

A Review of Stress Corrosion Cracking of Welded Stainless Steels

Ekaterina A. Krivonosova

Perm National Research Polytechnic University, Perm, Russia Email: katerinakkkkk@mail.ru

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Copyright © 2018 by author and Open Access Library Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0). http://creativecommons.org/licenses/by/4.0/ Abstract

This article gives a brief review of scientific researches of high-alloyed chromium-nickel steels stress corrosion cracking (SCC) process of welded joints. Welded joints are one of the most complex objects from the standpoint of the general theory of corrosion fatigue of metals. During their operation a number of problems arise related to the heterogeneity of the material properties, the complexity of the structure, the presence of structural and technological stress concentrators, residual stresses, etc. The characteristic features of corrosion cracking cited in the studies of Russian and foreign scientific schools are noted. The main types of corrosion damage at various sections of the welded joint are examined: corrosion of the weld metal, damage to the zones of thermal influence, knife damage occurring at the boundary between the joint and the base metal. The models of nucleation and development of cracks in the mechanism of Inter-granular corrosion (IGC) were analyzed. The article provides information on the causes of the steel's propensity to Inter-granular corrosion. The data on the effect of heat treatment on the tendency of the weld metal to Inter-granular corrosion were systematized. The main regularities of corrosion-resistant alloying are noted. Data on the methods for preventing Inter-granular corrosion and reducing the tendency of the weld metal to stress corrosion cracking are given. Methods for estimating the tendency of weld metal to stress corrosion cracking are classified. The analysis of methods for preventing the tendency of welded joints to stress corrosion is given: metallurgical methods related to the effect on the chemical composition of the weld and the structure of the welded joint and technological methods associated with controlling the parameters of the welding and heat treatment regime.

Subject Areas

Metal Material, Thermochemistry

Keywords

Stress Corrosion Cracking (SCC), Inter-Granular Corrosion (IGC), Welded

Joint, Alloying, Structure, Heat Treatment

1. Introduction

From the point of the general theory of corrosion of metals welded joints are among the most difficult objects. A number of problems related to the heterogeneity of the material properties arise during the operation: the complexity of the structure, the presence of structural and technological stress concentrators, residual stresses, etc. as discussed [1]-[14]. With the simultaneous operation of static tensile stresses (external or internal) and corrosive environment many structures are susceptible to stress-corrosion cracking precisely at the welds and near-weld zones. This fully applies to such structures as reservoirs, pipelines, etc.

The characteristic features of the stress-corrosion cracking noted in all the studies are:

- fragile nature of destruction;
- development of cracks perpendicular to tensile stresses; the cracks being inter-granular, trans-granular or mixed;
- the dependence of time to failure on the magnitude of tensile stresses: the time to cracking increases with decreasing level of tensile stresses.

There are three main types of corrosion damage to the welded joint which depends on the location, as shown in the **Figure 1**.

1.1. Corrosion of Weld Metal

With simultaneous action of corrosive medium and load or residual stresses may have the character of local corrosion which manifests itself in the form of corrosion cracking or a grid of cracks. According to the mechanism of occurrence and development this destruction is the **inter-granular** corrosion, as shown in the **Figure 2** and **Figure 3**.

1.2. Defeat of Zones of Thermal Influence

In some high-strength and stainless steels there is a significant change in the structure of the metal in the heat-affected zone at a distance of 10 - 15 mm from the weld, as shown in the **Figure 4** and **Figure 5**. The appearance of foci of corrosion in the zone of thermal influence is associated with the prolonged residence of the metal in the temperature range of 450°C to 850°C and the loss of complex carbides from the austenite impoverishing the peripheral portions of the austenite grains. This leads to its destruction along the grain boundaries. In [15] corrosion cracking in these zones is associated with the occurrence of residual stresses. The greatest stress concentration is observed when welding overlapping sheets in the zone lying between the seams.

1.3. Knife Corrosion

Occurs at the boundary between the seam and the base metal in stainless steels



Figure 1. Localization of different types of corrosion of the welded joint: a—cross-section; B—top view; 1—cracking of the seam itself, 2—cracking to the base metal in the zone of thermal influence of welding, 3—cracking directly at the fusion boundary ("knife" or "toe" corrosion), as described [14].



Figure 2. Inter-granular corrosion of weld metal 12Cr18Ni10Ti, obtained by manual arc welding with OK 61.30 electrode, after testing in a boiling solution of a mixture of salts of MgCl2, NaCl and KCl for 600h, ×450, as described [10].



Figure 3. Corrosion cracking along the spiral weld of the pipeline, as described [15].



Figure 4. Corrosion cracking along the thermal influence zone of the longitudinal weld of the pipeline, as described [15].



Figure 5. Corrosion cracking of the thermal influence zone of weld of 09Cr16Ni4Nb, x450, as described [10].

stabilized with titanium, niobium and molybdenum, usually in areas that have heated to temperatures above 1250° C, as shown in the **Figure 6**. In this case titanium and niobium carbides are dissolved in austenite. Repeated thermal impact on this metal of critical temperatures of 500° C to 800° C (for example with multi-layer welding) will lead to the preservation of titanium and niobium in a solid solution and the release of chromium carbides. However at present the problem of knife corrosion has become somewhat less relevant due to the distribution of steels with a particularly low carbon content, as discussed [12].

2. Mechanism of Crack Formation

Most researchers believe that the SCC failure has an electrochemical nature. The formation of the SCC cracks is associated with the appearance of a galvanic cell "stress concentrator (anode)—the rest of the surface (cathode). The anodic areas can be grain and phase boundaries while the grains themselves are cathodes. In this case the most dangerous form of corrosion develops is the inter-granular corrosion (IGC). It is almost imperceptible from the surface and extends deep



Figure 6. A detailed view of knife corrosion in the weld metal at the outlet of the technological pipeline made of 12Cr18Ni10Ti steel, as described [12].

into the metal along boundaries of the grains. As a result of inter-granular corrosion the bond between the grains is broken and after loading the metal collapses easily. This is particularly true for welded joints from chromium-nickel austenitic steels. The chemical composition and marking of chromium-nickel stainless steels in accordance with the main European and American systems are presented in Table 1. The inter-granular corrosion of high-chromium steel is due to the release of carbides of the type (Cr, Me) 23C6 or Cr23C6 at elevated temperatures along the faces of grains. These carbides are formed due to diffusion of carbon from the whole volume of grain and chromium—only from the border regions, as shown in the Figure 7. Carbon is displaced along the interstitial mechanism of diffusion (by the mechanism of implantation) which is characterized by high mobility in comparison with the displacement of atoms along the substitution mechanism. This leads to a decrease in the chromium content in the border areas below its critical concentration of 12% - 14% and a sudden drop in the electrode potential from +0.2 to -0.6 V, as shown in the Figure 8. The grain boundaries become an anode to the metal inside the grains as discussed [6]. When stainless steel meets an aggressive environment the center of the crystal becomes a cathode and the grain boundary becomes a very active local anode.

The researchers [16]-[22] explains following as the reasons for the tendency of steel to inter-granular corrosion. At high temperature heating over 1250° C - 1300° C the carbides in Ti (Nb)-stabilized steels are dissociate. Titanium (niobium) and carbon are converted into a solid solution of austenite. In this case carbon segregates at grain boundaries preferably. Subsequent heating at the temperature of 600° C - 700° C leads to carbides formation, which contains a significant amount of chromium. Its content in the border regions of grains sharply decreases and steel becomes susceptible to inter-granular corrosion in the local area. In addition one can believe that the heterogeneity of the structure of the weld zone evokes the unevenness of the electrochemical properties of the metal.



Figure 7. Scheme for the formation of inter-granular corrosion of high-chromium steel: arrows indicate the direction of diffusion of chromium and carbon, 1—the distribution of chromium in the boundary region, 2—grain boundary, A—anode region, K—cathode region, \bigcirc —carbides $Cr_{23}C_6$, as described [16].



Figure 8. Dependence of the electrochemical potential V on the chromium content in austenite, as described [16].

 Table 1. Correspondences of the main grades of chromium-nickel stainless steels and chemical composition.

Standards of stainless steels				Content of alloying elements, mas. %					
DIN	AISI	GOST	С	Mn	Si	Cr	Ni	Мо	Ti
1.4301	304	12X18H9	0.07	2.0	0.75	18.0 - 19.0	8.0 - 10.0		
1.4948	304H	08X18H10	0.08	2.0	0.75	18.0 - 20.0	8.0 - 10.5		
1.4306	304L	03X18H11	0.03	2.0	1.0	18.0 - 20.0	10.0 - 12.0		
1.4833	309S	20X23H13	≤0.2	2.0	1.5	19.0 - 21.0	11.0 - 13.0		
1.4541	321	08X18H10T	0.08	2.0	1.0	17.0 - 19.0	9.0 - 12.0		0.7
1.4401	316	03X17H14M2	0.08	2.0	1.0	16.0 - 18.0	10.0 - 14.0	2.0 - 2.5	
1.4435	316S	03X17H14M3	0.08	2.0	1.0	16.0 - 18.0	12.0 - 14.0	2.5 - 3.0	
1.4404	316L	03X17H14M3	0.03	2.0	1.0	17.0 - 19.0	10.0 - 14.0	2.0 - 3.0	
1.4571	316Ti	08X17H13M2T	0.08	2.0	0.75	16.0 - 18.0	11.0 - 12.5	2.0 - 3.0	0.8
1.4845	310S	20X23H18	0.08	2.0	0.75	24.0 - 26.0	19.0 - 21.0		

Conventional notation: DIN—Deutsche Industrie Norm. EN—Standard of the EuroNorm EN 10027. AISI—American Iron and Steel Institute. GOST—State system of standards of the Russian Federation.

The grain boundaries which have weak interatomic bonds due to the segregation of dissolved elements have a potential differ from the potential of the grain body and serve as an anode. The precipitation of a dense chain of carbides at the grain boundaries causes a sharp increase in the density of the corrosion current in these anode regions which as a result rapidly corrodes. Corrosion of the boundary layers of grains is also affected by the stresses noted above which appear in the lattice of the solid solution when the excess phase is isolated.

An interesting mechanism of SCC proposed in [16]. Corrosion cracking occurs if there are more or less permanent "channels" in the alloy over which corrosion can develop. For example boundaries of grains can serve as such channels. Narrow slits (cracks) are formed with localized electrochemical corrosion propagating through these channels. The bottom of these cracks has a radius of curvature of the order of atomic dimensions. Initial small cracks can pass along the grain boundaries or along the grain body. Formation of such cracks is possible. As the crack deepens tensile stresses concentrate on its bottom. Depending on the shape of the sample the stress loading method the experimental conditions and the energy state of the alloy the crack can propagate through the entire section of the sample, or it may stop when encountering an obstacle (unfavorable grain boundary orientation, nonmetallic inclusion, etc.) or as a result of stess relaxation, etc. The mechanical advancing of the crack leads to the exposure of a new metal surface, the corrosive medium under the action of capillary forces rapidly penetrates to this surface and the period of propagation of tires as a result of intensive corrosion. In the same period, a branch of the crack occurs. According to this hypothesis a crack development consists of alternating processes of localized corrosion and mechanical destruction as discussed [17].

In [16] two ways of the cracks development after the formation of the foci of cracking are distinguished: inter-granular and trans-granular. Inter-granular fracture is typical for the material of the bodies of nuclear water boiling reactors at a temperature of 200°C - 300°C and voltages above the yield point [16] as well as for welded seams. Trans-granular stress corrosion cracking occurs most often in media with a high chloride content but can also be detected in the presence of concentrated alkaline agents. In practice stress-induced stress corrosion cracking is associated with local enrichment of chlorides on hot surfaces as a result of evaporation. An essential condition for trans-granular corrosion cracking is the high temperature profile; the chloride cracking is seldom observed below 60°C, and alkaline-below 100°C. Trans-granular cracking can be subjected to austenitic stainless steels; but their resistance increases with increasing nickel content and alloys containing 40% nickel or more can be considered as practically resistant. Ferritic chromium steels with a low content of other alloying components are usually considered resistant to this type of injury. Steels with a ferritic-austenitic structure are generally less sensitive than pure austenitic steels. A study of the kinetics of crack development during corrosion under stress of high-strength steels in [16] showed that the process of development of cracks

consists of three stages. At the first stage a corrosion crack. At the second stage there is an abrupt development of the crack, which indicates a significant role of the mechanical factor. The transition from the first stage to the second is accompanied by a significant increase in the rate of development of the crack. At the third stage there is an avalanche-like development of the crack.

The life cycle of stress corrosion cracking of pipeline welds is well described by the Parkins model [15]. The SCC life cycle is often described generically in terms of a "bathtub model" as depicted in the **Figure 9**. Destruction passes serial four stage: stage 1—incubative period, without damage, dependent from conditions operation pipeline, quality protective cover and other; 2—stage origin hearth crack, is consequence violation protective cover, imperfection structure steel, stress level and other; 3—coalescence and further development cracks, and stage 4—catastrophic distribution cracking with very high speed.

The model of the Fe-Fe (stressed) corrosion element, described in [17], is of interest.

When tensile stresses are applied, the electrode potential of the steels is shifted to the negative side. Of great interest is the fact of a selective decrease in the electrode potential of steel at the bottom of the concentrator in comparison with its side when tensile stresses are applied, as established in [5]. Thus, the bottom of the stress concentrator serves as the anode, and the rest of the surface is the cathode. A stronger decreasing of stress concentrators in comparison with the rest of the surface of the stressed specimen made it possible to assume that the development of cracks in SCC is related to the operation of the corrosion element "stress concentrator—the rest of the surface". It was assumed that the



Figure 9. The SCC life cycleof pipeline welds (Parkins model as described [15]).

greater the amperage of this corrosive element, the shorter the time to cracking. It has been established that a stressed sample of high-strength steel in a Fe-Fe (stressed) pair acts as an anode, and an increase in tensile stresses leads to an increase in the amperage. The formation of a corrosion crack on a stressed sample accompanies a sharp increase in the amperage as discussed [16].

3. Influence Alloying on the Process of Stress Corrosion Cracking of Stainless Steels

Carbon. The most effective way to prevent the tendency to selective corrosion of austenitic steels under the influence of a welding thermal cycle is to reduce the carbon content to the limit of its solubility in austenite at room temperature. However as we will show below chromium-nickel austenitic steels with a very low carbon content is also not devoid of drawbacks related to the sensitivity to the welding thermal cycle as discussed [14] [16] [18] [19].

Titanium, molybdenum, niobium, vanadium. A great influence on the resistance to stress-corrosion cracking of steels is provided by elements that bind carbon and nitrogen in the form of compounds in soluble in γ - and α -iron.

These elements include strong carbide formers-titanium, molybdenum, niobium, vanadium, which increase the resistance to stress-corrosion cracking of low-carbon steels by the mechanism described above, but to varying degrees. Less susceptible to knife corrosion have austenitic steels stabilized by niobium, compared to steels stabilized with titanium. This can be explained by the fact that niobium in contrast to titanium is more difficult to dissolve in austenite under high temperature heating, concentrates mainly in the boundary layers of grains and binds all carbon diffusing to the grain boundaries during tempering and chromium carbides are not released. The separation of niobium carbides from the solid solution occurs much faster than titanium carbides. Therefore the stresses arising in the crystal cell in the first case are many times less than in the second. Corrosion of the metal near the fusion line in steels with Nb is also much weaker than in steels with Ti. For example, in welded joints of 08Cr17Hi5Mn9NNb steel knife corrosion was not detected at all, even taking into account the expenditure of a part of niobium on the formation of nitrides as discussed [11].

It can not be assumed that the stress-corrosion cracking of structural steels in various environments is determined only by the arrangement of the released carbides. The structural factor also has significance: studies of the effect of heat treatment have shown that steels with a martensitic structure exhibit the least resistance to stress-corrosion cracking.

Chromium. Chromium significantly increases the corrosion resistance of steel. It refers to self-passivating materials. Due to the passivation of chromium, which is part of the alloy, a passive film (protective layer of oxides or adsorbed oxygen) is formed on the surface of the alloy, which substantially increases the corrosion resistance of the alloy. It is established that for the production of

stainless steel, the minimum chromium content should be not lower than 13 - 15 mass.%, as discussed [14] [16] [19].

Manganese. When manganese is added to the steel, the stability of the austenite increases and the degree of its supercooling increases, thereby reducing the critical quenching rate and increasing the hardenability of the steel. With increasing manganese content, the resistance to SCC of high-strength martensitic steel is reduced. Manganese can hold near to itself nitrogen atoms in the volume of the crystal, why carbon is disposed on dislocations located along the grain boundaries. This in turn lowers the resistance to SCC of high-strength steel, as discussed [14] [16] [19].

Nickel. With an increase in the nickel content the resistance of steel to SCC is decreases [14].

Silicon. The main property of silicon is to significantly impede coagulation of carbides released during tempering. Silicon slightly increases the strength and yield strength of steel, as well as the stability of sorbitol structures against tempering, as discussed [16] [19].

Nitrogen. Many researchers note the increased propensity to SCC of low-carbon steels containing nitrogen. It has a small atomic radius and, due to this, it can form solid interstitial solutions with α - and γ -iron and some other metals, as discussed [10] [13] [14] [19].

Impurity of phosphorus. An increase in the phosphorus content leads to a decrease in the resistance of steel to SCC, increases the intensity of hydrogenation. The phosphorus is concentrated along grain boundaries [16] [19].

Impurity of hydrogen. These mechanisms typically speculate that atomic hydrogen plays a role in causing embrittlement of strained material immediately ahead of the crack tip as discussed [15] [10] [13].

4. Influence of Heat Treatment on Corrosion Resistance of Stainless Steels

Effect of tempering temperature. First of all one should note that the intermetallic aging regimes of austenitic chromium-nickel steels, which provide the maximum hardening and regimes providing the greatest resistance against to SCC do not coincide.

Resistance to SCC of all high-strength steels with increasing tempering temperature first increases, and then at a certain tempering temperature, decreases; with further increase in tempering temperature, the resistance to SCC rises again. The tempering temperature at which a reduction in the resistance of steel to SCC is observed depends on its composition.

For example, the resistance to SCC steels was studied in [2], depending on the tempering temperature after quenching—for steel 08Cr15Ni5Cu2Ti and quenching and cold treatment—for steel 13Cr15Ni4NMo3. The steels are most sensitive to cracking after tempering at a temperature of 425 - 475°, which provides the maximum level of strength. At low temperature tempering (200°C -

 350° C) and at higher temperatures (525° C - 560° C), the resistance to SCC rises until the cracking is eliminated. It is established that the behavior of welded joints welded after tempering below 400° and above 500° is significantly different. In the first case, the SCC only slows down, in the second case, it can be excluded. To provide high resistance to SCC welded joints, steel 08Cr15Ni5Cu2Ti was developed to leave before welding at a temperature of 500 - 550°. Such processing in the over-age mode leads to coagulation of the strengthening phase, violation of its coherence with the matrix, reduction of elastic distortions and disappearance of the regions of concentration inhomogeneity. These subtle structural changes not only eliminate SCC welded joints in an atmosphere containing chlorides, but also dramatically increase resistance to IGC.

At low tempering the dispersed carbide particles formed are uniformly distributed inside the crystals. Reducing the carbon content in the a-solution leads to a decrease in internal stress, resulting in an increase in the resistance of steel to SCC. Increasing the tempering temperature leads to further precipitation from the solid solution. In this case, coagulation of the carbide particles takes place, as well as the formation of martensite from the residual austenite. The decay of martensite along the grain boundaries of the former austenite can proceed faster than in the grain. At a certain stage of tempering at the grain boundaries, the decay almost completely ends, and a supersaturated solution of carbon in the a-iron still remains inside the grain.

This preferential decay of martensite along the grain boundaries of the former austenite increases the internal tensile stresses between the grains, since the specific volume of precipitated carbides is greater than the volume of the mother liquor. In addition, this leads to the appearance of a corrosion element carbide—carbon-depleted martensite, in which the carbide is a cathode, and areas depleted by carbon-anode. With a further increase in tempering temperature, the decay of martensite proceeds throughout the grain, the internal stresses decrease, as a result of which the resistance of steels to SCC increases as discussed [1] [2] [10].

5. Classification of Test Methods for SCC

Test methods for assessing SCC can be classified according to the following characteristics:

- 1) purpose;
- 2) the type of the object under test;
- 3) type of stress;
- 4) types of corrosive environment;
- 5) indicators of durability, depending on the type of corrosion destruction.

Tests are conducted to identify the causes, nature, kinetics and mechanism of destruction; Reasonable choice of material, design and manufacturing technology; Solving problems of an expert type when clarifying the causes of design failures. At the same time, the analysis of operating conditions, revealing the causes

of destruction, development of measures to increase resistance to destruction [14] are envisaged.

In determining the tendency of alloys to corrosion cracking, tensile stresses in the samples are created by two methods:

- by applying a constant stress;
- by applying a constant deformation (bending).

A complete characterization of the alloy's propensity to SCC can be obtained by removing corrosion stress cracking curves from the magnitude of tensile stresses.

The formation of corrosion cracks is associated with an uneven increase in the corrosion rate of the alloy when tensile stresses are applied. If v_1 is the corrosion rate at the stress concentration site, v_2 is the corrosion rate on the rest of the alloy surface, the formation of a corrosion crack will occur at voltages when $v_1 > v_2$. The greater the difference in the rate of corrosion of $v_1 - v_2$, the greater the tendency of the alloy to stress corrosion cracking as discussed [14].

The value of the critical voltage (when exceeding which corrosive destruction occurs) is influenced by:

- composition of the corrosive environment;
- the chemical and phase composition of the alloy;
- heat treatment;
- the state of the surface layer;
- the magnitude and nature of internal stresses.

Tests under uniaxial external stress are the main type of tests to evaluate the resistance of materials to SCC, but it should be considered primarily as comparative, since it do not fully reproduce the stress state of most structures. These tests are carried out to obtain a comparative evaluation of the properties of materials, the influence of various technological factors, the study of mechanisms of failure in the stressed state in bending, tension and torsion with a constant stress as discussed [4] [5] [13] [14] [20] [21] [22].

6. Prevention of Stress Corrosion Cracking

Methods for preventing the tendency of welded joints of austenitic chromium-nickel steels to stress-corrosion cracking can be divided into metallurgical and technological ones. Metallurgical methods are associated with the effect on the chemical composition of the weld and the structure of the welded joint, and technological methods—with control of the parameters of the welding and heat treatment regime.

6.1. The Maximum Decrease of the Carbon Content and the Introduction into Steel of Such Strong Carbide-Forming Elements as Titanium, Niobium, Molybdenum, Vanadium, etc.

An effective means of suppressing inter-granular corrosion of high-chromium steels is the maximum decrease of carbon content [16]. It is known that if the carbon content in steel does not exceed $0.02\% \dots 0.03\%$, the limit of its solubility

in austenite (0.02%), then carbides will not fall out. Thus, welded joints made of steel 03Cr18Ni11 (with 0.02% C) are not prone to knife corrosion even when tested in 50% - 65% nitric acid. Therefore, it is preferable that the maximum decrease in the carbon content of the steel is less than 0.03% However, in practice, taking into account the strength requirements, the carbon content is higher and is $0.08\% \dots 0.12\%$. When the content of carbon in the steel is greater than the limit of its solubility in austenite, the use of such strong carbide-forming elements as titanium, niobium, molybdenum, etc., which have a greater affinity for carbon than chromium, is introduced into the steel. Then carbon will not be released in the form of chromium carbides, but in the form of TiC, NbC, MoC carbides; Chromium is retained in the solid solution and the corrosion resistance of the steel does not decrease. However, this will increase strength and decrease the ductility of steel. The results of experimental studies on increasing the corrosion resistance of welded joints due to a change in the concentration of molybdenum nanopowder introduced into the weld pool together with a protective gas jet during arc welding with a consumable electrode are presented in [8]. It is established that at different concentrations, a different microstructure of the weld metal is formed. It is shown that the nature of nanopowders affects the corrosion resistance of welded joint specimens. The most corrosion-resistant samples were obtained using nanopowders of molybdenum and tungsten.

6.2. The Formation of a Favorable 2-Phase Austenitic-Ferritic Structure in the Weld

The next method of reducing the tendency to stress corrosion cracking is to form a favorable weld metal structure. It is established that the production of a 2-phase austenitic-ferric structure (the alloying of the weld metal by ferritic elements) can completely eliminate the appearance of fracture. The presence of primary ferrite in the austenitic seam increases the resistance to SCC, thanks to the rapid restoration of the necessary chromium concentration in depleted areas due to the high rate of diffusion of chromium in ferrite as discussed [3] [7] [17].

It is particularly difficult to control the structure of the weld metal by selecting filler materials for welding and surfacing of dissimilar materials. When surfacing corrosion-resistant steel on low-carbon or low-alloy steel, the structure of the weld metal can be determined using the Schaeffler diagram shown in the **Figure 10**. The structural regions A + M, M, M + F are unfavorable due to the occurrence of cracks or embrittlement under the influence of heat treatment. Therefore, the materials and the weld regime must be selected with orientation to the triangular area of the Scheffler diagram, limited by the values of Cr_{eq} . within the range of 18% - 24% and Ni_{eq}, within the limits of 7% - 18%. This region in the diagram corresponds to the structure A + F (2% - 6%). It follows from the diagram that when welding low-carbon steel (point **a**) with corrosion-resistant AISI304 steel (point **b**), the weld metal structure corresponding to point c consists of a mixture of austenite and martensite.



Figure 10. Scheffler diagram. Structural areas of austenite—A, martensite—M, ferrite—F, as described [16].

When this structure is formed, there is a risk of cracks. For welding low-carbon steel to obtain a weld metal that is similar in composition to AISI304 corrosion-resistant steel, welding (with a 25% bond of the parent metal in the joint) must be performed with AISI309 steel (point **d**) with a higher content of alloying elements (25% Cr and 12% Ni). The seam structure in this case corresponds to the point **e** located in the favorable structural area. In this connection, when welding dissimilar metals, a subcoat of steel AISI309 is often used for surfacing. The chemical composition of the main material is given in **Table 1**.

The paper [6] presents the results of work on the additional research and modernization of steel grade EP-302 (10Cr15Ni9Si3Nb1) and welding materials (wire 03Cr14Ni8Si3Nb), developed in industrial conditions and successfully used for manufacturing equipment of power plants with lead-bismuth coolant with operating temperature up to 450°C. These grades are doped with silicon, which, as is known, is an effective way to improve heat resistance and resistance to liquid metal corrosion. Studies of the microstructure of silicon-containing austenitic-ferritic Cr-Ni-Nb welded joints have been carried out using a wide range of methods of electron transmission and raster microscopy and X-ray analysis. Of particular interest was the study of the content of the ferrite phase, the limit of its content in 2% - 5% is one of the conditions that contribute to improving the processability of semifinished products during welding. The transformation of delta-ferrite into a sigma phase in the weld metal in the samples after prolonged aging at temperatures of 500°C - 600°C has been detected.

Article [10] established the temperature-time region and the composition of the weld metal, which provide resistance to SCC welded joints. So the weld metal of low-nickel austenitic steel 08Cr18NNi5, containing <0.05% C, ~2% Mn, 17% - 18% Cr, 6% - 7% Nb, 0.12% - 0.15% N, has the lowest propensity to the MCC in range of technological heating in welding.

6.3. Ensuring a High Cooling Rate in the Critical Temperature Range (500°C to 800°C) during Welding

The shortest soak time necessary for the metal to acquire sensitivity to the IGC lies in the interval T = 650 °C - 700 °C. The time corresponding to this interval is called critical (tcr), as shown in the **Figure 11**. Both below and above these temperatures, the time needed for the appearance of corrosion sensitivity in the metal increases.

Thus, to reduce the likelihood of the appearance of IGC in the weld metal, it is necessary to provide a high cooling rate in the critical temperature range (500°C to 800°C) during welding, and thereby increase t_{cr} .

6.4. Homogenizing Heat Treatment

Conducting homogenizing heat treatment—quenching or stabilizing annealing is another effective method of preventing ICC and SCC. Austenitization (hardening) is carried out at temperatures of 1050° C to 1100° C, but when reheating in the interval of critical temperatures (500° C to 800° C), the steel repeatedly acquires a tendency to intercrystalline corrosion; Stabilizing annealing is carried out at a temperature of 850° C to 900° C for 2 - 3 hours.

Avoiding the appearance of ICC in the zone of heat sealing of welded joints allows:

- Hardening for a homogeneous solid solution. When heated for quenching, the precipitated chromium carbides dissolve in austenite. Subsequent rapid cooling allows obtaining a uniform austenite.
- Stabilizing (diffusion) annealing. Heating at T = 850 °C to 900 °C for 2 3 hours with the subsequent cooling in the air. Carbides in this case fall more fully, but due to diffusion processes, the chromium content in the bulk of the austenite grain is leveled and the metal becomes insensitive to the MCC.

6.5. Correct Selection of Welding Parameters

Optimum regime for prevention of welded joints of austenitic chromium-nickel steels is the welding regime, which excludes overheating of the metal (welding



Figure 11. Temperature-time dependence of inter-granular corrosion of welded joints of austenitic chromium-nickel steels, as described [14].

with a small running energy, artificial cooling of the zones of thermal influence) (Table 1).

7. Conclusions

Thus the analysis and systematization of scientific investigations of the process of high-alloyed chromium-nickel steels stress corrosion cracking allow us to make a reasonable choice in methods of preventing inter-granular corrosion and reducing the tendency of the weld metal to stress corrosion cracking:

- The maximum decrease of the carbon content and the introduction into steel of such strong carbide-forming elements as titanium, niobium, molybdenum, vanadium;
- The formation of a favorable 2-phase austenitic-ferritic structure in the weld;
- Ensuring a high cooling rate in the critical temperature range (500°C to 800°C) during welding;
- Homogenizing heat treatment.

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