Typical Failures of CuNi 90/10 Seawater Tubing Systems and How to Avoid Them

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For many decades, copper-nickel alloy CuNi 90/10 (UNS C70600) has extensively been used as a piping material for seawater systems in shipbuilding, offshore, and desalination industries. Attractive characteristics of this alloy combine excellent resistance to uniform corrosion, remarkable resistance to localised corrosion in chlorinated seawater, and higher erosion resistance than other copper alloys and steel. Furthermore, CuNi 90/10 is resistant to biofouling providing various economic benefits.

In spite of the appropriate properties of the alloy, instances of failure have been experienced in practice. The reasons are mostly attributed to the composition and production of CuNi 90/10 productscompounds, occurrence of erosion-corrosion and corrosion damage in polluted waters. This paper covers important areas which have to be considered to ensure successful application of the alloy for seawater tubing. For this purpose, the optimum and critical operating conditions are evaluated. It includes metallurgical, design and fabrication considerations. For the prevention of erosion-corrosion, the importance of hydrodynamics is demonstrated. In addition, commissioning, shut-down and start-up measures are compiled that are necessary for the establishment and re-establishment of the protective layer.

Keywords: copper-nickel, CuNi 90/10, seawater piping systems, typical failures, application recommendations

Introduction

During last decades, many thousand of tons of the copper-nickel alloy (UNS C70600, CuNi 90/10) have been installed in different marine engineering structures manly as piping for seawater handling and heat exchangers in the shipbuilding, offshore, power, and desalination industries. This alloy that has been adopted by various standards (*Table 1*) reveals sufficient physical and mechanical properties and is easily fabricated.

In clean oxygenated seawater, this alloy has remarkable resistance to uniform and localised corrosion. Due to the release of copper ions and the structure of oxide layers that are established during natural corrosion processes, copper-nickel provides bacteriostatic properties and is resistant to microfouling. In many cases, the resistance to erosion-corrosion of the alloy allows its economical use as a piping material.

However, some instances of failure in copper-nickel systems have been reported. The main focus of attention given to failure cases and research activities have been enhanced corrosion rates in seawater polluted with sulphide and erosion-corrosion in heat exchanger applications. Based on a literature review and experience of KME, this paper describes the relevant corrosion mechanisms and provides useful service recommendations particularly for piping systems.

Effect of Alloying Elements

The influence of iron on the properties of this alloy was extensively studied by many scientists[1, 2, 3, 4]. Bailey[1] revealed the effect of iron additions in a series of copper-nickel alloys on impingement corrosion and corrosion under stagnant conditions in natural seawater. It was found that both iron content and microstructure of the alloy play an important role, whereas the presence of visible iron precipitates deteriorate the performance. Data collected from different literature sources[15] for CuNi 90/10 quenched from its solution temperature, reveals the optimum iron content is between 1.5 and 2%.

North and Pryor[5] attempted to understand the role of iron in improving the properties of the passive film on copper-nickel alloys in terms of erosion-corrosion and impingement attack. Iron and nickel atoms incorporated into the Cu_2O oxide film resulting in a reduction in the number of positive holes there due to higher uptake of higher charged cations. This provides a decrease in number of cavities, and, thus, a reduction in ionic conductivity. Manganese increases mechanical strength and re-crystallisation temperatures.[6] However, the beneficial effect on impingement resistance was found to be less than that of iron.[1]

Table 1: Comparison of chemical composition between various specifications for cupronickel 90/10 used as tubing material

| Standard	DIN/EN	ASTM	ISO	EEMUA	KME
Designation	CuNi10Fe1Mn		CuNi10Fe1Mn		CuNi10Fe1,6Mn
Ref. No.	2.0872/ CW352H	UNS C70600		UNS 7060X	Osna10 ®
Copper	Rem.	Rem.	Rem.	Rem.	Rem.
Nickel	9.0-11.0	9.0-11.0	9.0-11.0	10.0-11.0	10.0-11.0
Iron	1.0-2.0	1.0-1.8	1.0-2.0	1.5-2.00	1.50-1.8
Manganese	0.5-1.0	1.0	0.5-1.0	0.5-1.0	0.6-1.0
Tin	0.03	-	0.03	-	0.03
Carbon	0.05	0.05	0.05	0.05	0.02
Lead	0.02	0.02	0.02	0.01	0.01
Phosphorus	0.02	0.2	0.02	0.02	0.02
Sulphur	0.05	0.02	0.02	0.02	0.005
Zinc	0.05	0.5	0.5	0.2	0.05
Cobalt	0.1	-	0.05	-	0.1
Total other impurities	0.2	-	0.1	0.3	0.02
Single values represent the maximum content.					
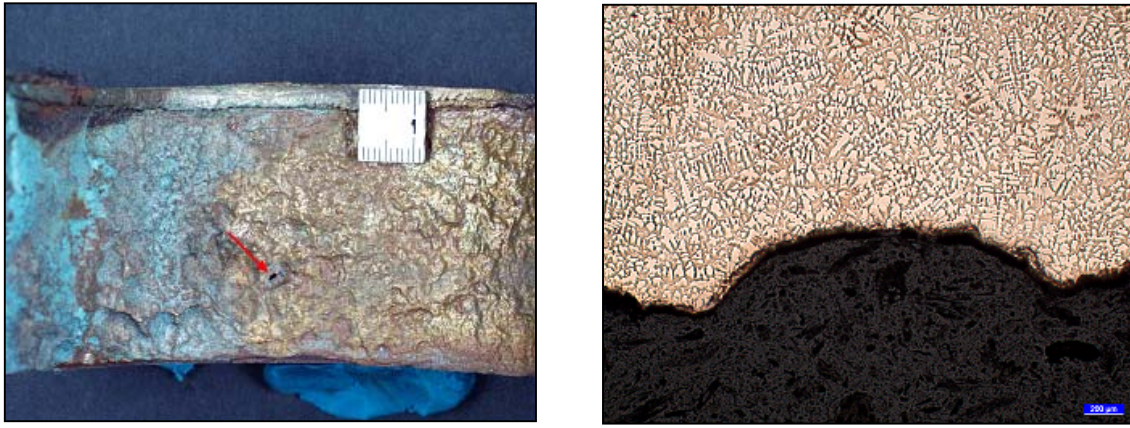
Figure 1: Erosion—corrosion damage of the inner surface of the weld neck. The arrow indicates a perforation (left), cross—section of the weld neck demonstrates a cast structure of the compound (right).

It is emphasised that, in order to ensure reliable service of a copper-nickel system, the components must comply with international standards. *Figure 1* illustrates one of many weld necks installed on an offshore unit operating off the coast of South America. The system was operated at ambient temperature and at a flow rate below 3,5 m/s. The cross-section of the weld neck shows a cast structure that is not allowed by international standards.[7] This is because the copper-nickel melt has strong tendency to segregation that has to be eliminated by hot forging or cold working with a subsequent recrystallisation anneal. The chemical analysis of the weld neck revealed the presence of only 0.952 % Fe, 0.012 % Mn, and 0.087 % S. Finally, to ensure the appropriate quality of CuNi 90/10 compounds, the cooling rate from the solution annealing temperature must keep the precipitation of iron containing particles to a minimum. The quality of the piping can be easily assessed by measurement of magnetic permeability, which should be lower than 1.5.[8]

General Corrosion

The corrosion behaviour of copper-nickel depends on the presence of oxygen and other oxidisers because it is cathodic to the hydrogen electrode. During the primary anodic reaction, a cuprous oxide film is produced that is predominately responsible for the corrosion protection. The products of corrosion reactions can react with compounds in seawater e.g. to $CuCl_2 3Cu \cdot (OH)_2$ or $Cu_2(OH)_3Cl$, and diffuse from the surface into the electrolyte precipitating again on the surface and in so doing build a multi-layered oxide structure.[9]

The corrosion rate quickly decreases significantly over a few days, with one study indicating that the associated discharge of copper ions was reduced tenfold during 10 min and 100-fold in the first hour.[10] However, establishment of a fully mature film takes from 2[9] to 3[10] months at temperatures of 15-17°C. At 27°C, common inlet temperature for the Middle East, the establishment of the protective film within a few hours was reported.[11] The long term general corrosion rates of CuNi 90/10 have been found to continuously decrease with time of exposure to below 2.5 µm/yr.[12] As will be discussed later, it is important to ensure appropriate formation of the protecting film and, thus, to avoid premature failures. The following recommendations commonly work well during hydrotesting and commissioning:

- The system should be cleaned from dirt, lubricants and debris. Introduction of solid matter should be avoided by installation of strainers.
- Use clean seawater or fresh water for hydrostatic testing. If polluted water has been used, it should be disposed of and the pipe work should be rinsed properly with clean seawater or fresh water. If subsequent long stagnant conditions are expected, blow-drying of the system is advisable.

- During commissioning of a new or retubed system, continuous exposure to clean seawater for up to 3 months, depending on water temperature, is needed to establish a mature protective film.
- A system with continuous pumping activity, such as a cooling system, can be operated under normal operating conditions. In seawater and water containing high levels of suspended matter, the min. flow rate should not be below 1 m/s in order to prevent the formation of deposits. In seawater containing sand, the designed flow rate should be decreased by 1-1.5 m/s.[13]
- The commissioning of a system with intermittent flow, such as a fire fighting system, should be conducted in seawater free from suspended matter, e.g. in water from the open sea. However, the seawater has to be replaced by oxygenated seawater within 4-5 days to avoid putrefaction.[14]

Localised Corrosion

In clean natural seawater or in seawater chlorinated to levels sufficient to control the biological metabolism, CuNi 90/10 is resistant to localised attack. Due to its biofouling resistance, there is a limited number of potential sites for pitting attack, even in slowly moving seawater. However, in polluted water containing hydrogen sulphide, pitting usually takes place in the form of wide and shallow pits. The undercut type of pitting attack normally associated with stainless steel is not common for CuNi 90/10.

Only a limited amount of information is available on failures of copper-nickel due to crevice corrosion.[15] The crevice corrosion behaviour of the alloy is generally controlled by an ion concentration cell mechanism where the accumulation of copper ions in the crevice leads to ennoblement. Thus, if encountered, the corrosion attack tends to take place in the region adjacent to the crevice, which is exposed to the bulk water.

Under-deposit corrosion is really crevice corrosion beneath deposits. There is a tendency for deposition of suspended matter at flow rates below 1 m/s. Copper-nickel performs well as a material for fire fighting systems with predominantly quiet conditions. However, if the region under deposits become anaerobic, contributing to the establishment of sulphate reducing bacteria, the situation can become critical.

To improve operating conditions in the seawater system, it is advisable to apply screens and strainers between the water box and pumps to remove travelling debris from intake waters. It is advantageous to apply a pair of strainers so that one can be in operation while the other is being backwashed. When specifying fine filtration, a designer should consider the diameter of the tubes and orifice in heat exchanger equipment. Another possibility is to apply side stream filtration or centrifugal separators, which distinguish themselves by a low pressured drop and are capable of removing sand and other small solids.[16] Various chemical treatments are described elsewhere in the literature.[17]

Since, stagnating conditions should be avoided in seawater containing high levels of suspended particles or biological matter, it is advisable to use the water from the open sea in stand-by systems. In addition, the frequent refreshment of seawater is preferable at least once every 4-5 days. The chlorination of seawater could improve the water quality by control of microbiological activity. During prolonged shutdown periods of the plant, it is recommended to rinse the system with clean seawater and keep it dry.

Microbiologically Influenced Corrosion (MIC)

The bacteriostatic properties and resistance of copper-nickel to macrofouling are well recognised and widely used.[18] This properties are attributed to a continuous release of copper ions that cannot be tolerated by many organisms and decelerates the establishment of the primary bacterial film considerably. Also the biofouling resistance is attributed to the mechanical prop-

erties of the top oxide layer formed during secondary corrosion reactions; the top layers can be fouled but they slough off leaving a clean surface.

Nevertheless, bacteria of certain genus, which are protected by a polysaccharide lining from the copper ions and build up a slime layer, can remain intact even within the layer of secondary corrosion products.[19] In contrast to stainless steels, however, the slime layer on copper-nickel surfaces exposed to natural seawater does not change the free corrosion potential of the alloy.[20, 21]

Since most reported MIC cases of copper-nickel were related to the activity of SRB and presence of hydrogen sulphide mostly originating from biochemical reactions, the following measures are advisable to ensure reliable performance of the material:

- Avoid establishment of deposits.
- Fill the system with clean seawater prior to entering, while within and when leaving the harbour.
- Replace the water in systems with stagnating conditions every 4-5 days with oxygenated clean seawater.
- Avoid prolonged utilisation of the alloy in waters containing hydrogen sulphide when not using any precautionary measures.
- Generally, recommended measures including monitoring procedures and biocide treatment can be applied.[22]

Effect of Polluted Water

As mentioned above, most accelerated corrosion problems and premature failures have been associated with copper-nickel tubing operating in polluted seawater. It was demonstrated[23] that, in seawater containing no sulphide, the free corrosion potential of CuNi 90/10 lies on the noble side of hydrogen evolution. In the presence of sulphide, however, the corrosion potentials are shifted to negative values. Therefore, hydrogen evolution becomes possible as a part of the cathodic reaction. Sulphur can be reduced to sulphide at the cathodic site. The elemental or colloidal sulphur contained in seawater may be reduced to sulphide. HS^- reacts with Cu^+ and produces a non-protective black cuprous sulphide which is poorly adherent and results in enhanced probability of erosion attack.

Eiselstein et al[24] investigated the behaviour of CuNi 90/10 tubing during alternating exposure to de-aerated sulphide polluted, aerated unpolluted, aerated polluted and aerated unpolluted seawater at 3 m/s while monitoring the corrosion rate as a function of exposure history. During the exposure of samples to deaerated sulphide polluted water, the corrosion rate of copper-nickel was comparably lower than that during the exposure to aerated water. Moreover, it was found that the samples pre-exposed to de-aerated sulphide polluted water corroded more rapidly than fresh tube (initial difference more than 1.4 times) after exposure to aerated water. After exposure of the samples to aerated polluted water, significant enhancement of localised corrosion was detected. In addition, it was demonstrated that samples pre-exposed to aerated water corroded much slower even than fresh material in aerated polluted water. This indicated that corrosion films formed in sulphide-free environments offered some protection against accelerated attack although not longer than for three days. Finally, samples pre-exposed to aerated polluted and then exposed to aerated unpolluted water were re-passivated in less than five days. In contrast, Kirk and co-worker[25] reported that protective films formed on copper-nickel during four months exposure to clean seawater provided nearly total corrosion immunity in seawater containing up to 0.5 ppm H_2S.

From general experience, CuNi 90/10 installed on offshore systems or seagoing vessels provides sufficient resistance to sulphide induced corrosion. However, care should be taken if there is a risk of prolonged exposure to sulphide polluted water as is commonly the case in harbours and brackish water. Seawater containing hydrogen sulphide should not be left in a new system.

In a commissioned system, the water should be replaced by clean seawater or fresh water at least after every few days exposure.

Effect of Iron Containing Solutions

It has been recognised that specific levels of sulphide pollution may deteriorate the corrosion performance of copper-nickel, however, the presence of Fe^{2+} in the solution, which originates from additions of ferrous sulphate ($FeSO_4$) or installation of stimulated iron anodes, can reduce the extent of sulphide induced corrosion.

It was indicated[26] that protection was due to establishment of a protective film consisting primarily of lepidocrocite (γ-FeO·OH). Two possibilities for film formation were suggested: lepidocrocite was electrophoretically deposited on the surface from γ-FeO·OH colloid formed in the solution, or, through an intermediate step, ferrous ions are transported to cathodic sites and ultimately oxidised to γ-FeO·OH. The substance acted as a cathodic inhibitor increasing the cathodic polarisation. In another study[27], considering the zeta potentials and colloidal chemistry of $FeSO_4$, it was postulated that the film formation takes place due to direct attraction of lepidocrocite from the colloid by Cu_2O.

However, it has been recognised that extensive application of ferrous ions can result in formation of a bulky scale on the tube surface leading to deterioration of the heat exchanger performance. Therefore, the control of treatment efficiency and periodical mechanical cleaning of the heat exchanger might be required. Sato[28] recommended a gradual decrease in dosing levels after the initial film formation.

Effertz and Fichte[33] investigated the effect of temperature, retention time, and pH on colloid concentration as well as treatment efficiency. Between 5 and 25°C, it was demonstrated that 10°C rise in temperature doubled the yield of colloid. For up to 5 ppm $FeSO_4$, the colloid concentration increases with concentration of Fe^{2+} ions. In addition, the yield of colloid increased linearly up to 50 % max. possible concentration and approached asymptotically the maximum level approximately after 1000s, whereas the formation was finished between 400 and 1000s. Provided that the colloid concentration is constant, the deposition rate [g Fe^{2+}/ cm²*s] was independent of pH, retention time, and Fe^{2+}-concentration. The Fe^{2+} concentration in the stock solution should be between 5-50 g/l with pH between 2 and 3. The presence of suspended matter might deteriorate the efficiency of the treatment. Since, the lepidocrocite layer took up a significant amount of water, the drying out of the tube surface can result in sloughing

Table 2: Ferrous ion treatments capable of preventing sulphide induced corrosion.

Type of Treatment	Dosage Regime	Fe^{2+} Concentration [ppm]	S^- Concentration [ppm]	Remarks	Ref.
Simulated Anode	Continuous	0,01-0,2	0,01-0,1	No appreciable effect of 0,01 S^- on general corrosion, but increased localised attack. The corrosion was significantly reduced by ferrous ion treatment but not completely eliminated; the pitting was eliminated after 90 days.	34
Ferrous Sulphate	Continuous	5	0,1	Build up of sludge	29
Ferrous Sulphate	2 h/day	1	0,01	20 to 40 days were necessary for inhibitor to achieve the full effectiveness	29
Ferrous Sulphate	Continuous	0,1	0,05	90 days of exposure were necessary for full counter-action of inhibitor	30
Ferrous Sulphate	Continuous	2-3	See remark	The treatment is recommended during commissioning period to accelerate the formation of protective film	31
Ferrous Sulphate	1 h/day	5	See remark	The treatment is recommended during commissioning period to accelerate the formation of protective film	31
Ferrous Sulphate	Continuous	0,18	0,08	In combination with sponge ball cleaning to control the heat exchanger efficiency the treatment achieved best results in an extensive project.	32

off the protecting films. Assessment of the film quality by application of polarisation resistance measurements was suggested.

In contrast to ferrous sulphate treatment, it has been reported that ferrous ions released from a stimulated iron electrode were oxidised within 3 min. Thus, it was recommended to situate the anode so that ions reach the points to be protected within 2 min after generation.[34] In the same report was shown that corrosion already actively proceeding (5 days of pre-exposure to 0.2 mg/l sulphide followed by continuous 0.01 mg/l sulphide) was significantly reduced and adverse effects of additional low level sulphide exposure were nullified by ferrous ion treatment in the range between 0.05-0.2 mg/l Fe^+.

Simultaneous treatment with ferrous ions and chlorine is not recommended due to possible re-actions of chlorine with ferrous ions to from ferric chloride. The ferrous sulphate is consumed and is not available for the establishment of protective layers. It is recommended to stop the treatment with ferrous ions one hour before chlorination. The concentration and type of dosage capable of preventing sulphide induced corrosion are given in *Table 2*. During normal service on offshore units or seagoing vessels, additional ferrous sulfate dosing is seldom required. However, if exposure to known polluted water is going to occur (e.g. when entering port), a reasonable additional precaution might be to apply dosing prior to entering, while in and after leaving port.[31] In addition it has been reported that application of ferrous sulfate treatment is beneficial in combating the erosion of condenser tubing.[35]

Erosion-corrosion

Erosion-corrosion is a combined process, which is partly the mechanical impact of a moving medium (or sandblasting) over a metal surface, and partly (or entirely) electrochemical proc-esses.[36] In case of copper alloys, it has been generally recognised that increasing flow veloci-ties have no significant effect on the corrosion rate until a critical velocity – so called breaka-way velocity – is reached. The maximum flow rates in CuNi 90/10 systems are known to be limited to 3.5 m/s.[37]

The mechanism of erosion-corrosion is affected by hydrodynamic characteristics of the flow depending on the thickness of both the velocity boundary layer and the diffusion boundary layer at similar average flow velocities. As a result, the increasing boundary layer causes a decreased concentration gradient and thus reduces the mass transport. Consequently, if the passive film breaks down and metal removal corresponds to the shear stress in the surface, or if the corrosion process is determined by the mass transport from or to the surface, it can be expected that an increasing pipe diameter results in lowering erosion-corrosion rates and an increased breakdown velocity.[36] Efird[38] estimated that the critical velocity was 4.4 m/s for a tube 0.03 m in di-ameter and 6 m/s for a tube 3 m in diameter at 27°C. The calculated critical shear stress was 43.1 N/m² for CuNi 90/10 in seawater indicating the conditions, under which the passive film is formed, must be considered.

Sand is typically present in estuarine or brackish waters and may be detrimental to the perform-ance of the alloy. The severity of this is complicated to quantify because it is affected by many factors such as sand content, size of sand particles, flow profile, magnitude of impingement, and water chemistry. A survey on sand loading in seawaters used as coolant in power plants re-vealed that in most cases the sand content is less than 1000 ppm with particle size in the range of less than 50 ~250 μm. At 10 Pa shear stress, it was shown using a rotating drum test that 1000 ppm sand particles up to 30 μm do not impose any appreciable effect. Larger diameters tend to be increasingly abrasive. At flow rates of 2 m/s, the effect of 20 ppm sand particles with a size less than 100 μm caused a negligible corrosion increase whereas higher sand content caused enhanced corrosion. It has to be noted that this data was collected for aluminium brass condenser tubing[35] and the critical sand content for copper-nickel can be different.

Severe conditions might be expected if the pipe opening has a foreign body lodged in it causing throttling of the flow and leading to an abnormal increase locally of flow velocity.[35] Therefore,

entrance of debris has to be prevented by installation of strainers. Also growth of macrofouling accumulations must be prevented by appropriate biocide treatment..

Further, Campbell[39] evaluated the effect of controlled bubble size (1.0 and 2.3 mm) on erosion-corrosion resistance and compared these results with bubble free water using a jet impingement apparatus. The deleterious effect decreases with smaller bubble size.

It appears reasonable to suppose that an occasional reduction in velocity may contribute to repassivation and thickening of the surface film[36]. Knutsson[40] presented results of an examination of flow regimes over 12 months using a copper alloy. From 1 to 25 % flow duration, no attack was observed at 11.9 m/s. Continuous flow produced results of <15 μm/yr at 6.1 m/s and 76 μm/yr at 11.9 m/s. Therefore, for emergency situations, as in fire fighting systems which do not experience frequent pumping activity, the flow velocities up to 10-15 m/s are reasonable for CuNi 90/10. During two years of testing with sand loaded natural seawater by means of a once-through loop operated intermittently, no appreciable corrosion attack was detected at velocities up to 7 m/s.[41]

Negative effects of erosion are preventable by good design which is also necessary to improve the efficiency of the piping system. The general guidelines for reduction of friction loss depend on the flow velocity, pressure drop in the system due to the geometry of bends and valves, the required pumping power, and the probability of erosion-corrosion:

- The layout of the system should be as direct as possible.
- Control the flow with the least number of valves.
- Ask the valve manufacturer for data related to the effect of valve geometry on the pressure drop in the system. In most instances, there are considerable variations for nominally similar valves.[37]
- Consider the effect of r/d-ratio of elbows and the effect of sudden enlargement and contractions on the pressure drop.
- When fittings are used, specify long radius and full-form types.
- Cut the gasket flush with the inner surface of the pipe.
- Provide a minimum distance of 5 x I.D. between a pump or a valve and a bend.

The exact adjustment of pipe ends and outlet is important to avoid protrusions than can lead to erosion damage in service. In all cases, 100 % weld penetration without excessive penetration of the root into the tube cavity is required to avoid causing any turbulence of the fluid in service. Mismatching of pipe-ends should not exceed half of the wall thickness; however, it should be less than 2 mm. `Table 3` recommends the maximum excessive penetration of the root including the mismatch of the pipe depending on the pipe diameter.

Effect of Chlorination

Chlorination of seawater is the most common method to control biofouling and it has been reported that continuos chlorination to a residual free chlorine level of 0.25 ppm can be 100 % effective against fouling.[42]

There is only limited information on the effect of chlorination on the corrosion behaviour of copper-nickel. It has been reported that, in presence of 0.25 ppm free chlorine, the corrosion of CuNi 90/10 increased during 30 days of exposure but the effect of the chlorine weakened subsequently.[43] Kirk and co-worker[25] stated that according to general experience no negative

`Table 3: The maximum depth of excessive weld root penetration including the mismatch of the pipe depending on pipe diameter according to DIN 85004:1996-06`

Pipe diameter [mm]	The max. excessive penetration of the weld root [mm]
<40	1.5
50-150	2
175-250	2.5
>300	3

effect of chlorine concentrations 0.2-0.5 ppm was indicated on the corrosion behaviour of copper-nickel alloy during many years in coastal power and process industries. In spite of the biofouling resistance of copper-nickel, the chlorine treatment extended the intervals between mechanical cleanings to restore the performance of heat exchangers from 2 months without chlorination to up to 1 year under chlorinated conditions in coastal plants.

Francis[44, 45] published the results of tests related to the effect of chlorine additions in the range between 0.3 and 4.0 ppm on corrosion and jet impingement tests (jet velocity 9 m/s for 2 months) of CuNi 90/10 exposed to natural seawater. The products formed on CuNi 90/10 during chlorination led to appreciable anodic and cathodic polarisation, and, thus, somehow to an improvement in corrosion resistance. Nevertheless, these products impaired the mechanical resistance of the copper-nickel surface leading to an increase in impingement susceptibility. For continuous and intermittent chlorine additions, the concentrations of 0.3 and 0.5 ppm respectively were recommended. Finally, the author pointed out that his results require more research in this area.

Another study[46] proposed a possible mechanism for the effect of free chlorine on corrosion performance of CuNi 90/10 in highly polluted brackish water containing appreciable amounts of planktonic and sessile SRB. It was assumed that the corrosion process in the presence of chlorine was controlled by transformation of Cu_2O layer into secondary compounds such $Cu_2(OH)_3Cl$ due to the high oxidising power of the medium. These secondary products are not well adherent to the surface and easily removed allowing further Cu_2O formation. Unfortunately, no mass loss or depth of corrosion attack were presented in this paper.

Obviously, more research is needed on the effect of chlorination on the corrosion behaviour of copper-nickel in clean and polluted seawater, or on the alteration of the critical shear stress. However, it can be concluded that an over-chlorination of seawater should be avoided.

Galvanic Corrosion

The avoidance of galvanic corrosion is a principal design consideration. Stainless steels undergo significant potential variations depending of chlorine and oxygen content, temperature, as well as presence of a biofilm, e.g. from +600 mV SCE in seawater containing 0.5-1.0 ppm free chlorine to less than −400 mV SCE in deaerated seawater. In contrast, CuNi 90/10 reveals only small changes. It has been reported that the corrosion potential of this alloy remains in the range between −50 and −300 mV SCE in natural aerated seawater at 10 and 40°C, in seawater from flowing at 3 to 15 m/s at same temperatures, and in seawater containing 0.5 ppm Cl at 15 °C. Finally, CuNi 90/10 is compatible with other copper alloys in seawater.[21]

Bardal et al.[47] studied coupling of CuNi 90/10 with high-alloy stainless steel in natural and chlorinated seawater. During connection of the metals in chlorinated water, no significant effect of galvanic corrosion was found. The difference was attributed to the establishment of biofilm on high-alloy stainless steel in natural seawater providing a much higher cathodic efficiency. However, precautionary measures should be taken if the chlorination might be turned off.

For prevention of galvanic corrosion, it is recommended to use compatible materials wherever possible. However, in multi-material systems, the combination of different metals is often unavoidable. Thus the electric contact of CuNi 90/10 with aluminium, nickel and titanium alloys, carbon and stainless steels should be avoided by application of commonly applied protection measures.

Conclusions

The available literature has been reviewed with emphasis on typical causes of failure in CuNi 90/10 seawater piping systems. The main reasons for premature failure are associated with incorrect chemical composition and production techniques for copper-nickel components, conditions during commissioning and operation of the system, presence of deposits and hydrogen

sulphide, erosion-corrosion and design layout of the system. Practical recommendations have been given to prevent such failures.

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