-2.20-2.50Cr-0.50-0.70V- 4.00-4.50W	
1.2787	X23CrNi17	Fe-≤0.10-0.25C-≤1.00Si-≤1.00Mn-≤0.035P- ≤0.035S-≤15.5-18.0Cr-≤1.0-2.5Ni	
1.2823	70Si7	Fe-≤0.65-0.75C-≤1.50-1.80Si-≤0.60-0.80Mn- ≤0.03P-≤0.03S	
1.2842	90MnCrV8	Fe-≤0.85-0.95C-≤0.10-0.40Si-≤1.80-2.20Mn- ≤0.030P-≤0.030S-≤0.20-0.50Cr-≤0.05-0.20V	UNS T31502; SAE O2; A 681 (O2); SAE O2
1.3247	HS2-9-1-8 S2-10-1-8	Fe-1.05-1.15C-≤0.70Si-≤0.40Mn-≤0.030P- ≤0.030S-7.50-8.50Co-3.50-4.50Cr- 9.00-10.00Mo-0.90-1.30V-1.20-1.90W	UNS T11342
1.3355	HS 18-0-1	Fe-≤0.70-0.78C-≤0.45Si-≤0.4Mn-≤0.030P- ≤0.030S-≤3.8-4.5Cr-≤1.0-1.2V-≤17.5-18.5W	A 600
1.3505	100Cr6	Fe-≤0.93-1.05C-≤0.15-0.35Si- ≤0.25-0.45Mn-≤0.025P-≤0.015S-≤0.05Al- ≤1.35-1.60Cr-≤0.30Cu-≤0.10Mo	SAE 52100; A 29
1.3551	80MoCrV42-16	Fe-≤0.77-0.85C-≤0.40Si-≤0.15-0.35Mn- ≤0.025P-≤0.015S-≤3.90-4.30Cr-≤0.30Cu- ≤4.00-4.50Mo-≤0.90-1.10V-≤0.25W	SAE M50; A 600 (M50)
1.3728	AlNiCo 9/5	Fe-≤11.0-13.0Al-5.0Co-2.0-4.0Cu-≤57.0Fe- 21.0-28.0Ni-≤1.0Ti	
1.3813	X40MnCrN19	Fe-≤0.30-0.50C-≤0.80Si-≤17.0-19.0Mn- ≤0.10P-≤0.030S-≤3.0-5.0Cr-≤0.08-0.12N	
1.3817	X40MnCr18	Fe-0.30-0.50C-≤1.00Si-17.00-19.00Mn- ≤0.060P-≤0.030S-≤3.00-5.00Cr-≤0.100N- ≤1.00Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.3914	X2CrNiMnMoNNb21-15-7-3	Fe-≤0.03C-≤0.75Si-6.00-8.00Mn-≤0.025P- ≤0.010S-20.00-22.00Cr-3.00-3.50Mo- 0.350-0.500N-0.100-0.250Nb-14.00-16.00Ni	
1.3940	GX2CrNiN18-13	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.020S-16.50-18.50Cr-0.100-0.200N- 12.00-14.00Ni	
1.3951	G-X 4 CrNiMoN 22 15	Fe-≤0.05C-0.80-1.10Si-0.50-1.00Mn- ≤0.030P-≤0.030S-22.00-23.50Cr- 1.10-1.30Mo-0.150-0.250N-17.00-18.00Ni	
1.3952	X2CrNiMoN18-14-3	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-16.50-18.50Cr-2.50-3.00Mo- 0.150-0.250N-13.00-15.00Ni	
1.3955	GX12CrNi18-11	Fe-≤0.15C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-16.50-18.50Cr-≤0.75Mo- 10.00-12.00Ni	
1.3964	X2CrNiMnMoNNb21-16-5-3	Fe-≤0.03C-≤1.00Si-4.00-6.00Mn-≤0.025P- ≤0.010S-20.00-21.50Cr-3.00-3.50Mo- 0.200-0.350N-≤0.250Nb-15.00-17.00Ni	NITRONIC 50
1.3974	X2CrNiMnMoNNb23-17-6-3	Fe-≤0.03C-≤1.00Si-≤4.50-6.50Mn-≤0.025P- ≤0.01S-≤21.00-24.50Cr-≤2.80-3.40Mo-≤0.30- 0.50N-≤0.10-0.30Nb-≤15.50-18.00Ni	
1.3981	NiCo 29 18; (X3NiCo29-18)	Fe-≤0.050C-≤0.30Si-≤0.50Mn- ≤17.0-18.0Co-≤28.0-30.0Ni	UNS K94610
1.4000	X6Cr13	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P- ≤0.015S-≤12.0-14.0Cr	SAE 403, 410S
1.4001	X 7 Cr 14	Fe-≤0.08C-≤1.00Si-≤1.00Mn-≤0.045P- ≤0.030S-≤13.00-15.00Cr	429 (SAE) A240 (410S) (ASTM) 410S (SAE)
1.4002	X6CrAl13	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P- ≤0.015S-≤0.10-0.3Al-≤12-14Cr	SAE 405
1.4003	X2CrNi12	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.04P- ≤0.015S-≤10.5-12.5Cr-≤0.03N-≤0.3-1.0Ni	UNS S40977
1.4005	X12CrS13	Fe-≤0.08-0.15C-≤1.0Si-≤1.5Mn-≤0.04P- ≤0.15-0.35S-≤12.0-14.0Cr-≤0.6Mo	SAE 416
1.4006	X12Cr13	Fe-≤0.08-0.15C-≤1.00Si-≤1.5Mn-≤0.04P- ≤0.015S-≤11.0-13.5Cr-≤0.75Ni	SAE 410
1.4008	GX7CrNiMo12-1	Fe-≤0.10C-1.0Si-1.0Mn-≤0.035P-≤0.025S- 12.0-13.5Cr-0.20-0.50Mo-1.0-2.0Ni	UNS J91150
1.4015	X8Cr18	Fe-≤0.10C-≤1.50Si-≤1.50Mn-≤0.030P- ≤0.030S-≤16.50-18.50Cr	S43080 (UNS)
1.4016	X6Cr17	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.04P- ≤0.015S-≤16.0-18.0Cr	SAE 430
1.4021	X20Cr13	Fe-≤0.16-0.25C-≤1.0Si-≤1.5Mn-≤0.04P- ≤0.015S-≤12.0-14.0Cr	SAE 420

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4024	X15Cr13	Fe-≤0.12-0.17C-≤1.0Si-≤1.0Mn-≤0.045P-≤0.03S-≤12.0-14.0Cr	SAE 420
1.4028	X30Cr13	Fe-≤0.26-0.35C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤12.0-14.0Cr	A 743; UNS J91153
1.4031	X39Cr13	Fe-≤0.36-0.42C-≤1.00Si-≤1.00Mn-≤0.04P-≤0.015S-≤12.5-14.5Cr	UNS S42080
1.4034	X46Cr13	Fe-≤0.43-0.5C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤12.5-14.5Cr	
1.4057	X17CrNi16-2	Fe-≤0.12-0.22C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤15.0-17.0Cr-≤1.5-2.5Ni	SAE 431
1.4085	GX70Cr29	Fe-≤0.50-0.90C-2.0Si-1.0Mn-≤0.045P-≤0.030S-27.0-30.0Cr	
1.4104	X14CrMoS17	Fe-≤0.10-0.17C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.15-0.35S-≤15.5-17.5Cr-≤0.2-0.6Mo	SAE 430 F
1.4105	X6CrMoS17	Fe-≤0.08C-≤1.50Si-≤1.50Mn-≤0.040P-≤0.15-0.35S-≤16.00-18.00Cr-≤0.20-0.60Mo	
1.4110	X55CrMo14	Fe-≤0.48-0.60C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤13.0-15.0Cr-≤0.5-0.8Mo-≤0.15V	
1.4112	X90CrMoV18	Fe-≤0.85-0.95C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤17.0-19.0Cr-≤0.9-1.3Mo-≤0.07-0.12V	SAE 440 B
1.4113	X6CrMo17-1	Fe-≤0.80C-≤1.0Si-≤1.00Mn-≤0.04P-≤0.03S-≤16.0-18.0Cr-≤0.90-1.40Mo	SAE 434
1.4116	X50CrMoV15	Fe-≤0.45-0.55C-1.0Si-1.0Mn-≤0.040P-≤0.015S-14.0-15.0Cr-0.5-0.8Mo-0.10-0.20V	
1.4117	X38CrMoV15	Fe-≤0.35-0.40C-1.0Si-1.0Mn-≤0.045P-≤0.030S-14.0-15.0Cr-0.4-0.6Mo-0.10-0.15V	
1.4120	X20CrMo13	Fe-≤0.17-0.22C-≤1.0Si-≤1.0Mn-≤0.04P-≤0.015S-≤12-14Cr-≤0.9-1.3Mo-≤1.0Ni	
1.4122	X39CrMo17-1	Fe-≤0.33-0.45C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤15.5-17.5Cr-≤0.8-1.3Mo-≤1.0Ni	
1.4125	X105CrMo17	Fe-≤0.95-1.20C-1.0Si-1.0Mn-≤0.040P-≤0.015S-16.0-18.0Cr-0.4-0.8Mo	SAE 617
1.4126	X 110 CrMo 13	Fe-≤1.05-1.15C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.030S-≤17.0-18.0Cr-≤0.8-1.0Mo	
1.4131	X 1 CrMo 26 1	Fe-≤0.010C-≤0.40Si-≤0.40Mn-≤0.020P-≤0.020S-≤0.015N-≤25.0-27.5Cr-≤0.75-1.50Mo-≤0.50Ni	
1.4133		Fe-≤0.01C-1.0Si-1.0Mn-≤0.030P-≤0.030S-26.0-30.0Cr-1.7-2.3Mo-0.010N	
1.4136	GX70CrMo29-2	Fe-≤0.50-0.90C-2.0Si-1.0Mn-≤0.045P-≤0.030S-27.0-30.0Cr-2.0-2.5Mo	
1.4138	GX120CrMo29-2	Fe-≤0.90-1.30C-2.0Si-1.0Mn-≤0.045P-≤0.030S-27.0-30.0Cr-2.0-2.5Mo	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4153	X80CrVMo13-2	Fe-≤0.76-0.86C-≤1.00Si-≤1.00Mn-≤0.045P- ≤0.030S-≤12.00-14.00Cr-≤0.40-0.60Mo- ≤1.50-2.10V	
1.4300	X 12 CrNi 18 8	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤17.0-19.0Cr-≤8.0-10.0Ni	
1.4301	X5CrNi18-10	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S≤17-19.5Cr-≤0.11N-≤8.0-10.5Ni	SAE 304
1.4302	X5CrNi19-9	Fe-≤0.05C-≤1.40Si-≤1.90Mn-≤0.025P- ≤0.015S-≤18.2-19.8Cr-≤8.70-10.30Ni	UNS S30888
1.4303	X4CrNi18-12	Fe-≤0.06C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17-19Cr-≤0.11N-≤11.0-13.0Ni	SAE 305/308
1.4304	X5CrNi18-12E	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤17-19Cr-≤8.0-10.0Ni	
1.4305	X8CrNiS18-9; X10CrNiS189	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.15- 0.35S-≤17-19Cr-≤1.0Cu-≤0.11N-≤8.0-10.0Ni	SAE 303
1.4306	X2CrNi19-11	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤18-20Cr-≤0.11N-≤10.0-12.0Ni	SAE 304 L
1.4307	X2CrNi18-9	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S- ≤17.5-19.5Cr-≤0.11N-≤8.0-10.0Ni	
1.4308	GX5CrNi19-10	Fe-≤0.07C-≤1.5Si-≤1.5Mn-≤0.04P-≤0.030S- ≤18.0-20.0Cr-≤8.0-11.0Ni	SAE 304 H
1.4310	X10CrNi18-8	Fe-≤0.05-0.15C-≤2.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.0-19.0Cr-≤0.8Mo-≤0.11N≤6.0- 9.5Ni	SAE 301
1.4311	X2CrNi18-10	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.5Cr-≤8.5-11.5Ni-≤0.12- 0.22N	SAE 304 LN
1.4312	GX10CrNi18-8	Fe-≤0.12C-≤2.0Si-≤1.5Mn-≤0.045P-≤0.03S- ≤17.0-19.5Cr-≤8.0-10.0Ni	A 743
1.4313	X3CrNiMo13-4	Fe-≤0.05C-≤0.7Si-≤1.5Mn-≤0.04P- ≤0.015S-≤12.0-14.0Cr-≤0.3-0.7Mo-≤0.02N- ≤3.5-4.5Ni	UNS J91540
1.4315	X5CrNi19-9	Fe-≤0.06C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.03S- ≤18.0-20.0Cr-≤0.12-0.22N-≤8.0-11.0Ni	
1.4317	GX4CrNi13-4	Fe-≤0.06C-≤1.00Si-≤1.00Mn-≤0.035P- ≤0.025S-≤12.00-13.50Cr-≤0.70Mo- ≤3.50-5.00Ni	UNS J91540 A 743 (CA-6NM)
1.4318	X2CrNi18-7	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S- ≤16.5-18.5Cr-≤0.1-0.2N-≤6.0-8.0Ni	
1.4319	X3CrNi17-8	Fe-≤0.05C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤16.00-18.00Cr-≤0.04-0.08N- ≤7.00-8.00Ni	
1.4330	X 2 CrNi 25 20	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.045P-≤0.035S- ≤18.0-22.0Cr-≤23.0-27.0Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4333	X 5 NiCr 32 21	Fe-≤0.07C-≤1.40Si-≤2.40Mn-≤0.045P- ≤0.030S-≤19.00-22.00Cr-≤30.00-34.00Ni	S33200 (UNS) S33200 (SAE) B 710 (N 08330) (ASTM)
1.4335	X1CrNi25-21	Fe-≤0.02C-≤0.25Si-≤2.0Mn-≤0.025P- ≤0.010S-≤24.0-26.0Cr-≤0.20Mo-≤0.110N- ≤20.0-22.0Ni	
1.4340	GX40CrNi27-4	Fe-≤0.30-0.50C-≤2.00Si-≤1.50Mn- ≤0.045P-≤0.030S-≤26.0-28.0Cr-≤3.5-5.5Ni	A 743
1.4347	GX6CrNiN26-7	Fe-≤0.08C-≤1.50Si-≤1.50Mn-≤0.035P- ≤0.020S-25.00-27.00Cr-0.100-0.200N- 5.50-7.50Ni	
1.4361	X1CrNiSi18-15-4	Fe-≤0.015C-≤3.70-4.50Si-≤2.00Mn- ≤0.025P-≤0.010S-≤16.5-18.5Cr-≤0.20Mo- ≤0.110N-≤14.0-16.0Ni	A 336
1.4362	X2CrNiN23-4	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤22.0-24.0Cr-≤0.10-0.60Cu- ≤0.10-0.60Mo-≤0.050-0.200N-≤3.5-5.5Ni	
1.4371	X2CrMnNiN17-7-5	Fe-≤0.30C-≤1.0Si-≤6.0-8.0Mn-≤0.045P- ≤0.015S-≤16.0-17.0Cr-≤0.15-0.20N- ≤3.5-5.5Ni	SAE 202
1.4401	X5CrNiMo17-12-2	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤0.110N-≤10.0-13.0Ni	SAE 316
1.4404	X2CrNiMo17-12-2; X2 CrNiMo 17 12 2	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo-≤10.0- 13.0Ni≤0.110N	SAE 316 L
1.4405	X 5 CrNiMo 16 5; GX4CrNiMo16-5-1	Fe-≤0.07C-≤1.0Si-≤1.0Mn-≤0.035P- ≤0.025S-≤15.0-16.5Cr-≤0.5-2.0Mo-≤4.5- 6.0Ni	
1.4406	X2CrNiMoN17-11-2; X2 CrNiMoN 17 12 2	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤0.12-0.22N-≤10.0-12.0Ni	SAE 316 LN
1.4408	GX5CrNiMo19-11-2	Fe-≤0.07C-≤1.50Si-≤1.50Mn-≤0.04P- ≤0.030S-≤18.0-20.0Cr-≤2.0-2.5Mo- ≤9.0-12.0Ni	CF-8M
1.4410	X2CrNiMoN25-7-4	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.035P- 0.015S-≤24.0-26.0Cr-≤3.0-4.5Mo- ≤0.200-0.350N-≤6.0-8.0Ni	2507; A 182
1.4413	X3CrNiMo13-4	Fe-≤0.05C-≤0.30-0.60Si-≤0.50-1.00Mn- ≤0.03P-≤0.02S-≤12.00-14.00Cr- ≤0.30-0.70Mo-≤3.50-4.00Ni	UNS S42400 A 988 (S 41500) SAE S41500
1.4417	GX2CrNiMoN25-7-3	Fe-≤0.03C-≤1.0Si-≤1.5Mn-≤0.030P- ≤0.020S-≤24.0-26.0Cr-≤1.0Cu-≤3.0-4.0Mo- ≤0.150-0.250N-≤6.0-8.5Ni-≤1.0W	3RE60; A 789

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4418	X4CrNiMo16-5-1	Fe-≤0.06C-≤0.7Si-≤1.5Mn-≤0.040P- ≤0.015S-≤15.0-17.0Cr-≤0.8-1.5Mo-≤0.020N- ≤4.0-6.0Ni	
1.4424	X2CrNiMoSi18-5-3	Fe-≤0.03C-1.40-2.00Si-1.20-2.00Mn- ≤0.035P-≤0.015S-18.00-19.00Cr- 2.50-3.00Mo-0.050-1.00N-4.50-5.20Ni	
1.4427	X12CrNiMoS18-11	Fe-≤0.12C-≤1.0Si-≤2.0Mn-≤0.06P- ≤0.15-0.35S-≤16.5-18.5Cr-≤2-2.5Mo- ≤10.5-13.5Ni	
1.4429	X2CrNiMoN17-13-3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.5-3.0Mo- ≤11.0-14.0Ni-≤0.12-0.22N	SAE 316 LN
1.4430	X2CrNiMo19-12	Fe-≤0.02C-≤1.40Si-≤1.90Mn-≤0.025P- ≤0.015S-17.20-19.80Cr-2.50-3.00Mo- 10.70-13.30Ni	S 31688 UNS S 31683 UNS
1.4434	X2CrNiMoN18-12-4	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤16.50-19.50Cr-≤3.00-4.00Mo- ≤0.10-0.20N-≤10.50-14.00Ni	
1.4435	X2CrNiMo18-14-3; X2 CrNiMo 18 4 3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤2.5-3.0Mo- ≤0.110N-≤12.5-15.0Ni	SAE 316 L
1.4436	X3CrNiMo17-13-3; X5 CrNiMo 17 13 3	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.5-3.0Mo-≤0.110N- ≤10.5-13.0Ni	SAE 316
1.4438	X2CrNiMo18-15-4	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.5-19.5Cr-≤3.0-4.0Mo-≤0.110N- ≤13.0-16.0Ni	SAE 317 L
1.4439	X2CrNiMoN17-13-5	Fe-≤0.030C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤4.00-5.00Mo- ≤12.5-14.5Ni-≤0.12-0.22N	
1.4440	X2CrNiMo18-16-5	Fe-≤0.03C-≤1.00Si-2.00-3.00Mn-≤0.025P- ≤0.025S-17.00-20.00Cr-4.00-5.00Mo- 16.00-19.00Ni	SAE 317 L
1.4441	X2CrNiMo18-15-3	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.025P- ≤0.01S-≤17.00-19.00Cr-≤0.50Cu- ≤2.50-3.20Mo-≤0.10N-≤13.00-15.50Ni	
1.4442	X2CrNiMoN18-15-4	Fe-≤0.03C-1.0Si-2.0Mn-≤0.025P-≤0.010S- 17.0-18.5Cr-3.7-4.2Mo-0.1-0.2N-14.0-16.0Ni	SAE 317 LN
1.4447	X5CrNiMo18-13	Fe-≤0.06C-1.5Si-2.0Mn-≤0.025P-≤0.020S- 17.0-19.0Cr-4.0-5.0Mo-12.5-15.5Ni	
1.4449	X3CrNiMo18-12-3	Fe-≤0.035C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤17.0-18.2Cr-≤1.0Cu- ≤2.25-2.75Mo-≤0.08N-≤11.5-12.5Ni	SAE 317
1.4457	X8CrNiMo17-5-3	Fe-≤0.07-0.11C-≤0.50Si-≤0.50-1.25Mn- ≤16.00-17.00Cr-≤2.50-3.25Mo-≤4.00-5.00Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4460	X3CrNiMoN27-5-2	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.035P- ≤0.015S-≤25.0-28.0Cr-≤1.3-2.0Mo- ≤0.05-0.2N-≤4.5-6.5Ni	SAE 329
1.4462	X2CrNiMoN22-5-3	Fe-≤0.03C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤21.0-23.0Cr-≤2.50-3.50Mo- ≤4.50-6.50Ni-≤0.1-0.22N	2205; A 182
1.4463	GX6CrNiMo24-8-2	Fe-≤0.07C-1.5Si-1.5Mn-≤0.045P-≤0.030S- 23.0-25.0Cr-2.0-2.5Mo-7.0-8.5Ni	
1.4464	GX40CrNiMo27-5	Fe-0.30-0.50C-≤2.00Si-≤1.50Mn-≤0.045P- ≤0.030S-26.00-28.00Cr-2.00-2.50Mo-4.00- 6.00Ni	
1.4465	X1CrNiMoN25-25-2	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.020P- ≤0.015S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤22.0-25.0Ni-≤0.08-0.16N	SAE 310 MoLN
1.4466	X1CrNiMoN25-22-2	Fe-≤0.02C-≤0.7Si-≤2.0Mn-≤0.025P- ≤0.010S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤21.0-23.0Ni-≤0.1-0.16N	
1.4467	X2CrMnNiMoN26-5-4	Fe-≤0.03C-≤0.8Si-≤4.0-6.0Mn-≤0.03P- ≤0.015S-≤24.5-26.5Cr-≤2.0-3.0Mo- ≤0.3-0.45N-≤3.5-4.5Ni	
1.4469	GX2CrNiMoN26-7-4	Fe-≤0.03C-1.0Si-1.0Mn-≤0.035P-≤0.025S- 25.0-27.0Cr-≤1.30Cu-3.0-5.0Mo-0.12-0.22N- 6.0-8.0Ni	UNS J93404
1.4492	X 8 CrNiMoN 17 5	Fe-≤0.07-0.11C-≤0.5Si-≤0.5-1.25Mn-≤0.04P- ≤0.03S-≤16.0-17.0Cr-≤2.5-3.25Mo- ≤4.0-5.0Ni	
1.4500	GX7NiCrMoCuNb25-20	Fe-≤0.08C-≤1.50Si-≤2.0Mn-≤0.045P- ≤0.03S-≤19.0-21.0Cr-≤1.5-2.5Cu- ≤2.5-3.5Mo-≤24.0-26.0Ni	A 351
1.4501	X2CrNiMoCuWN25-7-4	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.035P- ≤0.015S-≤24.0-26.0Cr-≤0.5-1.0Cu- ≤3.0-4.0Mo-≤0.2-0.3N-≤6.0-8.0Ni-≤0.5-1.0W	UNS S32760
1.4502	X8CrTi18	Fe-≤0.09C-≤1.40Si-≤1.40Mn-≤0.030P- ≤0.020S-16.70-18.30Cr-≤0.060N- 0.35-0.65Ti	
1.4503	X3NiCrCuMoTi27-23	Fe-≤0.04C-0.75Si-0.75Mn-≤0.030P-≤0.015S- 22.0-24.0Cr-2.5-3.5Cu-2.5-3.0Mo-26.0- 28.0Ni-0.4-0.7Ti	
1.4504		Fe-≤0.09C-≤0.50Si-≤1.00Mn-≤0.025P- ≤0.025S-≤0.75-1.25Al-≤16.00-17.25Cr- ≤6.50-7.75Ni	UNS S17780 SAE S17700 A 705 (631)
1.4505	X4NiCrMoCuNb20-18-2	Fe-≤0.05C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤19.0-21.0Ni-≤1.8-2.2Cu	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4506	X5NiCrMoCuTi20-18	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S-≤16.5-18.5Cr-≤2.0-2.5Mo-≤19.0-21.0Ni-≤1.8-2.2Cu	
1.4507	X2CrNiMoCuN25-6-3	Fe-≤0.03C-≤0.7Si-≤2.0Mn-≤0.035P-≤0.015S-≤24.0-26.0Cr-≤1.0-2.5Cu-≤0.15-0.30N-≤5.5-7.5Ni-≤2.7-4.0Mo	UNS S43940
1.4509	X2CrTiNb18	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.015S-≤17.5-18.5Cr-≤0.10-0.60Ti	
1.4510	X6CrTi17	Fe-≤0.05C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.015S-≤16.0-18.0Cr	SAE 430 Ti
1.4511	X3CrNb17; X6CrNb17	Fe-≤0.05C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.015S-≤16.0-18.0Cr	
1.4512	X2CrTi12	Fe-≤0.03C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.015S-≤10.5-12.5Cr	SAE 409
1.4515	GX2CrNiMoCuN26-6-3	Fe-≤0.03C-≤1.0Si-≤2.0Mn-≤0.030P-≤0.020S-≤0.12-0.25N-≤24.5-26.5Cr-≤2.5-3.5Mo-≤5.5-7.0Ni-≤0.8-1.3Cu	
1.4517	GX2CrNiMoCuN25-6-3-3	Fe-max. 0.03C-1.0Si-1.5Mn-0.035P-0.025S-24.5-26.5Cr-2.75-3.50Cu-2.50-3.50Mo-0.12-0.22N-5.0-7.0Ni	UNS J93372
1.4519	X2CrNiMoCu20-25	Fe-≤0.02C-≤1.40Si-≤2.10-4.90Mn-≤0.025P-≤0.02S-≤19.20-21.80Cr-≤0.90-1.90Cu-≤4.10-5.90Mo-≤24.30-26.70Ni	
1.4520	X2CrTi17	Fe-≤0.025C-≤0.5Si-≤0.5Mn-≤0.04P-≤0.015S-≤16.0-18.0Cr-≤0.015N-≤0.3-0.6Ti	
1.4521	X2CrMoTi18-2	Fe-≤0.025C-≤1.0Si-≤0.040P-≤0.015S-≤1.0Mn-≤17.0-20.0Cr-≤1.8-2.5Mo-≤0.030N	SAE 444
1.4522	X2CrMoNb18-2	Fe-≤0.025C-≤1.0Si-≤1.0Mn-≤0.040P-≤0.015S-≤17.0-19.0Cr-≤1.8-2.3Mo-≤0.25Ni	SAE 443
1.4523	X2CrMoTiS18-2	Fe-≤0.03C-≤1.0Si-≤0.5Mn-≤0.040P-≤0.15-0.35S-≤17.5-19.0Cr-≤2.0-2.5Mo-≤0.30-0.80Ti	
1.4525	GX5CrNiCu16-4; GX4CrNi-CuNb16-4	Fe-≤0.07C-≤0.80Si-≤1.00Mn-≤0.035P-≤0.025S-≤15.00-17.00Cr-≤2.50-4.00Cu-≤0.80Mo-≤0.050N-≤0.350Nb-≤3.50-5.50Ni	
1.4527	GX4NiCrCuMo30-20-4	Fe-≤0.06C-≤1.50Si-≤1.50Mn-≤0.040P-≤0.030S-19.00-22.00Cr-3.00-4.00Cu-2.00-3.00Mo-27.50-30.50Ni	
1.4528	X105CrCoMo18-2	Fe-≤1.0-1.1C-≤1.0Si-≤1.0Mn-≤0.045P-≤0.030S-≤16.5-18.5Cr-≤1.0-1.5Mo-≤0.30-0.80Ti-≤1.3-1.8Co-≤0.07-0.12V	
1.4529	X1NiCrMoCuN25-20-7	Fe-≤0.02C-≤0.50Si-≤1.00Mn-≤0.030P-≤0.010S-≤19.0-21.0Cr-≤6.0-7.0Mo-≤0.5-1.5Cu-≤0.15-0.25N-≤24.0-26.0Ni	A 249; ASTM N08926

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4530	X1CrNiMoAlTi12-9	Fe-≤0.015C-0.10Si-0.10Mn-≤0.020P- 0.6-1.0Al-11.0-12.5Cr-1.5-2.5Mo- 8.5-10.5Ni-0.25-0.40Ti	
1.4532	X8CrNiMoAl15-7-2	Fe-≤0.1C≤0.7Si≤1.2Mn≤0.04P≤0.015S- 0.7-1.5Al-14.0-16.0Cr-2.0-3.0Mo-6.5-7.8Ni	UNS S15700
1.4533	X6CrNiTi18-10S	Fe-≤0.06C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤0.20Co-≤17.00-19.00Cr- ≤9.00-12.00Ni	
1.4534	X3CrNiMoAl13-8-2	Fe-≤0.05C-≤0.10Si-≤0.10Mn-≤0.010P- ≤0.008S-≤0.90-1.20Al-≤12.25-13.25Cr- ≤2.0-2.50Mo-≤0.01N-≤7.50-8.50Ni	S 13800
1.4536	GX2NiCrMoCuN25-20	Fe-≤0.03C≤1.0Si≤1.0Mn≤0.035P≤0.01S- 19.0-21.0Cr-1.5-2.0Cu-2.5-3.5Mo- 24.0-26.0Ni	UNS J94650
1.4537	X1CrNiMoCuN25-25-5	Fe-≤0.02C-≤0.70Si-≤2.00Mn-≤0.030P- ≤0.010S-24.00-26.00Cr-1.00-2.00Cu-4.70- 5.70Mo-0.170-0.250N-24.00-27.00Ni	
1.4539	X1NiCrMoCu25-20-5	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.030P- ≤0.010S-≤19.0-21.0Cr-≤4.0-5.0Mo- ≤24.0-26.0Ni-≤1.2-2.0Cu-≤0.150N	SAE 904 L
1.4540		Fe-≤0.06C-1.0Si-1.0Mn-15.0-17.0Cr- 2.5-4.0Cu-0.050N-0.15-0.40Nb-3.5-5.0Ni	UNS J92130
1.4541	X6CrNiTi18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤9.0-12.0Ni	SAE 321
1.4542	X5CrNiCuNb16-4	Fe-≤0.07C-≤0.70Si-≤1.5Mn-≤0.040P- ≤0.015S-≤15.0-17.0Cr-≤3.0-5.0Ni- ≤3.0-5.0Cu-≤0.60Mo	SAE 630; 17-4 PH
1.4544	X 10 CrNiMnTi 18 10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.035P- ≤0.025S-≤17.0-19.0Cr-≤9.0-11.5Ni	SAE 321; UNS J92630
1.4545		Fe-≤0.07C-≤1.00Si-≤1.00Mn-≤0.03P- ≤0.015S-≤14.00-15.50Cr-≤2.50-4.50Cu- ≤0.50Mo-≤3.50-5.50Ni	UNS S15500 SAE S15500 A 705 (XM-12)
1.4546	X5CrNiNb18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.030S-≤17.0-19.0Cr-≤9.0-11.5Ni	SAE 347
1.4547	X1CrNiMoCuN20-18-7	Fe-≤0.02C-≤0.70Si-≤1.0Mn-≤0.030P- ≤0.010S-≤19.5-20.5Cr-≤0.5-1.0Cu- ≤6.00-7.00Mo-≤0.18-0.25N-≤17.5-18.5Ni	254 SMO; A 182
1.4548	X5CrNiCuNb17-4-4	Fe-≤0.07C-≤1.0Si-≤1.0Mn-≤0.025P- ≤0.025S-≤15.0-17.5Cr-≤3.0-5.0Cu- ≤0.15-0.45Nb-≤3.00-5.00Ni	17-4 PH; SAE 630
1.4550	X6CrNiNb18-10	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤17.0-19.0Cr-≤9.0-12.0Ni	SAE 347

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4551	X5CrNiNb19-9	Fe-≤0.06C-≤1.40Si-≤1.90Mn-≤0.025P- ≤0.015S-≤18.20-19.80Cr-≤8.20-9.80Ni	UNS S34780 S34781 S34788
1.4552	GX5CrNiNb19-11	Fe-≤0.07C-≤1.5Si-≤1.5Mn-≤0.04P-≤0.03S- 18.0-20.0Cr-9.0-12.0Ni	UNS J92710
1.4557	GX2CrNiMoCuN20-18-6	Fe-≤0.025C-≤1.00Si-≤1.20Mn-≤0.03P- ≤0.01S-≤19.50-20.50Cr-≤0.50-1.00Cu- ≤6.00-7.00Mo-≤0.18-0.24N-≤17.50-19.50Ni	
1.4558	X2NiCrAlTi32-20	Fe-≤0.03C-≤0.70Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.15-0.45Al-≤20.0-23.0Cr- ≤32.0-35.0Ni	
1.4561	X1CrNiMoTi18-13-2	Fe-≤0.02C-≤0.50Si-≤2.0Mn-≤0.035P- ≤0.015S-≤17.0-18.5Cr-≤2.0-2.5Mo- ≤11.5-13.5Ni-≤0.4-0.6Ti	
1.4562	X1NiCrMoCu32-28-7	Fe-≤0.015C-≤0.30Si-≤2.0Mn-≤0.020P- ≤0.010S-≤26.0-28.0Cr-≤1.0-1.4Cu- ≤6.0-7.0Mo-≤0.15-0.25N-≤30.0-32.0Ni	Alloy 31
1.4563	X1NiCrMoCu31-27-4	Fe-≤0.02C-≤0.70Si-≤2.0Mn-≤0.030P- ≤0.010S-≤26.0-28.0Cr-≤3.0-4.0Mo- ≤30.0-32.0Ni-≤0.70-1.5Cu-≤0.11N	B 668
1.4564		Fe-≤0.09C-≤1.00Si-≤1.00Mn-≤0.04P- ≤0.03S-≤0.75-1.50Al-≤16.00-18.00Cr- ≤0.50Cu-≤6.50-7.75Ni	UNS 17700 SAE S17700 A 705 (631)
1.4565	X2CrNiMnMoNbN25-18-5-4	Fe-≤0.03C-≤1.0Si-≤3.5-6.5Mn-≤0.030P- ≤0.015S-≤23.0-26.0Cr-≤3.0-5.0Mo- ≤0.3-0.5N-≤0.15Nb-≤16.0-19.0Ni	UNS S34565
1.4566	X3CrNiMnMoCuNbN 23-17-5-3	Fe-≤0.04C-≤1.0Si-4.5-6.5Mn-≤0.03P- ≤0.015S-21.0-25.0Cr-0.3-1.0Cu-3.0-4.5Mo- 15.0-18.0Ni-0.1-0.3Nb	
1.4567	X3CrNiCu18-9-4; X 3 CrNiCu 18 9	Fe-≤0.04C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤17.00-19.00Cr-≤3.00-4.00Cu- ≤0.110N-≤8.50-10.50Ni	304 Cu (SAE) S 30430 (UNS) A 493 (S 30430) (ASTM)
1.4568	X7CrNiMoAl17-7	Fe-≤0.09C-≤0.70Si-≤1.0Mn-≤0.040P- 0.015S-≤16.0-18.0Cr-≤6.5-7.80Ni- ≤0.70-1.5Al	17-7 PH; SAE 631
1.4571	X6CrNiMoTi17-12-2	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- 0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤10.5-13.5Ni	SAE 316 Ti
1.4573	GX3CrNiMoCuN24-6-5	Fe-≤0.40C-≤1.0Si-≤1.0Mn-≤0.030P- ≤0.020S-≤22.0-25.0Cr-≤1.5-2.5Cu- ≤4.5-6.0Mo-≤0.15-0.25N-≤4.5-6.5Ni	SAE 316 Ti
1.4574		Fe-≤0.09C-≤1.00Si-≤1.00Mn-≤0.040P- ≤0.030S-≤0.75-1.50Al-≤14.00-16.00Cr- ≤2.00-3.00Mo-≤6.50-7.75Ni	S 15700 (SAE) A 579 (63) (ASTM) S 15700 (UNS)

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4575	X1CrNiMoNb28-4-2	Fe-≤0.015C-≤1.0Si-≤1.0Mn-≤0.025P- ≤0.015S-≤26.0-30.0Cr-≤1.8-2.5Mo- ≤0.035N-≤3.0-4.5Ni	25-4-4; A 176
1.4577	X3CrNiMoTi25-25	Fe-≤0.04C-≤0.50Si-≤2.0Mn-≤0.030P- ≤0.015S-≤24.0-26.0Cr-≤2.0-2.5Mo- ≤24.0-26.0Ni	
1.4580	X6CrNiMoNb17-12-2	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤10.5-13.5Ni	SAE 316 Cb UNS J92971
1.4581	GX5CrNiMoNb19-11-2	Fe-≤0.07C-≤1.5Si-≤1.5Mn-≤0.04P-≤0.03S- 18.0-20.0Cr-≤2.0-2.5Mo-9.0-12.0Ni	
1.4582	X4CrNiMoNb25-7	Fe-≤0.06C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-≤24.00-26.00Cr-≤1.30-2.00Mo- ≤6.50-7.50Ni	
1.4583	X10CrNiMoNb18-12	Fe-≤0.10C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-≤16.5-18.5Cr-≤2.5-3.0Mo- ≤12.0-14.5Ni	318 (Spec)
1.4585	GX7CrNiMoCuNb1818	Fe-≤0.080C-≤1.50Si-≤2.0Mn-≤0.045P- ≤0.030S-≤16.5-18.5Cr-≤2.0-2.5Mo- ≤19.0-21.0Ni-≤1.8-2.4Cu	
1.4586	X5NiCrMoCuNb22-18	Fe-≤0.07C-1.0Si-2.0Mn-≤0.045P-≤0.030S- 16.5-18.5Cr-1.5-2.0Cu-3.0-3.5Mo- 21.5-23.5Ni	
1.4589	X5CrNiMoTi15-2	Fe-≤0.080C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.030S-≤13.0-15.5Cr-≤0.2-1.2Mo- ≤1.0-2.5Ni-≤0.3-0.5Ti	UNS S42035
1.4591	X1CrNiMoCuN33-32-1	Fe-≤0.015C-≤0.5Si-≤2.0Mn-≤0.020P- ≤0.010S-≤31.0-35.0Cr-≤0.3-1.2Cu- ≤0.5-2.0Mo-≤0.35-0.6N-≤30.0-33.0Ni	
1.4592	X1CrMoTi29-4	Fe-≤0.025C-1.0Si-1.0Mn-≤0.030P-≤0.010S- 28.0-30.0Cr-3.5-4.5Mo-0.045N	
1.4593	GX3CrNiMoCuN24-6-2-3	Fe-≤0.04C-1.5Si-1.5Mn-≤0.030P-≤0.020S- 23.0-26.0Cr-2.75-3.5Cu-2.0-3.0Mo-0.1-0.2N- 5.0-8.0Ni	
1.4603	X1CrTi17	Fe-≤0.02C-≤1.00Si-≤1.00Mn-≤0.040P- ≤0.015S-≤16.00-18.00Cr	
1.4604	X2CrTi20	Fe-≤0.03C-≤1.00Si-≤1.00Mn-≤0.040P- ≤0.015S-≤19.00-21.00Cr-≤0.40-0.80Ti	
1.4652	X1CrNiMoCuN24-22-8	Fe-≤0.02C-≤0.5Si-≤2.0-4.0Mn-≤0.03P- ≤0.005S-≤23.0-25.0Cr-≤0.3-0.6Cu- ≤7.0-8.0Mo-≤0.45-0.55N-≤21.0-23.0Ni	
1.4712	X10CrSi6	Fe-≤0.12C-≤2.00-2.50Si-≤1.00Mn-≤0.045P- ≤0.030S-≤5.50-6.50Cr	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4713	X10CrAl7; X10CrAlSi7	Fe-≤0.12C-≤0.50-1.00Si-≤1.00Mn-≤0.040P- ≤0.015S-≤0.5-1.0Al-≤6.00-8.00Cr	
1.4718	X45CrSi9-3	Fe-0.4-0.5C-2.7-3.3Si-≤0.6Mn-≤0.04P- ≤0.03S-8.0-10.0Cr-≤0.5Ni	S65007 (UNS)
1.4720	X7CrTi12	Fe-≤0.08C-1.0Si-1.0Mn-≤0.040P-≤0.030S- 10.5-12.5Cr	SAE 409
1.4722	X 10 CrSi 13	Fe-≤0.12C-≤1.90-2.40Si-≤1.00Mn-≤0.045P- ≤0.030S-≤12.0-14.0Cr	
1.4724	X10CrAl13; X10CrAlSi13	Fe-≤0.12C-≤0.70-1.40Si-≤1.00Mn-≤0.040P- ≤0.015S-≤0.70-1.20Al-≤12.0-14.0Cr	
1.4725	CrAl 14 4; (X8CrAl14-4)	Fe-≤0.1C-≤0.5Si-≤1.0Mn-≤0.045P-≤0.03S- 3.5-5.0Al-13.0-15.0Cr	K91670 (UNS)
1.4742	X10CrAlSi18; X10CrAl18	Fe-≤0.12C-≤0.70-1.40Si-≤1.00Mn-≤0.040P- ≤0.015S-≤0.70-1.20Al-≤17.00-19.00Cr	
1.4749	X18CrN28	Fe-0.15-0.20C-1.0Si-1.0Mn-≤0.040P- ≤0.015S-26.0-29.0Cr-0.15-0.25N	
1.4762	X10 CrAl 24; X10CrAlSi25	Fe-≤0.12C-≤0.70-1.40Si-≤1.00Mn-≤0.040P- ≤0.015S-≤1.20-1.70Al-≤23.0-26.0Cr	SAE 446
1.4765	CrAl 25 5; (X8CrAl25-5)	Fe-≤0.10C-≤1.00Si-≤0.60Mn-≤0.045P- ≤0.030S-≤4.50-6.00Al-≤22.00-25.00Cr	
1.4773	X8Cr30	Fe-≤0.09C-≤1.90Si-≤1.40Mn-≤0.030P- ≤0.025S-≤28.80-31.20Cr-≤2.00Ni	
1.4776	GX40CrSi28	Fe-0.30-0.50C-1.0-2.5Si-1.0Mn-≤0.040P- ≤0.030S-27.0-30.0Cr-0.50Mo-1.0Ni	UNS J92605
1.4777	GX130CrSi29	Fe-1.20-1.40C-1.0-2.5Si-0.5-1.0Mn-≤0.035P- ≤0.030S-27.0-30.0Cr-0.50Mo-1.0Ni	
1.4821	X15CrNiSi25-4; X20 CrNiSi 25 4	Fe-0.1-0.2C-0.8-1.5Si-≤2.0Mn-≤0.04P- ≤0.015S-24.5-26.5Cr-≤0.11N-3.5-5.5Ni	
1.4828	X15CrNiSi20-12	Fe-≤0.20C-≤1.50-2.50Si-≤2.0Mn-≤0.045P- ≤0.015S-≤19.0-21.0Cr-≤0.11N-≤11.0-13.0Ni	SAE 309
1.4829	X12CrNi22-12	Fe-≤0.14C-0.90-1.90Si-1.90Mn-≤0.025P- ≤0.015S-20.8-23.2Cr-10.2-12.8Ni	UNS S30980
1.4833	X7CrNi23 14; X12CrNi23-14	Fe-≤0.15C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.015S-≤22.0-24.0Cr-≤0.11N-≤12.0-14.0Ni	SAE 309 S
1.4835	X9CrNiSiNCE21-11-2	Fe-≤0.05-0.12C-≤1.4-2.5Si-≤1.0Mn- ≤0.045P-≤0.015S-≤0.030-0.080Ce- ≤20.0-22.0Cr-≤0.12-0.20N-≤10.0-12.0Ni	253 MA; A 182
1.4841	X15CrNiSi25-20; X15CrNiSi25-21	Fe-≤0.20C-≤1.50-2.50Si-≤2.00Mn- ≤0.045P-≤0.015S-≤24.0-26.0Cr-≤0.11N- ≤19.0-22.0Ni	3RE60; SAE 310; SAE 314
1.4845	X8CrNi25-21; X12CrNi25-21	Fe-≤0.15C-≤1.50Si-≤2.00Mn-≤0.045P- ≤0.015S-≤24.0-26.0Cr-≤0.11N- ≤19.0-22.0Ni	SAE 310 S

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4847	X8CrNiAlTi20-20	Fe-≤0.08C-≤1.0Si-≤1.0Mn-≤0.030P- ≤0.015S-≤0.6Al-18.0-22.0Cr-18.0-22.0Ni- 0.6Ti	334 (SAE)
1.4848	GX40CrNiSi25-20	Fe-≤0.30-0.50C-≤1.00-2.50Si-≤1.50Mn- ≤0.035P-≤0.030S-≤24.0-26.0Cr- ≤19.0-21.0Ni	A 297 (HK)
1.4856	GX40NiCrSiNbTi35-25	Fe-≤0.35-0.45C-≤1.00-1.50Si-≤0.5-1.50Mn- ≤0.035P-≤0.030S-≤23.0-27.0Cr- ≤0.9-1.5Nb-≤33.0-37.0Ni-≤0.10-0.25Ti	
1.4857	GX40NiCrSi35-25	Fe-≤0.30-0.50C-≤1.00-2.50Si-≤1.50Mn- ≤0.035P-≤0.030S-≤24.0-26.0Cr- ≤34.0-36.0Ni	A 297 (HP)
1.4862	X8NiCrSi38-18	Fe-≤0.1C-1.5-2.5Si-0.8-1.5Mn-≤0.03P- ≤0.03S-17.0-19.0Cr-≤0.5Cu-35.0-39.0Ni- ≤0.2Ti	
1.4864	X12NiCrSi35-16; X12 NiCrSi 36 16	Fe-≤0.15C-≤1.0-2.0Si-≤2.0Mn-≤0.045P- ≤0.015S-≤15.0-17.0Cr-≤0.11N-≤33.0-37.0Ni	SAE 330
1.4871	X53CrMnNiN21-9	Fe-≤0.48-0.58C-≤0.25Si-≤8.00-10.00Mn- ≤0.045P-≤0.030S-≤20.00-22.00Cr- ≤0.35-0.50N-≤3.25-4.50Ni	S 63008 (UNS) EV 8 (SAE)
1.4873	X45CrNiW18-9	Fe-≤0.40-0.50C-≤2.00-3.00Si-≤0.80-1.50Mn- ≤0.045P-≤0.030S-≤17.00-19.00Cr- ≤8.00-10.00Ni-≤0.80-1.20W	
1.4875	X55CrMnNiN20-8	Fe-≤0.50-0.60C-≤0.25Si-≤7.00-10.00Mn- ≤0.045P-≤0.030S-≤19.50-21.50Cr- ≤0.20-0.40N-≤1.50-2.75Ni	S 63012 (UNS) EV 12 (SAE)
1.4876	X10NiCrAlTi32-21; X10 NiCrAlTi 32 20	Fe-≤0.12C-≤1.00Si-≤2.00Mn-≤0.030P- ≤0.015S-≤0.15-0.60Al-≤19.00-23.00Cr- ≤30.00-34.00Ni-≤0.15-0.60Ti	N 08332 (UNS) B 366 (N08332) (ASTM) N 8810 (SAE)
1.4877	X6NiCrNbCe32-27	Fe-0.04-0.08C-≤0.3Si-≤1.0Mn-≤0.02P- ≤0.01S-≤0.025Al-0.05-0.1Ce-26.0-28.0Cr- 0.11N-0.6-1.0Nb-31.0-33.0Ni	S33228 (UNS)
1.4878	X10CrNiTi18-10; X12 CrNiTi 18 9	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-0.015S- ≤17.0-19.0Cr-≤9.0-12.0Ni	
1.4903	X10CrMoVNb9-1	Fe-≤0.08-0.12C-≤0.20-0.50Si- ≤0.30-0.60Mn-≤0.020P-≤0.010S- ≤0.04Al-≤8.0-9.5Cr-≤0.85-1.05Mo- ≤0.030-0.070N-≤0.06-0.1Nb-≤0.4Ni- ≤0.18-0.25V	A 182
1.4913	X19CrMoNbVN11-1	Fe-0.17-0.23C-0.50Si-0.40-0.90Mn-≤0.025P- ≤0.015S-≤0.02Al-≤0.0015B-10.0-11.5Cr- 0.5-0.8Mo-0.05-0.1N-0.25-0.55Nb- 0.20-0.60Ni-0.10-0.30V	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4919	X6CrNiMo17-13	Fe-≤0.04-0.08C-≤0.75Si-≤2.0Mn-≤0.035P- ≤0.015S-≤0.0015-0.0050B-≤16.0-18.0Cr- ≤2.0-2.5Mo-≤0.11N-≤12.0-14.0Ni	SAE 316 H
1.4922	X20CrMoV11-1	Fe-≤0.17-0.23C-≤0.50Si-≤1.00Mn-≤0.030P- ≤0.030S-≤10.0-12.5Cr-≤0.80-1.20Mo- ≤0.30-0.80Ni-≤0.25-0.35V	
1.4943	X4NiCrTi25-15	Fe-≤0.06C-≤1.0Si-≤2.0Mn-≤0.025P- ≤0.015S-≤0.35Al-≤0.003-0.01B-≤13.5-16Cr- ≤1.0-1.50Mo-≤24.00-27.00Ni-≤1.70-2.00Ti- ≤0.10-050V	SAE HEV 7 UNS S66545 ASI S 66286 A 891
1.4944		Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.025P- ≤0.015S-≤0.35Al-≤0.003-0.01B- ≤13.50-16.0Cr-≤1.0-1.50Mo- ≤24.00-27.00Ni-≤1.90-2.30Ti-≤0.10-0.50V	UNS S66286; ASI 660; A 638
1.4947		Fe-≤0.07C-0.50-1.2Si-1.5-2.0Mn-≤0.035P- ≤0.025S-22.0-23.0Cr-≤0.3Cu-≤0.75Mo- 9.5-10.5Ni	UNS J93001
1.4948	X6CrNi18-10	Fe-≤0.04-0.08C-≤0.75Si-≤2.0Mn-≤0.035P- ≤0.015S-≤17.0-19.0Cr-≤10.0-12.0Ni	SAE 304 H
1.4958	X5NiCrAlTi31-20	Fe-0.03-0.08C-≤0.7Si-≤1.5Mn-0.015P- ≤0.01S-0.2-0.5Al-0.5Co-19.0-22.0Cr-≤0.5Cu- ≤0.03N-≤0.1Nb-30.0-32.5Ni-0.2-0.5Ti	N08810 (UNS)
1.4959	X8NiCrAlTi32-21	Fe-0.05-0.1C-≤0.7Si-≤1.5Mn-≤0.015P- ≤0.01S-0.2-0.65Al-≤0.5Co-19.0-22.0Cr- ≤0.5Cu-≤0.03N-30.0-34.0Ni-0.25-0.65Ti	N08811 (UNS)
1.4961	X8CrNiNb16-13	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.035P- ≤0.015S-≤15.0-17.0Cr-≤12.0-14.0Ni	
1.4970	X 10 NiCrMoTiB 15 15	Fe-0.08-0.12C-0.25-0.45Si-1.6-2.0Mn- ≤0.03P-≤0.015S-0.003-0.006B-14.5-15.5Cr- 1.05-1.25Mo-15.0-16.0Ni-0.35-0.55Ti	
1.4971	X12CrCoNi21-20	Fe-≤0.08-0.16C-≤1.00Si-≤2.00Mn-≤0.035P- ≤0.015S-≤18.50-21.00Co-≤20.00-22.50Cr- ≤2.50-3.50Mo-≤0.10-0.20N-≤0.75-1.25Nb- ≤19.00-21.00Ni-≤2.00-3.00W	HEV 1 (SAE) 661 (SAE) R 30155 (UNS)
1.4977	X 40 CoCrNi 20 20	Fe-0.35-0.45C-≤1.00Si-≤1.50Mn-≤0.045P- ≤0.030S-19.00-21.00Co-19.00-21.00Cr-3.50- 4.50Mo-3.50-4.50Nb-19.00-21.00Ni-3.50- 4.50W	R 30590 UNS
1.4980	X6NiCrTiMoVB25-15-2; X5NiCrTi26-15	Fe-0.03-0.08C-≤1.0Si-1.0-2.0Mn-≤0.025P- ≤0.015S-≤0.35Al-0.003-0.01B-13.5-16.0Cr- 1.0-1.5Mo-24.0-27.0Ni-1.9-2.3Ti-0.1-0.5V	663 (SAE)
1.4981	X8CrNiMoNb16-16	Fe-≤0.04-0.10C-≤0.30-0.60Si-≤1.50Mn- ≤0.035P-≤0.015S-≤15.5-17.5Cr- ≤1.60-2.00Mo-≤15.5-17.5Ni	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.4982	X10CrNiMoMnNbVB15-10-1	Fe-≤0.07-0.13C-≤1.00Si-≤5.50-7.00Mn- ≤0.040P-≤0.030S-≤0.003-0.009B- ≤14.00-16.00Cr-≤0.80-1.20Mo-≤0.110N- ≤0.75-1.25Nb-≤9.00-11.00Ni-≤0.15-0.40V	
1.4986	X8CrNiMoBNb16-16	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.045P- ≤0.030S-≤0.05-0.1B-≤15.5-17.5Cr- ≤1.6-2.0Mo-≤15.5-17.5Ni	
1.4988	X8CrNiMoVNb16-13	Fe-≤0.04-0.1C-≤0.3-0.6Si-≤1.5Mn-≤0.035P- ≤0.015S-≤15.5-17.5Cr-≤1.1-1.5Mo- ≤12.5-14.5Ni-≤0.60-0.85V-≤0.06-0.14N	
1.5069	36Mn7	Fe-≤0.35C-≤0.5Si-≤1.6Mn-≤0.025P-≤0.025S	UNS H13400
1.5094	38MnS6	Fe-≤0.35-0.40C-≤0.20-0.65Si-≤1.30-1.60Mn- ≤0.045P-≤0.045-0.065S-≤0.01-0.05Al- ≤0.10-0.20Cr-≤0.015-0.020N	
1.5122	37MnSi5	Fe-≤0.33-0.41C-≤1.1-1.4Si-≤1.1-1.4Mn- ≤0.035P-≤0.035S	
1.5219	41MnV5	Fe-0.38-0.44C-0.1-0.4Si- 1.1-1.3Mn-≤0.035P-≤0.035S-0.1-0.15V	
1.5415	15 Mo 3; 16Mo3	Fe-≤0.12-0.2C-≤0.35Si-≤0.4-0.9Mn- ≤0.030P-≤0.025S-≤0.30Cr-≤0.30Cu- ≤0.25-0.35Mo-≤0.30Ni	A 204 (A)
1.5431	G12MnMo7-4	Fe-0.08-0.15C-≤0.6Si- 1.5-1.8Mn-≤0.02P-≤0.015S-≤0.2Cr- 0.3-0.4Mo-≤0.05Nb-≤0.1V	
1.5511	35B2	Fe-≤0.32-0.39C-≤0.4Si-≤0.5-0.8Mn- ≤0.035P-≤0.035S-≤0.02Al-≤0.0008-0.005B	
1.5662	X8Ni9	Fe-≤0.10C-0.35Si-0.30-0.80Mn-≤0.020P- ≤0.010S-≤0.10Mo-8.5-10.0Ni-0.05V	UNS K71340
1.5680	X12Ni5; 12 Ni 19	Fe-≤0.15C-≤0.35Si-0.3-0.8Mn-≤0.02P- ≤0.01S-4.75-5.25Ni-≤0.05V-≤0.5Cr-≤0.5Mo- ≤0.5Cu	A 2515 (SAE)
1.5736	36NiCr10	Fe-max. 0.32-0.40C-0.15-0.35Si- 0.40-0.80Mn-0.035P-0.035S-0.55-0.95Cr- 2.25-2.75Ni	SAE 3435
1.6354		Fe-≤0.03C-≤0.10Si-≤0.10Mn-≤0.01P- ≤0.01S-≤0.05-0.15Al-≤8.00-9.50Co- ≤4.60-5.20Mo-≤17.00-19.00Ni-≤0.60-0.90Ti	UNS J93150
1.6511	36CrNiMo4	Fe-≤0.32-0.40C-≤0.4Si-≤0.5-0.8Mn- ≤0.035P-≤0.035S-≤0.9-1.2Cr-≤0.15-0.3Mo- ≤0.9-1.2Ni	SAE 9840
1.6545	30NiCrMo2-2	Fe-≤0.27-0.34C-≤0.15-0.4Si-≤0.7-1.0Mn- ≤0.035P-≤0.035S-≤0.4-0.6Cr-≤0.15-0.3Mo- ≤0.4-0.7Ni	SAE 8630

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.6562	40 NiCrMo 8 4	Fe-≤0.37-0.44C-≤0.20-0.35Si- ≤0.70-0.90Mn-≤0.02P-≤0.015S- ≤0.005-0.05Al-≤0.70-0.95Cr-≤0.30-0.40Mo- ≤1.65-2.00Ni	UNS G43406 SAE 4340 UNS H 43406 A 829 SAE E 4340 H
1.6565	40NiCrMo6	Fe-0.35-0.45C-≤0.15-0.35Si-≤0.50-0.70Mn- ≤0.035P-≤0.035S-≤0.90-1.4Cr-≤0.20-0.30Mo- ≤1.4-1.7Ni	SAE 4340
1.6580	30CrNiMo8	Fe-≤0.26-0.34C-≤0.4Si-≤0.3-0.6Mn-≤0.035P- ≤0.035S-≤1.8-2.2Cr-≤0.3-0.5Mo-≤1.8-2.2Ni	
1.6582	34CrNiMo6	Fe-≤0.3-0.38C-≤0.4Si-≤0.5-0.8Mn-≤0.035P- ≤0.035S-≤1.3-1.7Cr-≤0.15-0.3Mo-≤1.3-1.7Ni	
1.6751	22NiMoCr3-7	Fe-≤0.17-0.25C-≤0.35Si-≤0.5-1.0Mn- ≤0.02P-≤0.02S-≤0.05Al-≤0.3-0.5Cr- ≤0.18Cu-≤0.5-0.8Mo-≤0.6-1.2Ni-≤0.03V	A 508
1.6900	X 12 CrNi 18 9	Fe-≤0.12C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-≤17.00-19.00Cr-≤0.5Mo- ≤8.00-10.00Ni	UNS J92801
1.6903	X 10 CrNiTi 18 10	Fe-≤0.10C-≤1.00Si-≤2.00Mn-≤0.045P- ≤0.030S-≤17.0-19.0Cr-≤0.5Mo-≤10.0-12.0Ni	
1.6906	X 5 CrNi 18 10	Fe-≤0.07C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S- ≤17.0-19.0Cr-≤0.50Mo-≤9.0-11.5Ni	
1.6932	28NiCrMoV8-5	Fe-0.24-0.32C≤0.4Si- 0.15-0.4Mn≤0.035P≤0.035S-1.0-1.5Cr- 0.35-0.55Mo-1.8-2.1Ni-0.05-0.15V	
1.6944		Fe-≤0.35-0.40C-≤0.15-0.35Si-≤0.50-0.80Mn- ≤0.015P-≤0.01S-≤0.65-0.90Cr-≤0.30-0.40Mo- ≤1.65-2.00Ni-≤0.08-0.15V	
1.6948	27NiCrMoV11-6; 26NiCr- MoV11-5	Fe-≤0.22-0.32C-≤0.15Si-≤0.15-0.40Mn- ≤0.010P-≤0.007S-≤1.20-1.80Cr-≤0.25- 0.45Mo-≤2.40-3.10Ni-≤0.05-0.15V	
1.6952	24NiCrMoV14-6	Fe-≤0.20-0.28C-≤0.15-0.40Si-≤0.30-0.60Mn- ≤0.035P-≤0.035S-≤1.20-1.80Cr-≤0.35- 0.55Mo-≤3.00-3.80Ni-≤0.04-0.12V	K 42885 (UNS) A 649 (6, 7, 8) (ASTM) A 470 (5, 6, 7) (ASTM)
1.6956	33NiCrMoV14-5; 33NiCrMo14-5	Fe-≤0.28-0.38C-≤0.40Si-≤0.15-0.40Mn- ≤0.035P-≤0.035S-≤1.00-1.70Cr- ≤0.30-0.60Mo-≤2.90-3.80Ni-≤0.08-0.25V	
1.6957	27NiCrMoV15-6	Fe-0.22-0.32C≤0.15Si- 0.15-0.4Mn≤0.01P≤0.007S-1.2-1.8Cr- 0.25-0.45Mo-3.4-4.0Ni-0.05-0.15V	ASTM A 470
1.7005	45Cr2	Fe-≤0.42-0.48C-≤0.15-0.40Si-≤0.50-0.80Mn- ≤0.025P-≤0.035S-≤0.40-0.60Cr	
1.7033	34Cr4	Fe-≤0.3-0.37C-≤0.4Si-≤0.6-0.9Mn-≤0.035P- ≤0.035S-≤0.9-1.2Cr	UNS G51320

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.7035	41Cr4	Fe-≤0.38-0.45C-≤0.4Si-≤0.6-0.9Mn- ≤0.035P-≤0.035S-≤0.9-1.2Cr	SAE 5140; UNS H51400
1.7120		Fe-≤0.1C-≤0.25Si-≤0.45Mn-≤0.16Cu- ≤0.07Ni-≤0.05Cr-≤0.035P-≤0.035S	
1.7131	16MnCr5	Fe-0.14-0.19C-≤0.40Si-1.00-1.30Mn- ≤0.035P-≤0.035S-0.80-1.10Cr	G 51170 UNS A 711 (5115) ASTM
1.7147	20MnCr5	Fe-≤0.17-0.22C-≤0.40Si-≤1.10-1.40Mn- ≤0.035P-≤0.035S-≤1.00-1.30Cr	UNS H51200 A 752 (5120) SAE 5120H
1.7214		Fe-≤0.22-0.29C-≤0.15-0.35Si-≤0.5-0.8Mn- ≤0.02P-0.015S-≤0.90-1.20Cr-≤0.15-0.20Mo- 0.30Ni	
1.7218	25CrMo4	Fe-≤0.22-0.29C-≤0.40Si-≤0.60-0.90Mn- ≤0.035P-≤0.035S-≤0.90-1.20Cr- ≤0.15-0.30Mo	SAE 4130
1.7219	26 CrMo 4; 26CrMo4-2	Fe-≤0.22-0.29C-≤0.35Si-≤0.5-0.8Mn- ≤0.03P-≤0.025S-≤0.9-1.2Cr-≤0.15-0.30Mo	A 372
1.7220	34CrMo4	Fe-≤0.3-0.37C-≤0.4Si-≤0.6-0.9Mn- ≤0.035P-≤0.035S-≤0.9-1.2Cr-≤0.15-0.30Mo	SAE 4130
1.7225	42CrMo4	Fe-≤0.38-0.45C-≤0.40Si-≤0.60-0.90Mn- ≤0.035P-≤0.035S-≤0.90-1.20Cr- ≤0.15-0.30Mo	UNS G41400 A 866 (4140) SAE 4140 RH
1.7242	16CrMo4	Fe-≤0.13-0.20C-≤0.15-0.35Si-≤0.50-0.80Mn- ≤0.035P-≤0.035S-≤0.90-1.20Cr- ≤0.20-0.30Mo-≤0.40Ni	
1.7259	26CrMo7	Fe-≤0.22-0.30C-≤0.15-0.35Si-≤0.50-0.70Mn- ≤0.035P-≤0.035S-≤1.50-1.80Cr- ≤0.20-0.25Mo	
1.7273	24CrMo10	Fe-≤0.20-0.28C-≤0.15-0.35Si-≤0.50-0.80Mn- ≤0.035P-≤0.035S-≤2.30-2.60Cr- ≤0.20-0.30Mo-≤0.80Ni	
1.7276	10CrMo11	Fe-≤0.08-0.12C-≤0.15-0.35Si-≤0.30-0.50Mn- ≤0.035P-≤0.035S-≤2.70-3.00Cr- ≤0.20-0.30Mo	
1.7279	17 MnCrMo 3 3	Fe-≤0.20C-0.50-0.90Si-0.70-1.10Mn- ≤0.035P-≤0.035S-0.60-1.00Cr-0.20-0.60Mo- 0.06-0.12V-0.06-0.12Zr	
1.7281	16CrMo9-3	Fe-≤0.12-0.20C-≤0.15-0.35Si-≤0.30-0.50Mn- ≤0.035P-≤0.035S-≤2.00-2.50Cr- ≤0.30-0.40Mo	
1.7335	13 CrMo 4 4; 13CrMo4-5	Fe-≤0.08-0.18C-≤0.35Si-≤0.4-1.0Mn- ≤0.030P-≤0.025S-≤0.7-1.15Cr-≤0.3Cu- ≤0.4-0.6Mo	A 182

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.7357	G17CrMo5-5	Fe-≤0.15-0.20C-≤0.60Si-≤0.50-1.0Mn- ≤0.020P-≤0.020S-≤1.00-1.50Cr- ≤0.45-0.65Mo	A 217; UNS J11872
1.7362	X12CrMo5	Fe-≤0.08-0.15C-≤0.50Si-≤0.30-0.60Mn- ≤0.025P-≤0.020S-≤4.00-6.00Cr- ≤0.45-0.65Mo	SAE 501
1.7375	12CrMo9-10	Fe-≤0.10-0.15C-≤0.30Si-≤0.30-0.80Mn- ≤0.015P-≤0.010S-≤0.01-0.04Al- ≤2.00-2.50Cr-≤0.20Cu-≤0.9-1.10Mo- ≤0.012N-≤0.30Ni	UNS K21590
1.7380	10CrMo9-10	Fe-≤0.08-0.14C-≤0.50Si-≤0.40-0.80Mn- ≤0.030P-≤0.025S-≤2.00-2.50Cr- ≤0.30Cu-≤0.90-1.10Mo	A 182 (F22); UNS J21890
1.7383	11CrMo9-10	Fe-≤0.08-0.15C-≤0.50Si-≤0.40-0.80Mn- ≤0.030P-≤0.025S-≤2.00-2.50Cr- ≤0.30Cu-≤0.90-1.10Mo	
1.7386	X12CrMo9-1	Fe-≤0.07-0.15C-≤0.25-1.0Si-≤0.30-0.60Mn- ≤0.025P-≤0.020S-≤8.0-10.0Cr-≤0.90-1.1Mo	SAE 504; UNS S50488
1.7388	X7CrMo9-1	Fe-≤0.04-0.09C-≤0.45-0.75Si- ≤0.43-0.72Mn-≤0.015P-≤0.015S- ≤8.60-9.90Cr-≤0.90-1.10Mo	S 50480 (UNS)
1.7707	30CrMoV9	Fe-0.26-0.34C-≤0.4Si-0.4-0.7Mn-≤0.035P- ≤0.035S-2.3-2.7Cr-≤0.25Mo-≤0.6Ni-0.1-0.2V	G43406 (UNS)
1.7711	40CrMoV4-6; 40CrMoV4-7	Fe-≤0.36-0.44C-≤0.40Si-≤0.45-0.85Mn- ≤0.03P-≤0.03S-≤0.015Al-≤0.90-1.20Cr- ≤0.50-0.65Mo-≤0.25-0.35V	A 437 (B4D)
1.7715	14MoV6-3	Fe-≤0.1-0.18C-≤0.1-0.35Si-≤0.4-0.7Mn- ≤0.035P-≤0.035S-≤0.3-0.6Cr-≤0.5-0.7Mo- ≤0.22-0.32V	UNS K11591
1.7734		Fe-≤0.12-0.18C-≤0.20Si-≤0.80-1.10Mn- ≤0.02P-≤0.015S-≤1.25-1.50Cr-≤0.80-1.00Mo- ≤0.20-0.30V	
1.7766	17CrMoV10	Fe-≤0.15-0.20C-≤0.15-0.35Si-≤0.30-0.50Mn- ≤0.035P-≤0.035S-≤2.70-3.00Cr- ≤0.20-0.30Mo-≤0.10-0.20V	
1.7779	20 CrMoV 13 5; 20CrMoV13-5-5	Fe-≤0.17-0.23C-≤0.15-0.35Si-≤0.30-0.50Mn- ≤0.025P-≤0.020S-≤3.00-3.30Cr- ≤0.50-0.60Mo-≤0.45-0.55V	
1.7783	X41CrMoV5-1	Fe-≤0.38-0.43C-≤0.80-1.0Si-≤0.20-0.40Mn- ≤0.015P-≤0.010S-≤4.75-5.25Cr-≤1.2-1.4Mo- ≤0.40-0.60V	SAE 610
1.8070	21CrMoV5-11	Fe-≤0.17-0.25C-≤0.30-0.60Si-≤0.30-0.60Mn- ≤0.035P-≤0.035S-≤1.20-1.50Cr- ≤1.00-1.20Mo-≤0.60Ni-≤0.25-0.35V	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.8075	10CrSiMoV7	Fe-≤0.12C-≤0.9-1.2Si-≤0.35-0.75Mn- ≤0.035P-≤0.035S-≤1.6-2Cr-≤0.25-0.35Mo- ≤0.25-0.35V	
1.8159	51CrV4; 50 CrV 4	Fe-≤0.47-0.55C-≤0.40Si-≤0.70-1.10Mn- ≤0.035P-≤0.035S-≤0.90-1.20Cr-≤0.10-0.25V	UNS G61500 A 866 (6150) SAE 6150H
1.8719	15MnCrMo3-2	Fe-0.10-0.20C-0.15-0.35Si-0.60-1.00Mn- ≤0.025P-≤0.025S-0.0005B-0.40-0.65Cr- 0.15-0.50Cu-0.40-0.60Mo-0.70-1.00Ni- 0.03-0.08V	
1.8812	18MnMoV5-2	Fe-≤0.20C-0.20-0.50Si-1.00-1.50Mn- ≤0.030P-≤0.025S-0.10-0.30Mo-≤0.02N- 0.05-0.10V	A 202 (A) (ASTM) A 202 (B) (ASTM) A 302 (A) (ASTM)
1.8850	S460MLH	Fe-≤0.16C-≤0.60Si-≤1.70Mn-≤0.030P- ≤0.025S-0.02Al-≤0.20Mo-≤0.025N- ≤0.050Nb-≤0.30Ni-≤0.05Ti-≤0.12V	A 514 (F) (ASTM) A 517 (F) (ASTM) A 592 (F) (ASTM)
1.8901	S460N	Fe-≤0.2C-≤0.6Si-1.0-1.7Mn-≤0.035P- ≤0.03S-≤0.3Cr-≤0.7Cu-≤0.1Mo-≤0.05Nb- ≤0.8Ni-≤0.03Ti≤0.2V	ASTM A 572
1.8905	P460N; StE 460	Fe-≤0.20C-≤0.60Si-≤1.00-1.70Mn-≤0.030P- ≤0.025S-≤0.02Al-≤0.30Cr-≤0.70Cu- ≤0.10Mo-≤0.025N-≤0.050Nb-≤0.80Ni- ≤0.03Ti-≤0.20V	A 225 (C), A 633 (E)
1.8907	StE 500	Fe-≤0.21C-≤0.1-0.6Si-≤1.0-1.7Mn-≤0.035P- ≤0.03S-≤0.02Al-≤0.30Cr-≤0.70Cu-≤0.10Mo- ≤0.020N-≤0.05Nb-≤1.0Ni-≤0.2Ti-≤0.22V	6386 B; UNS K02001
1.8912	S420NL; TStE 420	Fe-≤0.2C-≤0.6Si-≤1.0-1.7Mn-≤0.03P- ≤0.025S-≤0.02Al-≤0.3Cr-≤0.7Cu-≤0.1Mo- ≤0.025N-≤0.050Nb-≤0.8Ni-≤0.03Ti-≤0.2V	A 737: UNS K02002
1.8924	S500Q; StE 500V	Fe-≤0.2C-≤0.8Si-≤1.7Mn-≤0.025P-≤0.015S- ≤1.5Cr-≤0.5Cu-≤0.7Mo-≤0.06Nb-≤2.0Ni- ≤0.05Ti-≤0.15Zr	
1.8931	S690Q; StE 690V	Fe-≤0.2C-≤0.8Si-≤1.7Mn-≤0.025P-≤0.015S- ≤1.5Cr-≤0.5Cu-≤0.7Mo-≤0.06Nb-≤2.0Ni- ≤0.05Ti-≤0.15Zr	
1.8935	WstE 460; P460NH	Fe-≤0.20C-≤0.60Si-≤1.0-1.70Mn-≤0.030P- ≤0.025S-≤0.02Al-≤0.30Cr-≤0.70Cu- ≤0.10Mo-≤0.025N-≤0.050Nb-≤0.8Ni- ≤0.03Ti-≤0.2V	A 350; UNS K02900
1.8940	S890Q	Fe-≤0.2C-≤0.8Si-≤1.7Mn-≤0.025P-≤0.015S- ≤1.5Cr-≤0.5Cu-≤0.7Mo-≤0.06Nb-≤2.0Ni- ≤0.05Ti-≤0.15Zr	
1.8946	S355J2WP	Fe-≤0.12C-≤0.75Si-≤1.0Mn-0.06-0.15P- ≤0.035S-0.30-1.25Cr-0.25-0.55Cu-≤0.009N- ≤0.65Ni	K02601 (UNS)

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
1.8952	L450QB	Fe-≤0.16C-≤0.45Si-≤1.60Mn-≤0.025P- ≤0.020S-≤0.015-0.06Al-≤0.30Cr-≤0.25Cu- ≤0.10Mo-≤0.012N-≤0.05Nb-≤0.30Ni- ≤0.06Ti-≤0.09V	
1.8961	S235J2W; WTSt 37-3	Fe-≤0.13C-≤0.4Si-≤0.2-0.6Mn-≤0.040P- ≤0.035S-≤0.02Al-≤0.4-0.8Cr-≤0.25-0.55Cu- ≤0.015-0.060Nb-≤0.65Ni-≤0.02-0.10Ti- ≤0.02-0.10V	
1.8962	9CrNiCuP3-2-4	Fe-≤0.12C-≤0.25-0.75Si-≤0.2-0.5Mn- ≤0.07-0.15P-≤0.035S-≤0.5-1.25Cr- ≤0.25-0.55Cu-≤0.65Ni	A 242; UNS K11430
1.8963	S355J2G1W; WTSt 52-3	Fe-≤0.16C-≤0.50Si-≤0.50-1.5Mn-≤0.035P- ≤0.035S-≤0.02Al-≤0.40-0.80Cr- ≤0.25-0.55Cu-≤0.3Mo-≤0.015-0.060Nb- ≤0.65Ni-≤0.02-0.10Ti-≤0.02-0.12V-≤0.15Zr	A 588 (A)
1.8972	L415NB	Fe-≤0.21C-≤0.45Si-≤1.60Mn-≤0.025P- ≤0.020S-≤0.015-0.060Al-≤0.30Cr-≤0.25Cu- ≤0.10Mo-≤0.012N-≤0.050Nb-≤0.30Ni- ≤0.04Ti-≤0.15V	API 5LX 60 (API)
1.8975	L450MB; StE 445.7	Fe-≤0.16C-≤0.45Si-≤1.6Mn-≤0.025P- ≤0.02S-0.015-0.06Al-≤0.3Cr-≤0.25Cu- ≤0.1Mo-≤0.05Nb-≤0.3Ni-≤0.06Ti	API 5LX65
1.8977	L485MB; StE 480.7	Fe-≤0.16C-≤0.45Si-≤1.70Mn-≤0.025P- ≤0.020S-≤0.015-0.06Al-≤0.30Cr-≤0.25Cu- ≤0.10Mo-≤0.012N-≤0.06Nb-≤0.30Ni- ≤0.06Ti-≤0.10V	API 5LX70
2.4060	Ni 99,6	≤99.60Ni-≤0.08C-≤0.15Si-≤0.35Mn- ≤0.005S-≤0.15Cu-≤0.25Fe-≤0.15Mg-≤0.10Ti	UNS N02200
2.4061	LC-Ni 99,6	Fe-≤0.02C-0.15Si-0.35Mn-≤0.005S- ≤0.15Cu-≤0.25Fe-≤0.15Mg-99.6Ni-≤0.10Ti	UNS N02201
2.4066	Ni 99,2; S-Ni 99,2	≤99.20Ni-≤0.10C-≤0.25Si-≤0.35Mn- ≤0.005S-≤0.25Cu-≤0.40Fe-≤0.15Mg-≤0.10Ti	UNS N02200
2.4068	LC-Ni 99	≤99.0Ni-≤0.02C-≤0.25Si-≤0.35Mn- ≤0.005S-≤0.25Cu-≤0.40Fe-≤0.15Mg-≤0.10Ti	UNS N02201
2.4360	NiCu 30 Fe	≤63.0Ni-≤0.15C-≤0.50Si-≤2.0Mn-≤0.020S- ≤0.5Al-≤28.0-34.0Cu-≤1.0-2.5Fe-≤0.3Ti	UNS N04400
2.4361	LC-NiCu 30 Fe	Fe-≤0.04C-≤0.3Si-≤2.0Mn-≤0.02S-≤0.5Al- 28.0-34.0Cu-1.0-2.5Fe-63.0Ni-≤0.3Ti	N04402 (UNS)
2.4363	NiCu30Fe5	≤0.30C-≤0.50Si-≤2.0Mn-0.025-0.60S- ≤0.50Al-28.00-34.00Cu-≤2.50Fe- 63.00-70.00Ni-≤0.30Ti	
2.4365	G-NiCu 30 Nb	Ni-≤0.15C-0.5-1.5-0.5-1.5Mn-≤0.5Al- 26.0-33.0Cu-1.0-2.5-1.0-1.5Nb	UNS N24130

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
2.4366	EL-NiCu 30 Mn	≤62.0Ni-≤0.15C-≤1.0Si-≤1.0-4.0Mn- ≤0.030P-≤0.015S-≤0.5Al-≤27.0-34.0Cu- ≤0.5-2.5Fe-≤1.0Nb-≤1.0Ti	B 127-98
2.4368	G-NiCu 30Si4	Fe-≤0.25C-3.5-4.5Si-0.5-1.5Mn- 27.0-31.0Cu-1.0-2.5Fe-60.0-68.0Ni	UNS N10665
2.4374	NiCu30Al	≤0.25C-≤1.00Si-≤1.50Mn-≤0.010S- 2.00-4.00Al-27.00-34.00Cu-≤2.00Fe- ≥63.00Ni-0.25-1.00Ti	
2.4375	NiCu 30 Al	Ni-≤0.20C-≤0.50Si-≤1.5Mn-≤0.015S- ≤2.2-3.5Al-≤27.0-34.0Cu-≤0.5-2.0Fe- ≤63.0Ni-≤0.3-1.0Ti	UNS N05500
2.4566	ACN 17	Ni-≤0.12C-≤10Si-≤1.2Mn-≤4Co-≤3Cu	
2.4600	NiMo29Cr	Ni-≤0.01C-≤0.1Si-≤3.0Mn-≤0.025P-≤0.015S- ≤0.1-0.5Al-≤3.0Co-≤0.5-3.0Cr-≤0.5Cu- ≤1.0-6.0Fe-≤26.0-32.0Mo-≤0.4Nb- ≤0.2Ti-≤0.2V-≤3.0W	
2.4602	NiCr21Mo14W	Ni-≤0.01C-≤0.08Si-≤0.5Mn-≤0.025P- ≤0.010S-≤2.5Co-≤20.0-22.5Cr-≤2.0-6.0Fe- ≤12.5-14.5Mo-≤0.35V-≤2.5-3.5W	UNS N06022
2.4603	NiCr30FeMo	Ni-≤0.03C-≤0.08Si-≤2.0Mn-≤0.04P- ≤0.02S-≤5.0Co-≤28.0-31.5Cr-≤1.0-2.4Cu- 13.0-17.0Fe-≤4.0-6.0Mo-≤0.3-1.5Nb- ≤1.5-4.0W	UNS N06002
2.4605	NiCr23Mo16Al	Ni-≤0.01C-≤0.10Si-≤0.5Mn-≤0.025P- ≤0.015S-≤0.1-0.4Al-≤0.3Co-≤22.0-24.0Cr- ≤0.5Cu-≤1.5Fe-≤15.0-16.5Mo	UNS N06059
2.4606	NiCr21Mo16W	Ni-≤0.01C-≤0.08Si-≤0.75Mn-≤0.025P- ≤0.015S-≤0.5Al-≤1.0Co-≤19.0-23.0Cr- ≤2.0Fe-≤15.0-17.0Mo-≤0.02-0.25Ti-≤0.2V- ≤3.0-4.0W	UNS N06686
2.4607	SG-NiCr23Mo16	Ni-≤0.015C-≤0.08Si-≤0.50Mn-≤0.02P- ≤0.015S-≤0.1-0.4Al-≤0.3Co-≤22.0-24.0Cr- ≤1.5Fe-≤15.0-16.5Mo	UNS N06059
2.4608	NiCr26MoW	Fe-0.03-0.08C-0.7-1.5Si-≤2.0Mn-≤0.03P- ≤0.015S-2.0-4.0Cu-24.0-26.0Cr-≤0.5Cu- 2.5-4.0Mo-44.0-47.0Ni-2.5-4.0W	N06333 (UNS)
2.4610	NiMo16Cr16Ti	Ni-≤0.01C-≤0.08Si-≤1.0Mn-≤0.025P- ≤0.015S-≤2.0Co-≤14.0-18.0Cr-≤0.5Cu- ≤3.0Fe-≤14.0-18.0Mo-≤0.7Ti	UNS N06455
2.4612	EL-NiMo15Cr15Ti	≤0.02C-≤0.20Si-≤1.00Mn-≤0.015S-≤2.00Co- ≤14.00-18.00Cr-≤3.00Fe-≤14.00-17.00Mo-at least56Ni	
2.4615	SG-NiMo27	Fe-≤0.02C-≤0.10Si-≤1.0Mn-≤0.015S- ≤1.0Cr-≤2.0Fe-26.0-30.0Mo-64.0Ni	UNS N10665

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
2.4617	NiMo28	Ni-≤0.01C-≤0.08Si-≤1.0Mn-≤0.025P- ≤0.015S-≤1.0Co-≤1.0Cr-≤0.5Cu-≤2.0Fe- ≤26.0-30.0Mo	UNS N10665
2.4618	NiCr22Mo6Cu	Ni-≤0.05C-≤1.0Si-≤1.0-2.0Mn-≤0.025P- ≤0.015S-≤2.5Co-≤21.0-23.5Cr-≤1.5-2.5Cu- ≤18.0-21.0Fe-≤5.5-7.5Mo-≤1.75-2.5Nb- ≤1.0W	UNS N06007
2.4619	NiCr22Mo7Cu	Ni-≤0.015C-≤1.0Si-≤1.0Mn-≤0.025P- ≤0.015S-≤5.0Co-≤21.0-23.5Cr-≤1.5-2.5Cu- ≤18.0-21.0Fe-≤6.0-8.0Mo-≤0.5Nb-≤1.5W	UNS N06985
2.4621	EL-NiCr20Mo9Nb	Ni-≤0.1C≤0.8Si≤2.0Mn≤0.4Al-20.0-23.0Cr ≤0.5Cu≤6.0Fe-8.0-10.0Mo-2.0-4.0Nb≤0.4Ti	
2.4623	EL-NiCr23Mo7Cu	Ni-≤0.02C≤1.0Si≤1.0Mn≤0.04P ≤0.03≤5.0Co-21.0-23.5Cr-1.5-2.5Cu- 18.0-21.0Fe-6.0-8.0Mo≤0.5Nb≤0.5Ta≤1.5W	
2.4627	SG-NiCr22Co12Mo	Fe-≤0.1C-≤0.5Si-≤1.0Mn-≤0.015S- 0.8-1.5Al-10.0-14.0Co-20.0-24.0Cr-≤0.5Cu- ≤1.0Fe-8.0-10.0Mo-50.0Ni-≤0.6Ti	N06617 (UNS)
2.4630	NiCr20Ti	Fe-0.08-0.15C-≤1.0Si-≤1.0Mn-18.0-21.0Cr- ≤0.5Cu-≤5.0Fe-0.2-0.6Ti	N06075 (UNS)
2.4631	NiCr20TiAl	Ni-0.04-0.1C≤1.0Si≤1.0Mn≤0.03P≤0.015S- 1.0-1.8Al≤2.0Co-18.0-21.0Cr≤0.2Cu≤1.5Fe- 1.8-2.7Ti	UNS N07080
2.4632	NiCr20Co18Ti	Ni-≤0.13C≤1.0Si≤1.0Mn≤0.02P≤0.015S- 1.0-2.0Al-15.0-21.0Co-18.0-21.0Cr≤0.2Cu ≤1.5Fe-2.0-3.0Ti	UNS N07090
2.4633	NiCr25FeAlY	Fe-0.15-0.25C-≤0.5Si-≤0.5Mn-≤0.02P- ≤0.01S-1.8-2.4Al-24.0-26.0Cr-≤0.1Cu-8.0- 11.0Fe-0.1-0.2Ti-0.05-0.12Y-0.01-0.1Zr	
2.4634	NiCo20Cr15MoAlTi	Ni-0.12-0.17C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.015S-4.5-4.9Al-18.0-22.0Co-14.0-15.7Cr- ≤0.2Cu-≤1.0Fe-4.5-5.5Mo-0.9-1.5Ti	UNS N13021
2.4636	NiCo15Cr15MoAlTi	Ni-0.12-0.2C≤1.0Si≤1.0Mn≤0.045P≤0.03S- 4.5-5.5Al-13.0-17.0Co-14.0-16.0Cr≤0.2Cu ≤1.0Fe-3.0-5.0Mo-3.5-4.5Ti	NIMONIC alloy 115
2.4641	NiCr21Mo6Cu	Fe-≤0.025C-≤0.50Si-≤1.0Mn-≤0.025P- ≤0.015S-≤0.2Al-≤1.0Co-20.0-23.0Cr- 1.5-3.0Cu-5.5-7.0Mo-39.0-46.0Ni-0.6-1.0Ti	UNS N08042
2.4642	NiCr29Fe	≤58.0Ni-≤0.05C-≤0.5Si-≤0.5Mn-≤0.020P- ≤0.015S-≤0.5Al-≤27.0-31.0Cr-≤0.5Cu- ≤7.0-11.0Fe-≤0.5Ti	UNS N06690
2.4650	NiCo20Cr20MoTi	Ni-≤0.04-0.08C-≤0.4Si-≤0.6Mn-≤0.007S- ≤0.3-0.6Al-≤0.005B-≤19.0-21.0Co- ≤19.0-21.0Cr-≤0.2Cu-≤0.7Fe-≤5.6-6.1Mo- ≤1.9-2.4Ti	UNS N07263

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
2.4652	EL-NiCr26Mo	≤37.0-42.0Ni-≤0.03C-≤0.7Si-≤1.0-3.0Mn- ≤0.015S-≤0.1Al-≤23.0-27.0Cr-≤1.5-3.0Cu- ≤30.0Fe-≤3.5-7.5Mo-≤37.0-42.00Ni-≤1.0Ti	UNS S32654
2.4654	NiCr20Co13Mo4Ti3Al; NiCr19Co14Mo4Ti	Fe-0.02-0.2C-≤0.15Si-≤0.1Mn-≤0.015P- ≤0.015S-1.2-1.6Al-0.003-0.01B-12.0-15.0Co- 18.0-21.0Cr-≤0.1Cu-≤2.0Fe-3.5-5.0Mo-2.8- 3.3Ti-0.02-0.08Zr	N07001 (UNS)
2.4658	NiCr7030; NiCr 70 30	Fe-≤0.1C-0.5-2.0Si-≤1.0Mn-≤0.02P- ≤0.15S-≤0.3Al-≤1.0Co-≤29.0-32.0Cr-≤0.5Cu- ≤5.0Fe-60.0Ni	N06008 (UNS)
2.4660	NiCr20CuMo	≤32.0-38.0Ni-≤0.07C-≤1.0Si-≤2.0Mn- ≤0.025P-≤0.015S-≤19.0-21.0Cr-≤3.0-4.0Cu- ≤2.0-3.0Mo	UNS N08020
2.4662	NiCr13Mo6Ti3	Fe-0.02-0.06C-≤0.40Si-≤0.50Mn-≤0.020P- ≤0.020S-≤0.35Al-0.01-0.02B-≤1.0Co- 11.0-14.0Cr-≤0.04Cu-5.0-6.5Mo-40.0-45.0Ni- 2.8-3.1Ti	UNS N09901
2.4663	NiCr23Co12Mo	Ni-≤0.05-0.10C-≤0.2Si-≤0.2Mn-≤0.01P- ≤0.01S-≤0.7-1.4Al-≤0.006B-≤11.0-14.0Co- ≤20.0-23.0Cr-≤0.5Cu-≤2.0Fe-≤8.5-10.0Mo- ≤0.2-0.6Ti	UNS N06617
2.4665	NiCr22Fe18Mo	Fe-0.05-0.15C-≤1.0Si-≤1Mn-≤0.02P- ≤0.015S-≤0.5Al-0.01-0.1B-0.5-2.5Co-20.5- 23.0Cr-≤0.5Cu-17.0-20.0Fe-8.0-10.0Mo-0.2- 1.0W	680 (SAE)
2.4667	SG-NiCr19NbMoTi	Fe-≤0.08C-≤0.40Si-≤0.40Mn-≤0.015S- 0.2-0.8Al-≤0.006B-17.0-21.0Cr-≤0.30Cu- ≤22.0Fe-2.8-3.3Mo-4.8-5.5Nb-50.0Ni- 0.60-1.20Ti	
2.4668	NiCr19Fe19Nb5Mo3	Fe-0.02-0.08C-≤0.35Si-≤0.35Mn-≤0.015P- ≤0.015S-0.3-0.7Al-0.006B-≤1.0Co- 17.0-21.0Cr-≤0.30Cu-2.8-3.3Mo-4.7-5.5Nb- 50.0-55.0Ni-0.60-1.20Ti	UNS N07718
2.4669	NiCr15Fe7TiAl; NiCr15Fe7Ti2Al	Ni-≤0.08C-≤0.5Si-≤1.0Mn-≤0.02P-≤0.015S- ≤0.4-1.0Al-≤1.0Co-≤14.0-17.0Cr-≤0.5Cu- ≤5.0-9.0Fe-≤0.7-1.2Nb-≤2.25-2.75Ti	UNS N07750
2.4670	G-NiCr13Al6MoNb	Ni-≤0.08-0.20C-≤0.50Si-≤0.25Mn-≤0.015P- ≤0.015S-≤5.50-6.50Al-≤0.005-0.15B- ≤1.00Co-≤12.00-14.00Cr-≤0.50Cu- ≤3.80-5.20Mo-≤1.50-2.50Nb-≤0.40-1.00Ti- ≤0.05-0.15Zr	UNS N07713
2.4675	NiCr23Mo16Cu	Ni-≤0.01C-≤0.08Si-≤0.5Mn-≤0.025P- ≤0.015S-≤0.5Al-≤2.0Co-≤22.0-24.0Cr- ≤1.3-1.9Cu-≤3.0Fe-≤15.0-17.0Mo	

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
2.4679	G-NiCr35	Ni-≤0.10C-≤1.00Si-≤0.30Mn- ≤34.00-36.00Cr-≤1.00Fe-≤0.30N	
2.4680	G-NiCr50Nb	Ni-≤0.10C-≤1.00Si-≤0.50Mn-≤0.02P-≤0.02S- ≤48.00-52.00Cr-≤1.00Fe-≤0.50Mo-≤0.16N- ≤1.00-1.80Nb	
2.4681	CoCr26Ni9Mo5W	Ni-≤1.0C-≤1.0Si-≤1.5Mn-≤23.5-27.5Cr- ≤1.0-3.0Fe-≤4.0-6.0Mo-≤0.12N-≤7.0-11.0Ni- ≤1.0-3.0W	
2.4683	CoCr22NiW	Fe-0.05-0.15C-0.2-0.5Si-≤1.25Mn-≤0.02P- ≤0.015S-20.0-24.0Cr-≤3.0Fe-0.02-0.12La- 20.0-24.0Ni-13.0-16.0W	R30188 (UNS)
2.4686	G-NiMo 17 Cr	Ni-≤0.03C-≤0.5Si-≤1.0Mn-≤2.5Co- 15.5-17.5Cr-≤7.0Fe-16.0-18.0Mo	
2.4694	NiCr16Fe7TiAl	Fe-≤0.08C-≤0.5Si-≤0.5Mn-≤0.015P- ≤0.01S-0.8-1.6Al-14.0-17.0Cr-≤0.5Cu- 5.0-9.0Fe-0.7-1.2Nb-70.0Ni-2.0-2.6Ti	N07031 (UNS)
2.4800	S-NiMo 30	≤60.0Ni-≤0.05C-≤1.0Si-≤1.0Mn-≤0.045P- ≤0.025S-≤2.5Co-≤1.0Cr-≤4.0-7.0Fe- ≤26.0-30.0Mo-≤0.2-0.4V	UNS N10001
2.4810	NiMo 30	≤62.0Ni-≤0.05C-≤0.5Si-≤1.0Mn-≤0.030P- ≤0.015S-≤2.5Co-≤1.0Cr-≤0.5Cu-≤4.0-7.0Fe- ≤26.0-30.0Mo-≤0.6V	UNS N10001
2.4811		Fe-≤0.03C-≤0.05Si-≤0.80Mn-≤0.030P- ≤0.015S-19.0-21.0Cr-≤0.50Cu-≤2.5Fe- 14.0-17.0Mo-58.0Ni-0.35V	
2.4816	NiCr15Fe	≤72.0Ni-≤0.05-0.1C-≤0.5Si-≤1.0Mn- ≤0.020P-≤0.015S-≤0.3Al-≤0.0060B-≤1.0Co- ≤14.0-17.0Cr-≤0.5Cu-≤6.0-10.0Fe-≤0.3Ti	UNS N06600
2.4817	LC-NiCr15Fe	≤72.0Ni-≤0.025C-≤0.50Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤0.0060B-≤1.0Co- ≤14.0-17.0-≤0.5Cu-≤6.0-10.0Fe-≤0.3Ti	
2.4819	NiMo16Cr15W	Ni-≤0.01C-≤0.08Si-≤1.0Mn-≤0.025P- ≤0.015S-≤2.5Co-≤14.5-16.5Cr-≤0.5Cu- ≤4.0-7.0Fe-≤15.0-17.0Mo-≤0.35V-≤3.0-4.5W	UNS N10276
2.4831	SG-NiCr21Mo9Nb	Fe-≤0.10C-≤0.50Si-≤0.50Mn-≤0.015S- ≤0.4Al-20.0-23.0Cr-≤0.50Cu-≤5.0Fe- 8.0-10.0Mo-3.0-4.5Nb-60.0Ni-≤0.40Ti	UNS N06625
2.4851	NiCr23Fe	Fe-0.03-0.1C-≤0.5Si-≤1.0Mn-≤0.02P- ≤0.015S-1.0-1.7Al-≤0.006B-21.0-25.0Cr- ≤0.5Cu-≤18.0Fe-58.0-63.0Ni-≤0.5Ti	N06601 (UNS)
2.4856	NiCr22Mo9Nb	Ni-≤0.03-0.10C-≤0.5Si-≤0.5Mn-≤0.020P- ≤0.015S-≤0.4Al-≤1.0Co-≤20.0-23.0Cr- ≤0.5Cu-≤5.0Fe-≤8.0-10.0Mo-≤3.15-4.15Nb- ≤0.4Ti	UNS N06625

German Standard		Materials Compositions	US-Standard
Mat.-No.	DIN-Design	Percent in Weight	SAE/ASTM/UNS
2.4858	NiCr21Mo	≤38.0-46.0Ni-≤0.025C-≤0.50Si-≤1.0Mn- ≤0.025P-≤0.015S-≤0.20Al-≤1.0Co- ≤19.5-23.5Cr-≤1.5-3.0Cu-≤2.5-3.5Mo- ≤0.6-1.2Ti	B 163 UNS N08825
2.4869	NiCr80-20	Fe-≤0.15C-0.50-2.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤1.0Co-19.0-21.0Cr- ≤0.50Cu-≤1.0Fe-75.0Ni	UNS N06003
2.4882		Fe-≤0.12C-0.50-2.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤1.0Co-19.0-21.0Cr- ≤0.50Cu-≤1.0Fe-75.0Ni	UNS N10001
2.4883		Fe-≤0.03C-≤0.50Si-≤1.0Mn-≤2.50Co- 15.50-17.50Cr-≤7.0Fe-16.0-18.0Mo	UNS N10002
2.4886	SG-NiMo16Cr16W; UP-NiMo16Cr16W	≤50.0Ni-≤0.02C-≤0.08Si-≤1.0Mn-≤0.015S- ≤14.5-16.5Cr-≤4.0-7.0Fe-≤15.0-17.0Mo- ≤0.4V-≤3-4.5W	UNS N10276
2.4887	EL-NiMo15Cr15W	≤50.0Ni-≤0.02C-≤0.20Si-≤1.0Mn-≤0.015S- ≤14.5-16.5Cr-≤4.0-7.0Fe-≤15.0-17.0Mo- ≤0.4V-≤3-4.5W	
2.4951	NiCr20Ti	Ni-≤0.08-0.15C-≤1.0Si-≤1.0Mn-≤0.020P- ≤0.015S-≤0.3Al-≤0.0060B-≤5.0Co- ≤18.0-21.0Cr-≤0.5Cu-≤5.0Fe-≤0.2-0.6Ti	UNS N06075
2.4952	NiCr20FeMo3TiCuAl	Fe-≤0.03C-≤0.5Si-≤1.0Mn-≤0.03P-≤0.03S- 0.1-0.5Al-19.5-22.5Cr-1.5-3.0Cu-≤22.0Fe-2.5- 3.5Mo-≤0.5Nb-42.0-46.0Ni-1.9-2.4Ti	
2.4964	CoCr20W15Ni	≤9.0-11.0Ni-≤0.05-0.15C-≤0.4Si-≤2.0Mn- ≤0.020P-≤0.015S-≤19.0-21.0Cr-≤3.0Fe- ≤9.0-11.0Ni-≤14.0-16.0W	UNS R30605
2.4973	NiCr19CoMo	Ni-≤0.12C-≤0.50Si-≤0.10Mn-≤1.40-1.80Al- ≤10.00-12.00Co-≤18.00-20.00Cr-≤5.00Fe- ≤9.00-10.50Mo-≤2.80-3.30Ti	N 07041 (UNS) 683 (SAE)
2.4975	NiFeCr12Mo	Fe-≤0.10C-≤0.60Si-≤2.00Mn-≤0.020P- ≤0.010S-≤0.350Al-≤1.00Co-11.00-14.00Cr- 5.00-7.00Mo-40.00-45.00Ni-2.35-3.10Ti	
2.4976	NiCr20Mo	Ni-≤0.10C-≤1.00Si-≤1.00Mn-≤0.020P- ≤0.010S-0.50-1.80Al-≤2.00Co-18.00-21.00Cr- ≤5.00Fe-4.00-5.00Mo-1.80-2.70Ti	
2.4983	NiCr18Co	Ni-≤0.15C-≤0.50Si-≤1.00Mn-≤0.02P- ≤0.01S-≤2.50-3.20Al-≤17.00-20.00Co- ≤17.00-20.00Cr-≤4.00Fe-≤3.00-5.00Mo- ≤2.50-3.20Ti	UNS N07500 ASTM B637 (N07500)(864)
2.4999	MP35N	35.0Ni-≤0.01C-≤20.0Cr-≤9.5Mo	

Table 2: Chemical compositions of different American, CIS, Bulgarian and other steels

Steel	Materials Compositions, Percent in Weight	Note
000Ch16N13M2	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with SAE 316
000Ch16N13M3	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with SAE 316
000Ch16N16M4	Fe-≤0.07C-≤1.0Si-≤2.0Mn-16.5-18.5Cr-2-2.5Mo-10-13Ni-≤0.045P-≤0.015S-≤0.11N	CIS, formerly USSR, identical with SAE 316
000Ch18N10	Fe-≤0.03C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.3Mo-9-11Ni	CIS, formerly USSR/Bulg.
000Ch18N11	Fe-≤0.03C-≤1.0Si-≤2.0Mn-18-20Cr-10-12Ni-≤0.045P-≤0.015S-≤0.11N	Bulg., comparable with 1.4306
000Ch20N20	Fe-≤0.03C-≤18.57Cr-≤19.40Ni-≤0.71Mn-≤0.26Si	CIS, formerly USSR
000Ch21N6M2	Fe-≤0.036C-≤21.1Cr-6.5Ni-2.4Mo	CIS, formerly USSR
000Ch21N10M2	Fe-≤0.02C-≤19.8Cr-≤10.5Ni-≤2.1Mo	CIS, formerly USSR
000Ch21N21M4B	Fe-≤0.03C-≤20-22Cr-20-21Ni-3.4-3.7Mo-≤0.6Mn-≤0.6Si-≤0.03P-≤0.02S-0.45-0.8Nb	CIS, formerly USSR
005Ch25B	Fe-0.005C-0.007N-25Cr	CIS, formerly USSR
00Ch18G8N2T	Fe-≤0.08C-≤0.8Si-7-9Mn-17-19Cr-≤0.3Mo-1.8-2.8Ni-≤0.2W-≤0.3Cu-≤0.2Ti-0.2-0.5Al	CIS, formerly USSR
00Ch18N10	Fe-≤0.015C-≤0.7Si-≤1.7Mn-≤17.3Cr-≤10.4Ni	CIS, formerly USSR
0Ch20N6M2T	not available (n.a.)	CrNiMoTi 20 6 2
0Ch21N6M2T	n. a.	CrNiMoTi 21 6 2
1Ch21N5T	n. a.	–
1H18N9	n. a.	cf. 1.4541; SAE 321
2Ch18N9	n. a.	Fe-0.2C-18Cr-9Ni; cf. 1.4310, UNS 30200
02Ch12N10S5	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch12N10S5B	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch12N10S5T	Fe-0.02C-12Cr-10Ni-5Si, Nb-stabilized	CIS, formerly USSR
02Ch17NS6	Fe-0.02C-4-6.5Si-0.43-0.52Mn-16.3-18Cr-10.5-18.2Ni-0.005-0.008S-0.012-0.014P	CIS, formerly USSR
02Ch8N22S6	Fe-≤0.02C-≤5.4-6.7Si-0.6Mn-≤0.030P-≤0.020S-7.5-10Cr-0.3Mo-21-23Ni-≤0.2Ti-≤0.20W	CIS, formerly USSR
02Ch8N22S6B	Fe-0.02C-8Cr-122Ni-6Si, Nb-stabilized	CIS, formerly USSR
02Ch8N22T	Fe-0.02C-8Cr-122Ni-6Si, Ti-stabilized	CIS, formerly USSR
03Ch16N15M3	Fe-≤0.03C-15.0-17.0Cr-14.0-16.0Ni-2.5-3.0Mo-Ti	CIS, formerly USSR
03Ch18N11	Fe-0.03C-≤0.80Si-≤0.70-2.0Mn-≤0.035P-0.020S-17.0-19.0Cr-≤0.10Mo-10.5-12.5Ni-≤0.20W-0.30Cu-≤0.50Ti	CIS, formerly USSR, comparable with DIN-Mat.No. 1.4306
03Ch18N14	Fe-0.03C-18Cr-14Ni	CIS, formerly USSR
03Ch21N21M4B	n. a.	CrNiMoB 21 21 4

Steel	Materials Compositions, Percent in Weight	Note
03Ch21N21M4GB	Fe-≤0.03C-≤0.60Si-1.8-2.5Mn-≤0.030P-≤0.020S-20-22Cr-3.4-3.7Mo-20-22Ni-≤0.2W-≤0.3Cu-≤0.2Ti, Nb 15 x C-0.80	CIS, formerly USSR
03Ch23N6	Fe-≤0.03C-≤0.40Si-1.0-2.0Mn-≤0.035P-≤0.020S-22-24Cr-≤5.3-6.3Ni	CIS, formerly USSR
03Ch25	Fe-about 0.03C-25Cr-0.6Ni	CIS, formerly USSR
03ChN28MDT	Fe-≤0.03C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S-22.0-25.0Cr-2.5-3.0Mo-26.0-29.0Ni-0.50-0.90Ti-2.5-3.5Cu	CIS, formerly USSR
04Ch18N10	Fe-≤0.04C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.030P-≤0.02S-≤0.3Mo-9-11Ni-≤0.2W-≤0.3Cu-≤0.2Ti	CIS, formerly USSR
04Ch18N10T	Fe-≤0.04C-≤0.8Si-≤2.0Mn-17-19Cr-≤0.3Mo-9-11Ni-≤0.2W-≤0.3Cu-≤0.2Ti	CIS, formerly USSR
05Ch16N15M3	Fe-0.05C-16Cr-15Ni-3Mo	CIS, formerly USSR
06Ch17G15NAB	Fe-0.05C-18.36Cr-16.5Mn-1.6Ni-0.31Nb-β.12Si-0.01Ce-0.017P-0.014S	CIS, formerly USSR
06Ch23N28M3D3T	Fe-≤0.06C-≤0.8Si-≤2.0Mn-22-25Cr-≤2.4-3Mo-26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR/Bulg.
06Ch28MDT	Fe-≤0.06C-≤0.8Si-≤0.80Mn-22.0-25.0Cr-2.5-3.0Mo-26.0-29.0Ni-0.50-0.90Ti-2.5-3.5Cu	CIS, formerly USSR
06ChN28MDT	Fe-≤0.06C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.02S-22-25Cr-2.5-3.0Mo-26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR
06ChN40B	Fe-0.055C-17.01Cr-39.04Ni-1.99Mn-0.50Nb-0.60Si-0.013S-0.022P	CIS, formerly USSR
06XH28M?T	n. a.	
07Ch13AG20	Fe-≤0.07C-≤0.60Si-≤19-22Mn-≤0.035P-≤0.025S-≤0.0030B-≤0.1Ca-≤0.1Ce-12-14.8Cr-≤0.30Cu-≤0.1Mg-≤0.30Mo-≤0.08-0.18N-≤1.0Ni-≤0.20W-≤0.20Ti	CIS, formerly USSR
07Ch16N4B	Fe-0.05-0.10C-≤0.60Si-≤0.2-0.5Mn-≤0.025P-≤0.020S-15-16.5Cr-≤0.30Cu-≤0.30Mo-0.2-0.4Nb-3.5-4.5Ni-≤0.20W	CIS, formerly USSR
07Ch17G15NAB	Fe-0.05C-18.4Cr-16.5Mn-1.6Ni-0.01Ce-0.005B-0.32N	CIS, formerly USSR
07Ch17G17DAMB	Fe-0.06C-17.6Cr-15.2Mn-0.43Mo-0.3Nb-0.005B-0.38N	CIS, formerly USSR
08Ch17N5M3	Fe-0.06C-0.10C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S-16.0-17.5Cr-3.0-3.5Mo-4.5-5.5Ni-≤0.20W-≤0.30Cu-≤0.20Ti	CIS, formerly USSR
08Ch17N15M3B	Fe-≤0.08C-16.0-18.0Cr-14.0-16.0Ni-3.0-4.0Mo-Ti	CIS, formerly USSR
08Ch17N15M3T	Fe-≤0.08C-≤0.80Si-≤2.0Mn-≤0.35P-≤0.020S-16.0-18.0Cr-3.00-4.00Mo-14.0-16.0Ni-≤0.20W-0.30Cu-0.30-0.60Ti	CIS, formerly USSR
08Ch17T	Fe-≤0.08C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.025S-16.0-18.0Cr-≤0.6Ni-≤0.30Cu	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
08Ch18G8N2M2T	Fe-0.08C-18.2Cr-3.42Ni-8.9Mn-2.32Mo-0.22Ti	CIS, formerly USSR
08Ch18G8N2T	Fe-≤0.08C-≤0.80Si-7.0-9.0Mn-≤0.035P-17.0-19.0Cr-≤0.30Mo-1.80-2.80Ni-≤0.30Cu-≤0.035P-≤0.025S-≤0.20-0.50Ti-≤0.20W	CIS, formerly USSR
08Ch18N10	Fe-≤0.08C-≤0.8Si-≤2.0Mn-≤0.035P-≤0.020S-17-19Cr-0.3Mo-9.0-11.0Ni-≤0.2W-≤0.3Cu	CIS, formerly USSR
08Ch18N10T	Fe-≤0.08C-≤0.8Si-≤2.0Mn-≤0.035P-≤0.020S-17-19Cr-0.5Mo-9.0-11.0Ni-0.5Ti-≤0.2W-≤0.3Cu	CIS, formerly USSR
08Ch21N6M2T	Fe-≤0.08C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.025S-20-22Cr-1.8-2.5Mo-5.5-6.5Ni-0.2-0.4Ti-≤0.2W-≤0.3Cu	CIS, formerly USSR
08Ch22N6M2T	Fe-≤0.08C-≤0.80Si-≤0.80Mn-20.0-22.0Cr-1.80-2.50Mo-5.50-6.50Ni-≤50.20W-≤0.30Cu-≤0.035P-≤0.025S-0.20-0.40Ti	CIS, formerly USSR
08Ch22N6T	Fe-≤0.08C-≤0.8Si-≤0.8Mn-≤0.035P-≤0.025S-21-23Cr-≤0.3Mo-5.3-6.3Ni-≤0.2W-≤0.3Cu, 5x% C max. 0.65Ti	CIS, formerly USSR
08ChP	Fe-0.25Cr-0.25Ni-0.25Mo	CIS, formerly USSR
08-KP	n. a.	cf. 1.0335; UNS G 10060
08X21H6M2T	n. a.	—
08X22H6T	n. a.	—
09Ch16N15M3B	Fe-≤0.09C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.020S-15.0-17.0Cr-≤0.30Cu-2.5-3.0Mo-0.6-0.9Nb-14.0-16.0Ni-≤0.20Ti-≤0.20W	CIS, formerly USSR
09G2S	Fe-≤0.12C-0.5-0.8Si-1.3-1.7Mn-≤0.035P-≤0.035S-≤0.3Cr-≤0.3Ni-≤0.3Cu	Bulg.
0Ch17N16M3T	Fe-≤0.080C-≤0.8Si-≤2.00Mn-16.0-18.0Cr-3.00-4.00Mo-14.0-16.0Ni-≤0.035P-≤0.025S-0.30-0.60Ti	CIS, formerty USSR
0Ch18G8N3M2T	Fe-about 18 Cr-8Mn-3Ni-2Mo, Ti	CIS, formerly USSR
0Ch18N10T	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17-19Cr-9-12Ni, Ti 5xC-0.70	CIS, formerly USSR/Bulg.
0Ch18N12B	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17-19Cr-≤9.0-12Ni, Nb 10xC-1.00	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4550
0Ch20N14S2	Fe- about 20Cr-14Ni-2Si	CIS, formerly USSR
0Ch21N5T	Fe-≤0.08Cr-21Cr-5Ni, Ti	CIS, formerly USSR s. text HNO3
0Ch23N18	Fe-≤0.20C-≤1.00Si-1.50Mn-22.0-25.0Cr-≤0.30Mo-17.0-20.0Ni-≤0.035P-≤0.025S	CIS, formerly USSR
0Ch23N28M3D3T	Fe-≤0.06C-≤0.8Si-≤2Mn-22-25Cr-2.4-3Mo-26-29Ni-0.5-0.9Ti-2.5-3.5Cu	CIS, formerly USSR/Bulg.
0Ch25T	Fe-≤0.01C-25Cr, Ti-stabilized	CIS, formerly USSR
0H17N12M2T	Fe-≤0.05C-≤1.0Si-≤2.0Mn-16-18Cr-2-3Mo-11-14Ni-≤0.045P-≤0.030S, Ti 5xC-0.60	Poland

Steel	Materials Compositions, Percent in Weight	Note
10Ch13 (1Ch13)	Fe-0.08-0.15C-≤1.0Si-≤1.5Mn-≤0.040P-≤0.015S-11.5-13.5Cr-≤0.75Ni	CIS, formerly USSR/Bulg.
10Ch14AG15	Fe-≤0.10C-≤0.80Si-14.5-16.5Mn-≤0.045P-≤0.030S-13.0-15.0Cr-≤0.60Ni-≤0.60Cu-≤0.20Ti-0.15-0.25N	CIS, formerly USSR
10Ch14G14N4T	Fe-≤0.10C-≤0.80Si-13.0-15.0Mn-13.0-15.0Cr-≤0.30Mo-2.80-4.50Ni-≤0.20W-≤0.30Cu-≤0.035P-≤0.020S-5x% C max. 0.60Ti	CIS, formerly USSR
10Ch17	Fe-0.10C-17Cr	CIS, formerly USSR
10Ch17N13M2T	Fe-≤0.10C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S-16.0-18.0Cr-≤0.30Cu-2.0-3.0Mo-12.0-14.0Ni-≤0.20W, Ti>5x% C	USA, comparable with DIN-Mat. No. 1.4571
10Ch17N13M3T	Fe-≤0.10C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S-16.0-18.0Cr-≤0.30Cu-3.0-4.0Mo-12.0-14.0Ni-≤0.20W-≤0.7Ti	USA, comparable with DIN-Mat. No. 1.4573
10Ch18N9T(Ch18N9T)	Fe-0.08C-1.0Si-≤2Mn-≤0.045P-≤0.015S-17-19Cr-≤0.3Mo-9-12Ni-Ti5xC-0.70	CIS, formerly USSR/Bulg.
10Ch18N10M2T	Fe-≤0.10C-18Cr-10Ni-2Mo, Ti stabilized	CIS, formerly USSR
10Ch18N10T	Fe-≤0.10C-≤0.80Si-≤1.0-2.0Mn-≤0.035P-≤0.020S-≤17.0-19.0Cr-≤10.0-11.0Ni	CIS, formerly USSR/Bulg.
12Ch13G18D	Fe-0.12C-13Cr-18Mn-Cu	CIS, formerly USSR
12Ch17G9AN4	Fe-≤0.12C-≤0.80Si-8.0-10.5Mn-≤0.035P-≤0.020S-16.0-18.0Cr-≤0.30Mo-3.5-4.5Ni-≤0.20W-≤0.30Cu-≤0.20Ti-0.15-0.25N	CIS, formerly USSR
12Ch18N9T	Fe-≤0.12C-≤0.80Si-≤2.0Mn-≤0.035P-≤0.020S-17.0-19.0Cr-≤0.50Mo-8.0-9.5Ni-≤0.20W-≤0.30Cu-Ti = 5x % C	CIS, formerly USSR
12Ch18N10T	Fe-≤0.12C-≤0.8Si-≤2.0Mn-≤0.025P-≤0.020S-17.0-19.0Cr-≤0.30Cu-≤0.50Mo-9.0-11.0Ni-≤0.20W-≤0.70Ti	CIS, formerly USSR; comparable with DIN-Mat. No. 1.4878
12Ch2M1	Fe-0.12C-2Cr-1Mo	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.7380, A 182, F 22, B.S. 1501-622
12Ch2N4A	Fe-0.09-0.15C-0.17-0.37Si-0.30-0.60Mn-≤0.025P-≤0.025S-1.25-1.65Cr-3.25-3.65Ni-≤0.30Cu-≤0.15Mo-≤0.03Ti-≤0.05V-≤0.12W	CIS, formerly USSR
12Ch21N5T	Fe-0.09-0.14C-≤0.80Si-≤0.80Mn-≤0.035P-≤0.025S-20.0-22.0Cr-≤0.30Mo-4.80-5.80Ni-≤0.20W-≤0.30Cu-0.25-0.50Ti-≤0.08Al	CIS, formerly USSR
12ChN2	Fe-0.09-0.16C-0.17-0.37Si-0.30-0.60Mn-≤0.035P-≤0.035S-0.60-0.90Cr-1.50-1.90Ni-≤0.30Cu-≤0.15Mo-≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR/Bulg.
13-4-1	Fe-0.043C-12.7Cr-3.9Ni-1.5Mo-0.68Mn-0.39Si-0.009P-0.013S-0.030N	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
14Ch17N2	Fe-≤0.11-0.17C-≤0.80Si-≤0.80Mn-16.0-18.0Cr-≤0.30Mo-1.50-2.50Ni-≤0.20W-≤0.30Cu-≤0.030P-≤0.025S-≤0.20Ti	CIS, formerly USSR
15Ch17N2	Fe-0.13C-0.49Si-0.52Mn-17.17Cr-1.75Ni-0.012P-0.09S	CIS, formerly USSR
15Ch25T	Fe-≤0.15C-≤1.00Si-≤0.80Mn-≤0.035P-≤0.025S-24.0-27.0Cr-≤0.30Cu-≤1.00Ni-0.09Ti	CIS, formerly USSR
15Ch28	Fe-≤0.15C-≤1.00Si-≤0.80Mn-27.0-30.0Cr-0.60Ni-≤0.30Cu-≤0.035P-≤0.025S-≤1.0Ni-≤0.20Ti	CIS, formerly USSR
15Ch2M2FBS	Fe-about 0.15C-2Cr-2Mo-V-Nb-Si	CIS, formerly USSR
15Ch5M	Fe-≤0.15C-≤0.50Si-≤0.50Mn-4.50-6.00Cr-0.40-0.60Mo-≤0.60Ni-≤0.03Ti-≤0.030P-≤0.025S-≤0.20Cu-≤0.05V-≤0.30W	CIS, formerly USSR
16GS	Fe-≤0.12-0.18C-≤0.40-0.70Si-0.90-1.20Mn-≤0.30Cr-≤0.30Ni-≤0.30Cu-≤0.035P-≤0.040S-≤0.05Al-≤0.08As-≤0.012N-≤0.03Ti	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.0481, A 414, A 515, A 516
18/8-CrNi-steel	Fe-≤0.12C-1.0Si-≤2.0Mn-≤0.045P-≤0.030S-≤17.0-19.0Cr-≤8.0-10.0Ni	—
1815-LCSi	Fe-0.006C-18.3Cr-15.1Ni-1.5Mn-4.1Si-0.005S-0.010P-0.010N	UNS S30600, comparable with DIN-Mat. No. 1.4361
18-18-2	Fe-≤0.08C-1.5-2.5Si-≤2.0Mn-≤0.030P-≤0.030S-17.0-19.0Cr-17.5-18.5Ni	USA
18G2A	Fe-≤0.20C-≤0.50Si-≤0.9-1.7Mn-≤0.025P-≤0.020S-≤0.0200Al-≤0.30Cr-≤0.50Ni-≤0.30Cu-≤0.08Mo-≤0.020N-≤0.050Nb-≤0.03Ti-≤0.1V	Poland
20ChGS2	Fe-≤0.25C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤14.0Cr	Russia
20Ch13 (2Ch13)	Fe-0.16-0.25C-≤0.8Si-≤0.8Mn-12-14Cr-≤0.6Ni-≤0.030P-≤0.025S-≤0.30Cu-≤0.20Ti	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4021, SAE 420, 420 S 29
20Ch23N18	Fe-≤0.2C-≤1.0Si-≤2.0Mn-22-25Cr-≤0.3Mo-17-20Ni-≤0.2W-≤0.3Cu-≤0.2Ti-≤0.035P-≤0.025S	CIS, formerly USSR
20Ch2G2SR	Fe-0.16-0.26C-0.75-1.55Si-1.4-1.8Mn-≤0.040P-≤0.040S-1.4-1.8Cr-≤0.30Ni-≤0.30Cu-0.02-0.08Ti-0.015-0.050Al-0.001-0.007B	CIS, formerly USSR
23Ch2G2T	Fe-0.19-0.26C-0.40-0.70Si-1.4-1.7Mn-≤0.045P-≤0.045S-1.35-1.70Cr-≤0.30Ni-≤0.30Cu-0.02-0.08Ti-0.015-0.05Al	CIS, formerly USSR
36NChTJu	Fe-≤0.05C-≤0.3-0.7Si-≤0.8-1.2Mn-≤0.020P-≤0.020S-11.5-13Cr-35-37Ni-0.9-1.2Al-2.7-3.2Ti	CIS, formerly USSR
40Ch13	Fe-0.36-0.45C-≤0.80Si-≤0.80Mn-≤0.030P-≤0.025S-12.0-14.0Cr-≤0.30Cu-≤0.60Ni-≤0.20Ti	CIS, formerly USSR, comparable with DIN-Mat. No. 1.4031

Steel	Materials Compositions, Percent in Weight	Note
45 G2	Fe-0.41-0.49C-0.17-0.37Si-1.4-1.8Mn-0.035P- ≤0.035S-≤0.30Cr-≤0.30Cu-≤0.15Mo-≤0.30Ni- ≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR, comparable with DIN-Mat. No. 1.0912
50Ch	Fe-0.46-0.54C-0.17-0.37Si-0.50-0.80Mn-≤0.035P- ≤0.035S-0.80-1.10Cr-≤0.30Ni-≤0.30Cu-≤0.15Mo- ≤0.03Ti-≤0.05V-≤0.20W	CIS, formerly USSR
70G	Fe-0.67-0.75C-0.17-0.37Si-0.90-1.20Mn-≤0.035P- ≤0.035S-≤0.25Cr-≤0.25Ni- ≤0.20Cu	CIS, formerly USSR
80S	Fe-0.74-0.82C-0.60-1.10Si-0.50-0.90Mn-≤0.040P- ≤0.045S-≤0.30Cr-≤0.30Ni-≤0.30Cu-0.015-0.040Ti	CIS, formerly USSR
2320	Fe-≤0.08-1.0Si-1.0Mn-≤0.040P-≤0.030S-16.0-18.0Cr- ≤1.0Ni	Sweden, comparable with DIN-Mat. No. 1.4016; SAE 430, 10Ch17T
ASTM A-159	Fe-3.1-3.4C-1.9-2.3Si-0.6-0.9Mn-0.15S-0.15P	USA
ASTM A-516 Gr. 70	Fe-0.27C-0.13-0.45Si-0.79-1.30Mn-≤0.035P-≤0.040S	USA, comparable with DIN-Mat. No. 1.0050 and No. 1.0481
ASTM XM-27	Fe-≤0.01C-≤0.40Si-≤0.40Mn-≤0.020P-≤0.020S- 25.0-27.5Cr-≤0.20Cu-≤0.75-1.50Mo-≤0.015N- ≤0.050-0.2Nb-0.50Ni, Ni+Cu≤0.50	USA, comparable with SAE XM-27
C 1204	Fe-0.20C-0.35Si-0.50Mn-0.050P-0.050S-0.30Cr	Yugoslavia, comparable with DIN-Mat. No. 1.0425, B.S. 1501 Gr. 161-400, 164- 350, 164-400; 16 K
C 90	Fe-0.85-0.94C-≤0.35Si-≤0.35Mn-≤0.03P-≤0.03S	Italy
Carpenter 20 Cb-3	Fe-≤0.06C-≤1.00Si-≤2.00Mn-19.0-21.0Cr-2.0-3.0Mo- 32.5-35Ni-3.0-4.0Cu-≤0.035P-≤0.035S	USA
Ch12M	Fe-1.45-1.65C-0.15-0.35Si-0.15-0.4Mn-11-12.5Cr- 0.4-0.6Mo-≤0.35Ni-15-0.3V-≤0.2W-≤0.3Cu-≤0.03Ti	CIS, formerly USSR
Ch14N40SB	Fe-0.034C-4.0Si-0.05Mn-14.4Cr-38.9Ni-0.63Nb	CIS, formerly USSR
Ch15T	Fe-≤0.1C-≤0.8Si-≤0.8Mn-14-16Cr-≤0.3Mo-≤0.6Ni, 5x%C≤Ti≤0.8	CIS, formerly USSR/Bulg.
Ch16N15M3	n. a.	–
Ch17	Fe-≤0.08C-≤1Si-≤1Mn-≤0.040P-≤0.015S-16.0-18.0Cr	Bulg., comparable with DIN-Mat. No. 1.4016, SAE 430, 12Ch17T, X6Cr17
Ch17M2TL	n. a.	–
Ch17N2	Fe-17Cr-2Ni	CIS, formerly USSR
Ch17N5M3	n. a.	–
Ch17N12M3T	Fe-≤0.12C-≤1.5Si-≤2.0Mn-16-19Cr-3-4Mo-11-13Ni- 0.3-0.6Ti	CIS, formerly USSR/Bulg.
Ch17N13M2T	n. a.	cf. 1.4571; SAE 316 Ti; CrNiMoTi 17 13 2
Ch17N13M3T	n. a.	cf. 1.4571; UNS S31635; CrNiMoTi 17 13 3

Steel	Materials Compositions, Percent in Weight	Note
Ch17N18M2T	Fe-0.09C-0.6Si-1.4Mn-16.9Cr-1.9Mo-12.3Ni, Ti stab. (p.a.)	CIS, formerly USSR/Bulg.
Ch17T	Fe-≤0.05C-≤1Si-≤1Mn-≤0.040P-≤0.015S- 16.0-18.0Cr, Ti4x(C+N)+0.15-0.80	Bulg., comparable with DIN- Mat. No. 1.4510, 08Ch17T, X3CrTi17
Ch18AG14	Fe-18Cr-14Mg-0.5N	
Ch18N9T Ch18N10T	Fe-≤0.08C-≤1Si-≤2Mn-≤0.045P-≤0.015S- 17.0-19.0Cr-9.0-12.0Ni, Ti 5xC-0.70	CIS, formerly USSR/Bulg., comparable with DIN-Mat. No. 1.4541, X6CrNiTi18-10
Ch18N10	Fe-0.08C-18.4Cr-10.2Ni-1.08Mn-0.3Si-0.005P- 0.014S-0.005N	
Ch18N12M2T	Fe-≤0.15C-≤5 1.5Si-≤2Mn-17-19Cr-2-2.5Mo-11-13Ni, 4x%C≤Ti≤0.8	CIS, formerly USSR/Bulg.
Ch18N12T	Fe-0.08C-1.0Si-≤2.0Mn-≤0.045P-0.015S-17.0-19.0Cr- 9.0-12.0Ni-Ti = 5x%C≥0.70	CIS, formerly USSR/Bulg.
Ch18N14	Fe-0.035C-18.8Cr-14.6Ni-0.35Mn-0.75Si-0.005P- 0.03S-0.004N	
Ch18N40T	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S- 17-19Cr-9-12Ni-≤0.7Ti	Comparable with DIN-Mat. No. 1.4541, SAE 321
Ch20N20	Fe-0.004-0.015C-19.4-21.8Cr-19.3-20.8Ni- 0.05-5.40Si-0.002-0.1P	CIS, formerly USSR/Bulg.
Ch21N5	n. a.	—
Ch21N6M2	n. a.	—
Ch21N6M2T	n. a.	—
Ch22N5	Fe-0.07C-21.54Cr-5.73Ni	CIS, formerly USSR
Ch23N18	Fe-≤0.20C-≤1.00Si-≤1.50Mn-22.0-25.0Cr-≤0.30Mo- 17.0-20.0Ni-≤0.035P-≤0.025S	CIS, formerly USSR/Bulg.
Ch23N27M2T	Fe-27Ni-23Cr-2Mo-Ti	CIS, formerly USSR/Bulg.
Ch23N28M3D3T	Fe-28Ni-23Cr-3Mo-3Cu-Ti	CIS, formerly USSR
Ch25T	Fe-≤0.15C-≤1.00Si-≤0.80Mn-24.0-27.0Cr-≤0.30Mo- ≤0.60Ni-≤0.035P-≤0.025S-5x%C≤Ti≤0.9	CIS, formerly USSR/Bulg.
Ch28N18	Fe-0.16C-1.7Mn-1.1Si-22.6Cr-18Ni-0.4Ti (p.a.)	CIS, formerly USSR/Bulg.
ChN28MDT	Fe-0.03-0.046C-22.2-23.5Cr-26.55-27.88Ni- 2.55-3.06Mo-2.68-3.38Cu-0.54-0.76Ti-0.15-0.30Mn- 0.39-0.69Si-0.021-0.43P-0.008-0.017S	CIS, formerly USS
ChN40B	Fe-0.032C-18.2Cr-40.4Ni-0.08Si-0.05Mn-0.49Nb	CIS, formerly USSR
ChN40S	Fe-0.031C-20.0Cr-38.9Ni-4.2Si-0.05Mn-0.13Nb	CIS, formerly USSR
ChN40SB	Fe-0.04C-18.8Cr-39.4Ni-4.3Si-0.06Mn-0.63Nb	CIS, formerly USSR
ChN58W	Ni-0.03C-14.5-16.5Cr-15-17Mo-3.0-4.5W-1.5Fe- 1.0Mn-≤0.12Si-0.02S-0.025P	CIS, formerly USSR
ChN60V	Fe-0.01-0.02C-0.09N-max.0.05Zr-0.1Ti-0.015Ce- max.1.7Nb-max0.009B	CIS, formerly USSR
ChN77TJuR	Fe-≤0.07C-≤0.60Si-≤0.40Mn-≤0.015P-≤0.007S- 0.6-1.0Al-≤0.01B-≤0.02Ce-19.0-22.0Cr-≤1.0Fe- ≤0.001Pb-2.4-2.8Ti	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
ChN78T	Fe-≤0.25C-≤1.0Si-≤1.5Mn-≤0.04P-≤0.015S-≤14.0Cr	Russia
FC 20	Fe-3.92C-1.12Si-0.63Mn-0.072P-0.012S	Japan
JS 700	Fe-0.04C-≤1.0Si-≤2.0Mn-≤0.040P-≤0.030S-19-23Cr-4.3-5.0Mo-24-26Ni, Nb≥8xC≤0.40	USA
OZL-17u	Fe-0.04C-0.32Si-1.5Mn-23.2Cr-0.2Mo-29.4Ni-0.01P-0.01S-0.1Ti	CIS, formerly USSR
SAE 1008	Fe-0.10C-0.30-0.50Mn-≤0.030P-≤0.050S	USA, comparable with DIN-Mat. No. 1.0204
SAE 1018	Fe-0.15-0.20C-0.60-0.90Mn-≤0.030P-≤0.050S	USA
SAE C-1018	Fe-0.20C-0.25Si-0.58Mn-0.16Cr-0.04Mo-0.012-0.014P-0.02S	USA
S35C	Fe-0.32-0.38C-0.15-0.35Si-0.60-0.90Mn-≤0.030P-≤0.035S-≤0.20Cr-≤0.30Cu-≤0.20Ni	Japan, comparable with DIN-Mat. No. 1.0501
SIS 2333	Fe-≤0.05C-1.0Si-2.0Mn-≤0.045P-≤0.030S-17.0-19.0Cr-8.0-11.0Ni	Sweden, comparable with DIN-Mat. No. 1.4303; SAE 304, 03Ch18N11
SKH 2	Fe-0.73-0.83C-0.45Si-0.40Mn-≤0.030P-≤0.030S-3.8-4.5Cr-≤0.25Cu-17.0-19.0W-1.0-1.2V	Japan, comparable with DIN 1.3355
SKH-4A	Fe-0.80C-0.29Si-0.31Mn-4.16Cr-17.64W-9.3Co-1.1V	Japan
SKH-9	Fe-0.85C-0.16Si-0.31Mn-4.14Cr-4.97Mo-6.03W-1.88V	Japan
SS41	Fe-≤0.050P-≤0.050S	Japan, comparable with DIN-Mat. No. 1.0040
St35b-2	Fe-≤0.16C-0.17-0.40Si-0.35-0.65Mn-≤0.30Cr-≤0.30Ni-≤0.30Cu-0.050P-0.050S	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0309
St35hb	Fe-≤0.18C-≤0.17Si-0.35-0.65Mn-0.050P-0.050S	Germany, formerly GDR
St38	Fe-≤0.20C-≤0.080-≤0.060S	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0037
St38b-2	Fe-0.12-0.20C-0.17-0.37Si-0.40-0.65Mn-≤0.045P-≤0.050S-Cr+Cu+Ni≤0.70	Germany, formerly GDR, comparable with DIN-Mat. No. 1.0038, BS 4360-40C and A 570 Gr. 36
St5	Fe-≤0.045P-≤0.045S-≤0.009N	Poland, comparable with DIN-Mat. No. 1.0050
SUS 304	Fe-≤0.08C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.030S-18.0-20.0Cr-8-10.5Ni	Japan, comparable with DIN-Mat. No. 1.4301
SUS 430	Fe-≤0.12C-≤0.75Si-≤1.00Mn-16.0-18.0Cr-≤0.60Ni-≤0.040P-≤0.030S	Japan, comparable with DIN-Mat. No. 1.4016, SAE 430, 430 S 15, 12Ch17
Sv-08	Fe-≤0.10C-≤0.03Si-0.35-0.60Mn-≤0.040P-≤0.040S-≤0.015Cr-≤0.30Ni-≤0.01Al	CIS, formerly USSR
TsL-17	Fe-0.1C-5Cr-1Mo	CIS, formerly USSR
TsL-9	Fe-0.07C-1.00Si-2.3Mn-24.1Cr-12.9Ni-1.1Nb-0.03P-0.02S	CIS, formerly USSR

Steel	Materials Compositions, Percent in Weight	Note
U7A	Fe-0.65-0.75C-0.10-0.30Si-0.10-0.40Mn-≤0.030P-≤0.030S	CIS, formerly USSR, comparable with DIN-Mat. No. 1.1520
U8A	Fe-0.75-0.85C-0.10-0.30Si-0.10-0.40Mn-≤0.030P-≤0.030S	CIS, formerly USSR, comparable with DIN-Mat. No. 1.1525
U10A	Fe-0.96-1.03C-0.17-0.33Si-0.17-0.28Mn-≤0.025P-≤0.018S-≤0.20Cr-≤0.20Ni-≤0.20Cu	CIS, formerly USSR, comparable with DIN-Mat.No. 1.1545, SAE W 110
X5CrNiMoCuTi18-18	Fe-≤0.07C-≤0.80Si-≤2.0Mn-≤0.045P-≤0.030S-16.5-18.5Cr-2.0-2.5Mo-19.0-21.0Ni-1.8-2.2Cu-Ti≥7x%C	Germany, formerly GDR, comparable with DIN-Mat. No. 1.4506
X8CrNiTi18-10	Fe-≤0.10C-≤1.0Si-≤2.0Mn-≤0.045P-≤0.015S-17.0-19.0Cr-9.0-12.0Ni-Ti≥5 x C≤0.80	Germany, formerly GDR, comparable with DIN-Mat. No. 1.4541

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