

Influence of Steel Composition on Strain Induced Corrosion Cracking and Other Types of Corrosion

Strain Induced Corrosion Cracking (SICC), Corrosion under Heat Flux Conditions, Erosion Corrosion and Nitrate Stress Corrosion Cracking.

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Abstract

Purpose - To make clear that carbon steels can differ very much in corrosion resistance under practical conditions because of minor differences in the chemical composition of the steels.

Design/methodology/approach - In the electricity generating industry, 'mild' (i.e. 'plain carbon') and low-alloyed steels are used in huge quantities, for example in the construction of boilers, steam generators, heat recovery boilers and waste incineration boilers. The resistance to SICC was determined by measuring the "repassivation" behaviour of the steels at freshly ground surfaces with an electrochemical technique. The corrosion current measured with time was used to calculate the cracking rates of a CT specimen.

Findings - A correlation was found between chemical composition, corrosion resistance to SICC and experiences under practical conditions. The results of early published papers on boiler corrosion (testing in FeCl_2 solutions), erosion corrosion (testing in wet steam at 20 bar), Nitrate Stress Corrosion Cracking (testing in NH_4NO_3 solutions) and Strain Induced Corrosion Cracking (SICC), together with those originating from in-service failures, were compiled into a reference database. This paper is a compilation and review of that work.

Originality/value - The database and formulae presented make clear there is often a direct correlation between chemical composition of ordinary "C-steel" and these specific types of corrosion failures. The paper is of importance to designers, failure analysts and researchers.

Keywords Corrosion, Erosion corrosion, Stress corrosion, Steel

Paper type Research paper

1. Introduction

Corrosion failures in mild and low-alloyed steel can have great human and financial consequences. Typical examples include long periods of down-time of electricity boilers because of corrosion of the evaporator tubes and erosion corrosion in wet steam lines.

Occasionally hot steam leakages and explosion of boilers (as a result of Strain Induced Corrosion Cracking) result even in human casualties (fatalities).

To prevent such failures, much attention is given to control both the chemical and the physical operating conditions. In the past, however, the corrosion resistance of carbon steel often was not even considered worth of discussion. Designers frequently do not realise that within the group of these steel types, corrosion resistance can vary considerably.

In water-steam systems operating at high temperatures and pressures, Strain Induced Corrosion Cracking (SICC) is a very common corrosion phenomenon. Pressure vessels, such as deaerators and wet steam lines, have been susceptible to SICC (Pastoors 1986, 1989 and 1990). Extensive research on stress relieving of welds and the influence of water chemistry was undertaken but the influence of steel composition usually was neglected. Only one published paper, (by Lenz, 1986), considered to any extent the influence of steel composition as a variable that could affect corrosion and cracking behaviour.

In the period 1992-1997, the influence of steel composition on SICC was investigated as well at KEMA laboratories in the Netherlands. The findings are presented in this paper and comparisons have been made with other types of corrosion (corrosion under heat flux conditions, erosion corrosion and nitrate stress corrosion cracking). On these last-mentioned corrosion types, much research was done in the period 1968-1992 by KEMA and this work also is reported here. The behaviours of steels used in all these projects and of steel samples collected from the electricity generating companies have been collated in a database.

2. Database of 'mild' steels

Since 1968, much research was done on the corrosion resistance of C-steels and low-alloyed steels (15Mo3 and 1% Mn steels), in relation to several applications in the electricity utilities. Steel samples used in the various projects originated from in-service failures as well as from new materials. A typical phenomenon was that sometimes several heats of mild steel (with different chemical compositions) have been used to fabricate a particular component but only one steel heat showed the corrosion damage. All the available data of these steels (348 samples) were used to build a database. In Figure 1, the failed and non-failed steels in the database are summarized.

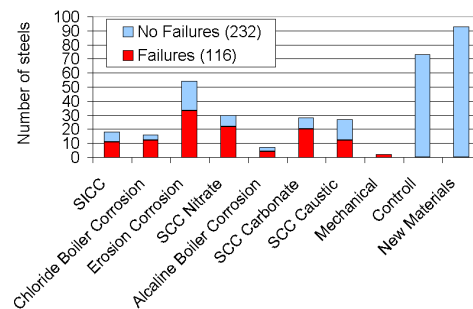


Figure 1 - Histogram of the origin of mild and low-alloyed steels investigated in the research projects since 1968

The influence of the chemical composition on various corrosion phenomena (chloride ion corrosion in boiler feedwater, erosion-corrosion in wet steam lines and nitrate SCC) will not be discussed in detail here because most of the research has been published elsewhere.

The database steels were categorised as follows:

1. SICC (Strain Induced Corrosion Cracking): Deaerators in electricity power units showed Stress Corrosion Cracking rather often. Unfortunately, compositional data were available only for a limited number of steels; (Pastoors, Huijbregts 1992).
2. Chloride boiler corrosion: Under heat flux conditions and chloride contamination of the boiler water, ferrous chlorides can form under the scales on the steel tubes and cause severe corrosion (Huijbregts 1972, 1975, 1977, 1981).
3. On load corrosion: High heat flux conditions combined with (too) high pH values often will result in alkaline boiler corrosion, (Huijbregts 1983).

4. Erosion corrosion: Erosion corrosion occurs often in wet steam lines, (Huijbregts 1977, 1981, 1982, 1985, 1997).
5. SCC in carbonate environments: In district heating systems, the presence of carbonate in the oxide scale combined with a high pH value of the water system result in carbonate stress corrosion cracking, (Huijbregts 2002).
6. SCC in nitrate environments: In condensing waste gases with high concentrations of NO₂, nitric acid and nitrates are formed resulting in intergranular SCC, (Leferink 2002).
7. Mechanical failure: There was only one case of mechanical failure in the database
8. Check of condition of tube materials: In cases of failures or when checking the condition of the components in the boiler, many tubes were sampled and examined on the laboratory for the presence of deposits and corrosion indications. These steels also were available for the laboratory research experiments.
9. New materials: During the laboratory studies, several new unused tube samples without an operational history also were tested.

3. Strain Induced Corrosion Cracking (SICC)

Two different models can be used to explain SICC in C-steels and low-alloyed steels, these being the “anodic dissolution model” and the “hydrogen embrittlement model”. The first model describes the start of the corrosion process and the second explains the continuation of the corrosion cracking process as a result of the evolution and diffusion of hydrogen. The basis of the process is in fact the corrosion occurring at local sites (pits, small cracks, welds). However, if the local environment and the steel quality allow a degree of “repassivation” of the material, the corrosion and the production of hydrogen will cease.

For the anodic dissolution model, Ford, (1995), and Parkins, (1973), gave the following formula:

$$V_t = \{M/(\rho z F)\} \times \{(i_0 t_0^n)/(1-n)\} \times \{(1/\epsilon) \times (d\epsilon/dt)\}^n \quad (1)$$

where:

V:	cracking velocity (cm/s)
M:	Molecular weight of iron (56 g/mol)
z:	electron valence of Fe ²⁺
ρ:	density of steel (7.8 g/cm ³)
i ₀ :	corrosion density of an active surface (A/cm ²)
t ₀ :	time where corrosion current density is measured before passivation
n:	slope of corrosion current density-time curve (passivation factor)
ε:	fracture strain of oxide (%)
dε/dt:	straining rate at crack tip (1/s)
F:	Faraday number (96500 Coulomb)

The corrosion current density and the value of the repassivation factor, n, are parameters that depend on the chemical composition of the steel.

The corrosion current density and the repassivation factor can be determined by means of electrochemical experiments. The dissipating corrosion current density on an active steel surface (fresh grind) is measured as a function of time. Based on the measurement data, the corrosion current density is then extrapolated for a time of 1 sec after immersion in the corroding liquid.

This can be expressed in the following formulae:

$$i = i_0 \times (t/t_0)^{-n} \quad (2)$$

$$\log(i) = \log(i_0) - n \log(t/t_0) \quad (3)$$

where

i:	corrosion current density on time t
i ₀ :	corrosion density of an active surface (A/cm ²)
t ₀ :	time where corrosion current density is measured before passivation occurs (t=1 sec)
n:	slope of corrosion current density-time curve (passivation factor)

The fracture strain ϵ of the oxide (which, on carbon steel, is magnetite), is generally assumed to be 0.1 %. In many cases, special specimens are used for the measurement of cracking velocities. A commonly-used specimen is the Compact Tension Specimen (see Figure 2).

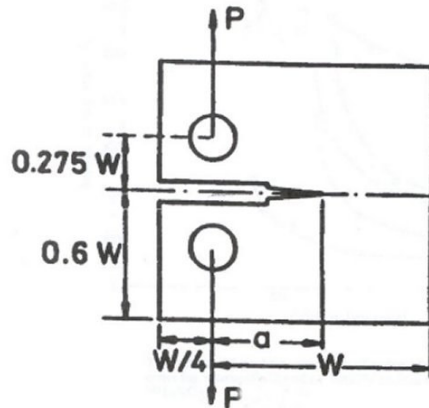


Figure 2 - A Compact Tension Specimen

The Stress Intensity Factor, K , is given in formula for this CT specimen as follows:

$$K = \{2P(2+x)(0.433+2.32x-6.66x^2+7.36x^3-2.8x^4)\} / \{B[(wy^{3/2})^{1/2}]\} \quad (4)$$

where:

- K: Stress Intensity factor
- P: Load (Newton)
- B: Thickness of specimen (10 mm)
- a: Crack length (mm)
- w: Breadth of specimen (40 mm)
- $x = a/w$
- $y = 1-x$

For a CT specimen the straining rate $d\epsilon/dt$ (Formula 1) at the crack tip is defined as:

$$d\epsilon/dt = 3.2878 \cdot 10^{-19} K^4 \quad (5)$$

All the factors in Equation 1, (the cracking velocity V_i), now can be determined and the cracking velocity for a CT specimen can be calculated from the data, i_0 and n , obtained from the electrochemical measurements.

3.1 Experimental

In a study conducted between 1995 and 1997 that was analogous to the work by Ford (1995) and Parkins (1973), the repassivation behaviour of mild steels was studied. It was expected that the environment at pitting locations on the steel would contain sulphate, originating from sulphide inclusions in the steel. So a sulphate environment was chosen in which an active steel could passivate at a moderate rate. After testing various combinations of concentrations and pH values, the most useful solution was found to be 0.1 Molar sodium sulphate with 0.5 mmol sodium hydroxide.

The test method was a simple electrochemical LPR measurement. The steel probe was ground and then without delay placed into the sulphate solution. After a short period (about 20 seconds), during which the free corrosion potential was measured, the polarisation resistance was measured with a scanning rate of 0.3 mV/s in between the range - 10 and + 10 mV, see Figure 3. After a short rest period, the LPR measurements were restarted. The total measuring time for each specimen was about 15 minutes. The increase in passivation (decrease in

corrosion rate) was plotted, see Figure 4. The slope of the line gives the repassivation rate n and the current value at $t=1$ sec is the $\log(i_0)$ value.

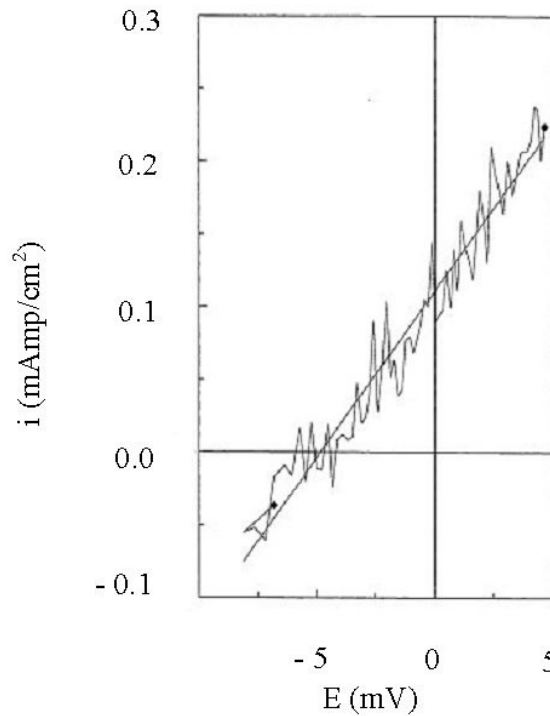


Figure 3 - The EPR plot in the active state of a C-steel, after grinding of the specimen

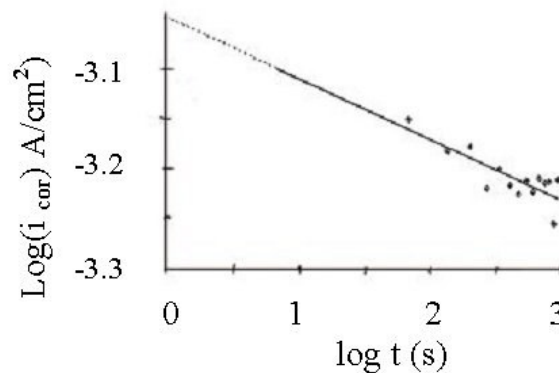


Figure 4 - The results of the EPR measurements, plotted in a log(time)-log(corrosion current) graph.

These electrochemical measurements were done on 8 different steels, given in Table 1.

The $\log(i_0)$ and $\log(n)$ values were correlated to the chemical composition of the 8 steels and the following regression formula were obtained:

$$\text{Log } i_0 = 2.7 \cdot \text{Cr} + 25 \cdot \text{C} + 2.2 \cdot \text{Cu} - 6.5 \cdot \text{Mo} - 1.5 \cdot \text{Si} - 44 \cdot \text{S} - 4.4$$

$$\text{Log } n = 0.3 \cdot \text{Cr} + 3.3 \cdot \text{C} + 0.3 \cdot \text{Cu} - 0.5 \cdot \text{Mo} + 0.5 \cdot \text{Si} - 13 \cdot \text{S} - 0.5$$

The significance values R^2 of both regression correlations were 0.99 and 0.63 respectively.

Knowing the chemical composition of the steel the crack growth can be calculated for a CT Specimen at a given Load P and crack length according to Formulas 1 up to 5. Table 1 gives the chemical compositions of the tested steels.

Table 1 - Chemical compositions of the steels tested in the electrochemical repassivation measurements

No	Steel	Cr	Cu	Mo	C	Si	S
A	St 35.8	0.08	0.323	0.033	0.118	0.21	0.028
B	13CrMo4.4	1	0.1	0.42	0.13	0.3	0.03
C	15Mo3	0.02	0.04	0.28	0.16	0.009	0.015
D	St 35.8	0.08	0.14	0.26	0.17	0.22	0.02
E	St 35.8	0.01	0.02	0.001	0.18	0.32	0.024
F	14Mn4	0.1	0.1	0.03	0.1	0.4	0.02
G	15Mo3	0.11	0.07	0.29	0.14	0.23	0.01
H	10CrMo9.1 0	2.3	0.1	1	0.09	0.2	0.01

Calculation of Cracking Rates for CT Specimen

For one condition (P=1000 N) the cracking rates of the 8 steels in Table 1 have been calculated. Figure 5 shows the cracking rates for increasing crack lengths.

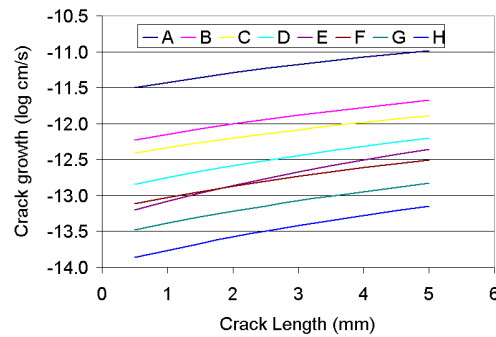


Figure 5 - Calculated crack growth of a CT specimen based on the electrochemical measurements in a sodium sulphate hydroxide environment for the 8 tested steels.

These calculations were also done for all steels in the database. Figure 6 is a histogram of these cracking rates for a crack length of 4 mm and P = 1000 N. Unfortunately, only 11 steels from SICC cracking failures in a deaerator were analysed and are presented in the database. When the histogram is plotted of the carbon and molybdenum content it appears that the cracked specimens had a relatively high C (>0.12%) and a low Mo (<0.3%) content, see Figures 7 and 8.

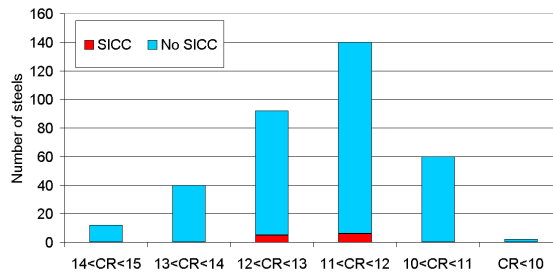


Figure 6 - Histogram of the calculated cracking rates of the steels of the database. (CR = -logV; V in cm/s)

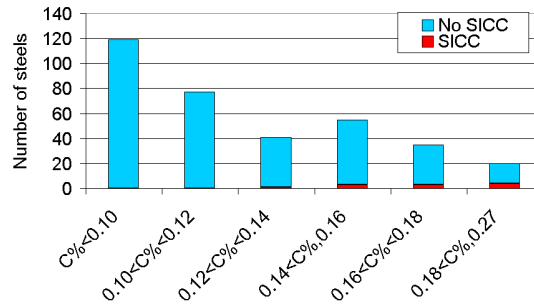


Figure 7 - Frequency diagram of the steels in the database on the C-content. Steels originating from SICC case failures had a carbon content more than 0.12 %.

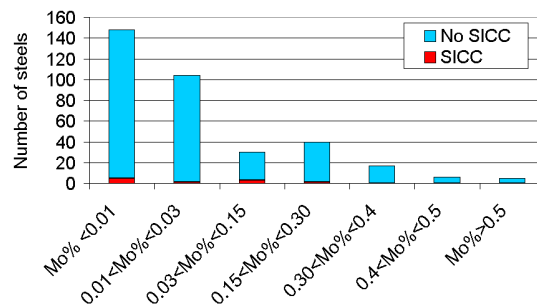


Figure 8 - Frequency diagram of the steels in the database on the Mo-content. Steels originating from SICC case failures have Mo contents of less than 0.3%.

From four failures the weld metal and the plate material could be analysed from the stored specimens, see Table 2.

Table 2 - Specimens from failures

Degasser	Case	Cracking rate (log CR)	Mo	C
A	Man hole ring , welding metal	-13.4	0.02	0.09
	Man hole ring, plate cracking	-11.4	0.005	0.16
B	Front, welding metal	-12.5	0.01	0.11
	Front, welding metal	-13.6	0.02	0.07
	Plate cracking	-11.5	0.01	0.14
	Plate cracking	-11.6	0.04	0.14
C	Hark, welding metal	-13.2	0.16	0.13
	Hark, welding metal	-14.4	0.24	0.1
	Hark, tube cracking	-9.9	0.01	0.22
	Hark , tube cracking	-11.5	0.03	0.15
D	Welding metal	-13.5	0.009	0.08
	Plate cracking	-10.1	0.005	0.19

As can be concluded from data, the calculated cracking rates (log CR) were higher than -11.6. The Mo and C contents of the cracked parts were lower and higher respectively than were the contents in the non-cracked parts. The Mo and C content of the cracked parts were lower than 0.3% Mo and more than 12% C. Unfortunately (from scientific point of view) there were no more failed cases.

4. Corrosion of boiler tubes under heat flux conditions

When boiler tubes are fouled with boiler sludge (mainly iron oxides), the water in the porous deposit layer is stagnant. Locally boiling will occur, often resulting in deposition of silicates, sulphates. Because of the growing solid silicate or sulphate deposit layer the metal temperature will locally rise. In some cases the boiler water may contain chlorides for instance due to leakage of a seawater cooled condenser. The chlorides will concentrate in cracks or pores in the solid deposit layer and result in high concentrating ferrous-chloride solutions

In this ferrous-chloride environment typical corrosion layers are formed. In a low concentrated ferrous chloride solution a homogeneous protective layer of magnetite can still be formed.

However in more concentrated chloride solutions the compressive stresses increase to levels where the oxide layer starts to flake off from the metal at regular intervals. This will result in the formation of thick non-protective magnetite layers, (Huijbregts 1972, 1981).

A corrosion test was developed to determine the corrosion resistance of boiler steels to ferrous chloride solutions. (Huijbregts 1977)

A total of 62 steel heats were immersed for 4 day in autoclaves filled with ferrous chloride solutions at 310 °C and 10 MP. Test solutions of various ferrous chloride concentrations were chosen ranging from 0.005 up to 0.375 molar ferrous chloride. After the exposure, the morphology of the corrosion scale was studied. Each of the 62 tested carbon steel heats had a critical concentration above which the oxide layer became non-protective (formation of laminated oxide). The same critical chloride concentration was attained in experiments where hydrochloric acid was used to substitute ferrous chloride. See Figures 9 and 10.

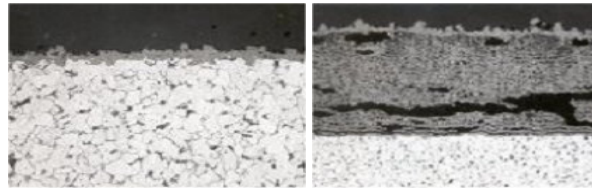


Figure 9 - Examples of a protective magnetite layer, formed in low concentrated ferrous chloride (left) and a non-protective laminated oxide formed in a more concentrated ferrous chloride (right).

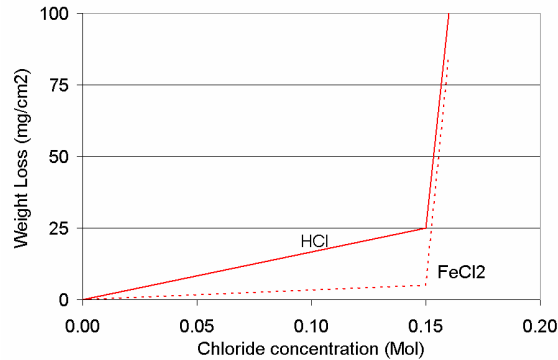


Figure 10 - Typical example of the critical chloride concentration of a steel when exposed to ferrous-chloride or hydrochloric acid concentrations. When chloride concentrations are above the critical point, the weight loss increases sharply, corresponding with a laminated oxide structure.

By correlating the critical ferrous chloride concentration with the steel composition a regression equation was found with which the critical ferrous chloride concentration for steels can be calculated.

$$\text{FeCl}_2 \text{ critical} = 0.1 \text{ Mn} + 2 \text{ P} + 0.2 \text{ Cr} + 0.04 \text{ Mo} - 0.05$$

This critical concentration was taken as a threshold value for corrosion resistance of the steel. The steel samples originated from waterwall tubes of several boilers in electrical power stations in the Netherlands. The tubes were taken from the evaporators because of corrosion failures or inspected for fouling of the boiler. From experience with corrosion in boilers it became clear that in case of severe corrosion in boilers the critical ferrous chloride value of the steel was always less than 35 mmolar.

In Figure 11a histogram is given for all the mild steels in the database. The Gauss curve of the resistance in the mild steels show a maximum at a resistance of 40 to 50 mmol ferrous-chloride. The steels of the failed boiler tubes have obviously lower resistances. So it is sensible to avoid the use of mild steels with a low resistance to ferrous chloride in evaporators of boilers or other technical components where presence of ferrous chlorides can not be excluded.

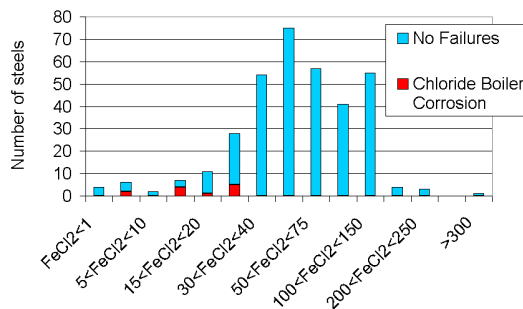


Figure 11 - Histogram of resistances of the steels in the KEMA database for ferrous chloride corrosion. All steel that contributed to a failure had a critical ferrous chloride value of less than 35 mmol.

5. Erosion-corrosion in wet steam

Erosion-corrosion failures are a result of a combination of water conditioning, design parameters and material. It was shown that selecting steels with some of the alloying elements Cu, Cr, Mo and C control the erosion-corrosion in ordinary water-steam systems. Several papers on the erosion-corrosion research about this topic have been published (Huijbregts 1981, 1982, 1984 and 1997).

The erosion-corrosion resistances of 70 heats of carbon steels and low-alloyed steels were determined in a jet stream of a water-steam (water content: 10 w% inlet and 25 w% outlet) mixture at a steam velocity of 960 m/s and an oxygen content of less than 2 ppb. Water conductivity was smaller than 30uS/m and metal temperature was 127 °C.

After an exposure time of 100 hours the weight losses of the specimens were determined. These weight losses were correlated with the steel composition, which resulted in the regression formula, mentioned below. The G_{KEMA} value is the expected calculated weight loss of steel in the erosion-corrosion test.

$$G_{KEMA} = 90 - 160 \cdot Cu - 115 \cdot Cr - 40 \cdot Mo + 35 \cdot C$$

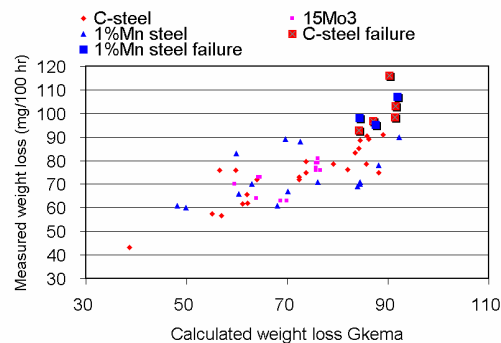


Figure 12 - Results of the erosion-corrosion experiments in the KEMA experimental boiler. A correlation was found between the measured weight loss against calculated weight loss using the G_{KEMA} value.

The calculated G_{KEMA} values were in the range of 40 up to 100 mg. The failures occurred in the steam-water circuit of power stations under various conditions. Hydraulic conditions and chemical water treatment can differ very much for these components. However, our experience is that in all observed erosion-corrosion failures in water-steam systems under usual applied wet steam conditions up to now the corroded steels had a G_{KEMA} value of more than 80. From the G_{KEMA} it is clear that chromium has a very beneficial effect with regard to the resistance to erosion-corrosion. With this value in mind, a minimum Cr-equivalent has been specified to obtain a sufficiently high erosion-corrosion resistance.

To obtain erosion-corrosion resistant steel (under not too excessive erosion-corrosion conditions) the Cr-equivalent should be more than 0.09.

$$Cr\text{-equivalent} = Cr + 1.4 Cu + 0.3 Mo - 0.3 C > 0.09$$

Figures 13, 14 and 15 show typical examples of erosion-corrosion failures, in components where steels with high and low Cr-equivalents were applied. The steels A, D and E with low Cr-equivalent values were attacked.

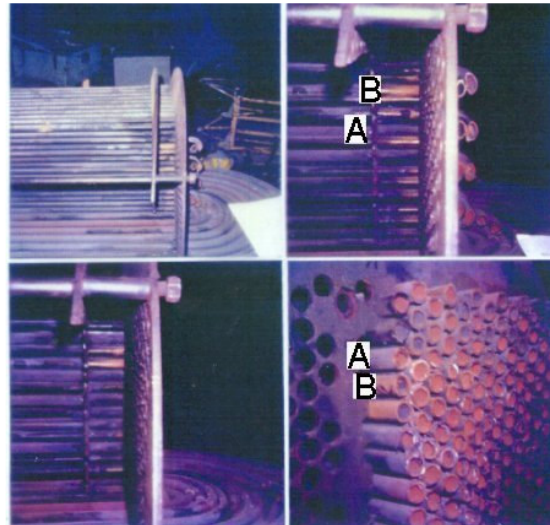


Figure 13 - Erosion-corrosion in high pressure preheater with 2 different heats of carbon steel, attacked (B) and non-attacked (A). The steel compositions appear in Table 4.

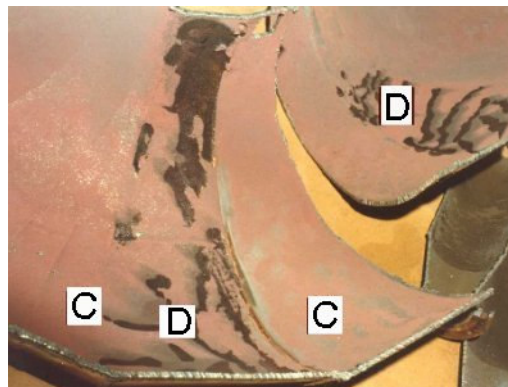


Figure 14 Erosion-corrosion in a wet steam line of a BWR water separator. The eroded corroded plate D was different from the non-attacked plates C

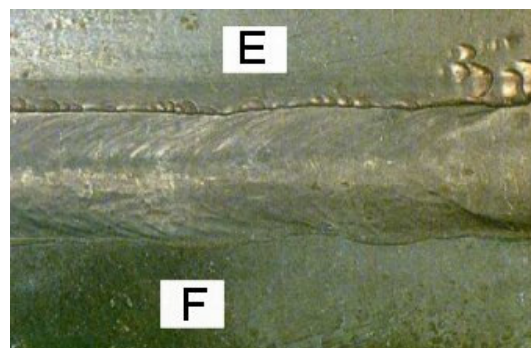


Figure 15 - Two welded plates in a water separator: one eroded-corroded (E) and one non-attacked (F). Again different heats were applied

Table 4 - Composition of the steels in the Figures 13, 14 and 15.

Steel	Cr	Cu	Mo	C	Erosion-corrosion	Cr- equivalent
A	0.07	0.04	0.02	0.12	No	0.10
B	0.03	0.03	0.01	0.12	Yes	0.04
C	0.04	0.11	0.01	0.14	No	0.16
D	0.01	0.02	0.003	0.17	Yes	-0.01
E	0.01	0.006	0.005		Yes	0.02
F	0.01	0.21	0.02		No	0.31

More examples of erosion corrosion failures have been mentioned in earlier publications (Huijbregts 1984, 1997).

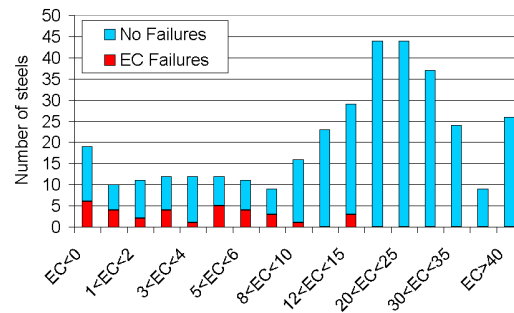


Figure 16 - Histogram of the erosion corrosion resistance of C-steel and low-alloyed steels. (EC = 100*Cr-equivalent)

In Figure 16, the histogram relating to erosion corrosion is given for all steels in the database. The Gauss curve of the resistances show a maximum at an EC (100*Cr-equivalent) of 20. Steels from the failures obviously had lower resistances (in general, they were lower than EC = 9). Failures of steels with EC values of 10 and 15 were obtained from failures where exceptionally severe flow conditions had occurred. Two failures occurred after butt welds of heights 1.6 and 1.8 mm, and one failure on a baffle plate had occurred in a steam expansion vessel.

Thus, it is sensible to avoid the use of steels with low Cr-equivalents in components with high erosion-corrosion risks, such as is the case in low-pressure pre-heaters and steaming economisers.

6. Nitrate Intergranular Corrosion (nitrate SCC)

SCC due to nitrates is always associated with intergranular corrosion. Parkins stated that stress corrosion cracking in nitrate environments starts with intergranular corrosion and that the “cracking” should be considered as strain-assisted intergranular corrosion (Parkins 1980). At KEMA laboratories, the resistance of several ferritic steels to intergranular corrosion in ammonium nitrate solutions was tested, (Leferink 2000).

Steel samples were exposed to aerated ammonium nitrate solutions of in a concentration range of 2 to 35 wt% for 100 hours at a temperature of 90°C. After exposure, cross sections of the steels were examined with an optical microscope. When the intergranular attack was more than three grains deep, the steel was considered to be sensitive to intergranular corrosion in the particular environment. A clear correlation was found between the steel composition and the concentration of ammonium nitrate in which the corrosion became three grains deep.

For all tested steels (C-steel, 15Mo3, 13CrMo44, 10CrMo910 and 12% Cr steel) the correlation was:

$$\text{Critical ammonium nitrate \%} = 6\text{Mo} + 2\text{Cr} + 1\text{Mn} + 8 - 12\text{Si} - 8\text{Cu} - 1\text{C}$$

The correlation between measured and calculated critical nitrate percentages is given in Figure 17.

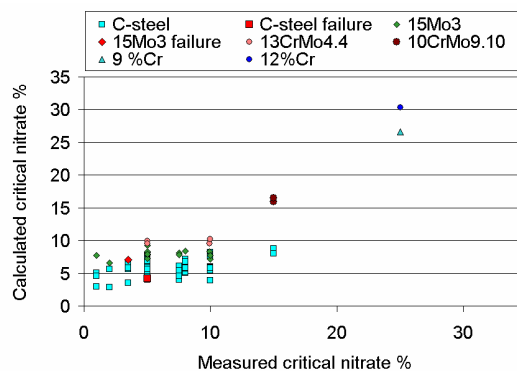


Figure 17- Correlation between measured and calculated critical nitrate concentrations of steels tested in ammonium nitrate solutions of varying nitrate concentrations.

After the results of this study were published, more samples of steels that had failed due to nitrate SCC were obtained from several sources. The steels were analysed for their chemical composition, and critical ammonium nitrate concentrations were calculated. The results of these calculations are presented in Table 5.

Table 5 - Steels from in service failures

Number	Steel	Chemical analysis of the steels						Calculated Critical % nitrate
		Cr	Cu	Mo	C	Mn	Si	
1*	C-steel	0.08	0.21	0.02	0.11	0.61	0.31	3.4
2	15Mo3	0.08	0.14	0.25	0.17	0.67	0.22	6.4
3	15Mo3	0.14	0.18	0.27	0.15	0.61	0.23	6.2
4	C-steel	0.07	0.2	0.02	0.12	0.46	0.22	4.4
5	C-steel	0.06	0.04	0.01	0.11	0.48	0.25	5.2
6*	15Mo3	0.08	0.32	0.33	0.12	0.61	0.15	6.3
7	C-steel	0.07	0.14	0.01	0.08	0.49	0.15	5.7
8	C-steel	0.08	0.52	0.03	0.05	1.17	0.14	3.6
15	C-steel	0.02	0.021	0.002	0.13	0.959	0.324	4.8
16	C-steel	0.03	0.024	0.006	0.111	1.19	0.193	6.7
9	C-steel	0.058	0.42	0.052	0.05	1.09	0.17	4.1
10	C-steel	0.036	0.44	0.03	0.05	1.11	0.17	3.8
11	C-steel	0.036	0.44	0.03	0.05	1.12	0.17	3.8
12	C-steel	0.036	0.48	0.03	0.06	1.16	0.15	3.7
13	C-steel	0.036	0.33	0.03	0.06	1.23	0.19	4.5
14	C-steel	0.036	0.25	0.03	0.07	1.07	0.34	3.2
17	C-steel	0.1	0.11	0.03	0.07	0.49	0.17	5.9

* Steels were tested in ammonium nitrate

It was evident that the steel samples from the failed constructions all had a rather low resistance to intergranular corrosion, according to the ammonium nitrate correlation formula. In addition, the difference in resistance between C-steels and 15Mo3 to intergranular corrosion in nitrate solutions was only minimal.

Critical nitrate % values also were calculated for all steels of the database, see Figure 18.

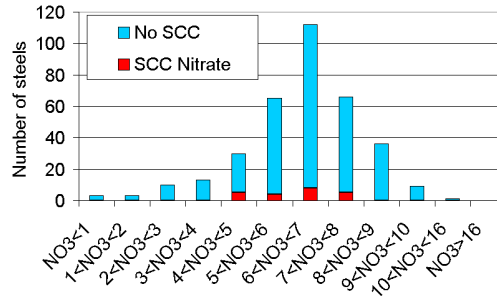


Figure 18 - Histogram of the C-steels and low-alloyed steels from the database for intergranular corrosion in ammonium nitrate environments

Though there was a difference in nitrate resistance of the failed and non-failed steels (Table 5), the failed steels were situated at the top of the Gauss curve for the database steels shown in Figure 18. The steels of the failures had critical nitrate values near to the maximum values of the Gauss curve. Hence, it would be very difficult to select a C-steel that had more resistance to nitrate intergranular corrosion cracking.

One option to combat nitrate intergranular corrosion cracking is to use alloyed steels like 10CrMo9.10. However, it is often found that the nitrate concentration will build up gradually to a critical level. In these conditions, steel with a higher critical ammonium nitrate % will only delay the moment when the conditions become critical.

A better option to combat intergranular nitrate stress corrosion cracking solutions therefore would be to improve the chemical operating conditions and prevent the formation of nitrate deposits. As an alternative, cleaning at regular intervals sometimes can be an option.

7. Conclusions

From the results of the research done on C-steel and low-alloyed steels over a long period of time it is clear that the chemical composition of can be a determining factor in the following types of failures:

1. Strain Induced Corrosion Cracking, as in deaerators
2. Boiler corrosion because of chloride ingress under heat flux conditions
3. Erosion corrosion in wet steam lines
4. Nitrate Intergranular Corrosion

Elements that were found to be beneficial in preventing these types of failures are included in Table 6.

Table 6 - Summary of the Conclusions

Type of failures	Beneficial elements in C-steels	Non beneficial elements	Failure mechanism
Boiler corrosion caused by chloride ingress under heat flux conditions	Mn, P, Cr and Mo		Formation of compressive stresses in the magnetite layer
Erosion corrosion in wet steam lines	Cu, Cr and Mo	C	Porosity of the magnetite layer
Nitrate Intergranular Stress Corrosion Cracking	Mo, Cr and Mn	Si, Cu and C	Intergranular corrosion
Strain Induced Corrosion Cracking (in deaerators)	Mo	C	Repassivation capacity on the crack tip

For a more reliable operation of equipment, designers therefore are advised strongly to specify carbon steel and low-alloyed steels with tighter compositional specifications than previously was usual.

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