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Effect of the Post-Weld Surface Condition on the Corrosion Resistance of Austenitic Stainless Steel AISI 304

Abstract: Surfaces of welded elements made of corrosion-resistant (stainless) steels develop temper colours. The removal of thickened oxide layers off steels exposed to temperatures below 300°C is necessary and entails the restoring of high corrosion resistance of the stainless steel. The article presents tests concerned with the effect of a method applied to remove post-weld temper on the corrosion resistance of austenitic stainless steel AISI 304. It was ascertained that the most favourable method enabling the obtainment of high corrosion resistance involved the use of an appropriate passivation process.

Keywords: stainless steel, TIG, AISI 304, temper colours, pitting corrosion

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Introduction

Because of their technological and operational properties, high-alloy stainless austenitic steels are commonly used as structural materials in numerous industrial sectors [1-5]. The primary advantages of the above-named steels include good weldability, high resistance to corrosion and high aesthetic qualities. Austenitic steels comprise many grades characterised by different properties resulting from contents of alloying elements, primarily C, Cr, Ni, Mo, Ti and Nb. The favourable properties of the aforesaid steels may be significantly reduced or even lost through exposure to many factors including processing technologies such as welding processes and related procedures, e.g. prefabrication and heat treatment. Improperly performed welding processes may lead to the precipitation

of the sigma phase and $M_{23}C_6$ type carbides (chromium carbides) on the boundaries of austenite grains and, simultaneously, to the reduction of chromium in areas adjacent to austenite grains [6]. The reduction of chromium content usually reaches the level precluding the initiation of passivation processes and the rebuilding of a corrosion resistant layer. One of the procedures enabling the dissolution of chromium carbides is solution annealing (one of heat treatment processes). The foregoing was demonstrated by the authors of publication [7,8], who ascertained that solution annealing causes changes of mechanical properties (R_m , $R_{p0.2}$, A_{50} , A_{80}) within permissible acceptance criteria and, at the same time, dissolves chromium carbides. Related tests [9,10] made it possible to determine the effect of the concentration

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of residual oxygen in the gas forming the weld root on hardness distribution and structure. The tests revealed that, as regards steel 304L, high contents of residual oxygen (500 ppm) lead to a significant increase in the hardness of joints. Other tests identified the significant effect of the ball peening process on the structure, microhardness and internal stresses of joints made of austenitic steel 1.4539. The tests revealed the refinement of the surface structure, an increase in the microhardness of the welded joints as well as the presence of compressive stresses [11]. As can be seen in the above-presented examples, changes in properties of welded joints made of stainless austenitic steels are dependent on numerous factors. However, it should be emphasized that operational properties depend not only on the quality of welded joints but also on operational parameters and work environment. Not all stainless austenitic steel grades can be exposed to long operation in environments considered as poorly aggressive, e.g. in cold water. Sadly, all too many fail to realise the importance of the appropriate matching of a given material to a related work environment or the necessity of providing an appropriate post-weld surface condition [12-14]. Only a properly selected base material, welded in an appropriate manner and subjected to appropriate preparation and heat treatment will provide high operational properties of welded structures. Examples concerning the degradation of stainless austenitic steels resulting from improper operation and inappropriately selected base materials are presented in Figures 1÷3.

In an environment containing oxygen, stainless steels intended for operation at ambient temperature become spontaneously covered with a thin layer of oxides rich in chromium. The layer of oxides having a thickness of 10 nm protects steels against the aggressive effect of the environment. When mechanically damaged, the above-named layer recovers spontaneously, obtaining the passive state in an environment rich in oxygen.

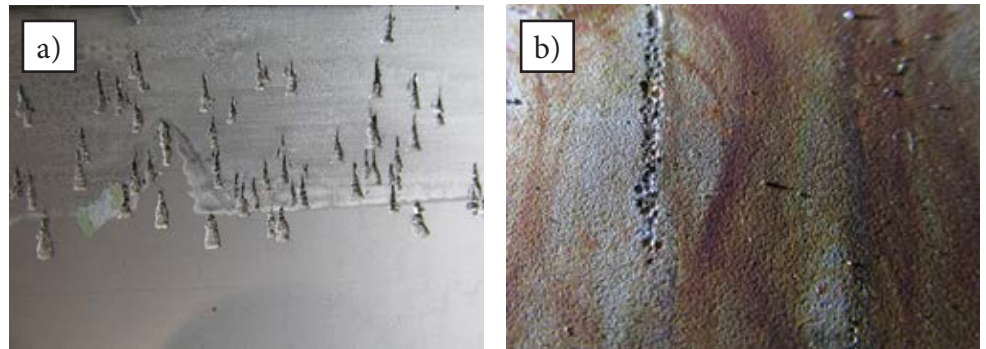


Fig. 1. Exemplary pitting corrosion of stainless austenitic steel: a) pitting corrosion of steel AISI 316, b) pitting corrosion of a heat exchanger jacket made of steel AISI 304L

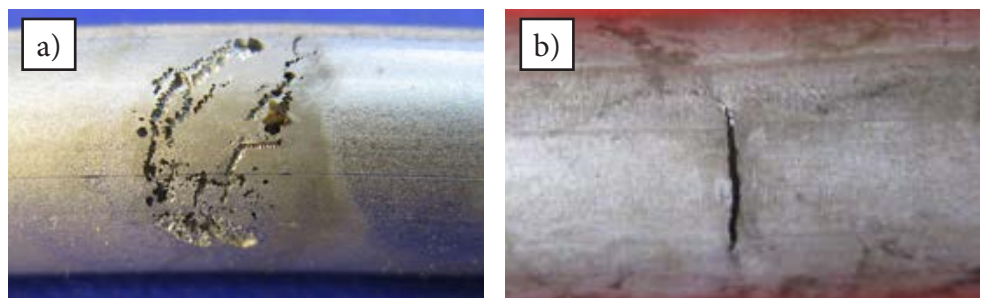


Fig. 2. Exemplary corrosion of tubes made of stainless austenitic steel: a) pitting corrosion of steel AISI 316L, b) stress corrosion-induced crack in a tube made of steel AISI 321

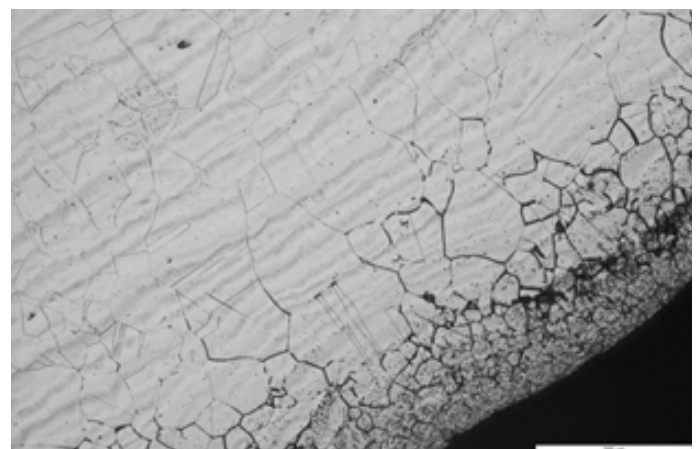


Fig. 3. Example of intergranular corrosion with visible chromium carbide (M₂₃C₆) precipitates on grain boundaries (thick and dark lines along grain boundaries) triggered by an excessive heat input during welding; mag. 200x

A heat input to the material during welding leads to the thickening of oxide layers. This phenomenon can be observed by the unaided eye as a temperature-induced increase in the thickness of oxide layers is accompanied by a change in the temper colour of steel from bright straw to dark navy blue. In addition, because of the nature of the phenomenon, a temper colour of steel makes it possible to estimate the range of temperature affecting the material. The formation of temper colours reduces the content of chromium in the material situated directly under the layer of oxides. In this manner, stainless steel with the reduced content of chromium loses its high resistance to corrosion. Welding imperfections and temper colours on the surface of stainless steels reduce their resistance to corrosion. For this reason, the removal of temper colours and any material surface imperfections is necessary to prevent the decline of the above-named loss of corrosion resistance. Temper colours can be removed from the surfaces of elements previously subjected to welding in a variety of ways. However, it should be emphasized that not all of the methods provide the appropriate removal of oxides.

Objective

The research work was aimed to identify the effect of the method used to remove temper colours formed in the GTAW process (141) on the corrosion resistance of joints made of AISI 304 steel.

Tests

Tests involved four welded joints on tubes made of stainless steel AISI 304. The consistency of the chemical composition of the material with the contents of a related conformity certificate was confirmed using an emission spectrometer. The test results are presented in Table 1. The outer diameter of the tubes amounted to 48.26 mm, whereas the thickness of the wall amounted to 5.08 mm. Three test joints were made properly and classified as representing quality level B according to PN-EN ISO 5817. Specimen no. 4 was made without the use of gas forming the weld root. All of the joints (except for specimen no. 4) were made using shielding gas and root-forming gas I1 (99.99 % Ar) in accordance with PN-EN ISO 14175. The gas flow rate was restricted within the range of 8 to 15 l/min and 6

Table 1. Chemical composition of the tubes made of AISI 304 steel

| | Chemical composition, % by weight | | | | | | | | |
|--|-----------------------------------|-------|------------|--------|-------|-------------|------------|-------|-------|
| | C | Mn | P | S | Si | Cr | Ni | Mo | Ti |
| AISI 304 | ≤0.07 | ≤2.00 | max. 0.045 | ≤0.015 | ≤1.00 | 17.00-19.50 | 8.00-10.50 | - | - |
| Chemical composition according to conformity certificate | 0.021 | 1.55 | 0.035 | 0.014 | 0.45 | 18.24 | 8.21 | - | - |
| Chemical composition according to emission spectroscopy | 0.042 | 1.21 | 0.030 | 0.009 | 0.421 | 18.180 | 8.67 | 0.062 | 0.005 |

Table 2. Welding parameters used when making test joints

| Spec. no. | Process | Welding current I [A] | Arc voltage U [V] | Current type (polarity) | Welding travel speed V_{sp} [mm/s] | Heat input Q_L^* [kJ/mm] | Amount of oxygen in shielding gas ppm O_2 |
|-----------|---------|-------------------------|---------------------|-------------------------|--------------------------------------|----------------------------|---|
| 1÷3 | 141 | 70÷120 | 9.9÷12.3 | DC (-) | 0.61÷0.79 | 0.61÷1.45 | 25 |
| 4 | 141 | 70÷120 | 9.9÷12.3 | DC (-) | 0.61÷0.79 | 0.61÷1.45 | 999 |

* Q_L – calculated in accordance with PN-EN 1011-1



to 10 l/min respectively. The process was performed maintaining an interpass temperature of 150°C. The welding process parameters are presented in Table 2. A proper test joint (no. 1) subjected to passivation is presented in Figure 4.

In cases of individual joints, temper colours were treated in the following manner:

1. Joint no. 1 – temper colours were removed through cleaning and passivation;
2. Joint no. 2 – temper colours were not removed;
3. Joint no. 3 – temper colours were removed mechanically; using abrasive cloth having a gradation of 600;
4. Joint no. 4 – specimen made without the use of forming gas on the weld root side; temper colours were not removed.

Test Results and Analysis

Chemical Composition of Areas Having Various Temper Colours

To identify contents of alloying elements in relation to a temper colour it was necessary to perform the analysis of chemical composition using an X-ray spectrometer. The specimen used for the determination of the chemical composition was sampled from joint no. 2. Areas subjected to the tests were straw-coloured, yellow and dark navy blue areas as well as the material located directly under the thickened layer of oxides. The results of the chemical composition analysis are presented in Table 3.

As can be seen in the results of the above-named analysis, the differences in the chemical composition of individual areas were only slight and restricted within the range allowed



Fig. 4. Test joint no. 1 viewed from the weld face side; the specimen was subjected to cleaning and passivation

by the related materials standard and the analysis of the chemical composition presented in Table 1. It could be assumed that the reduction of chromium content was low and should not result in corrosion.

Corrosion Tests and Metallographic Tests

A corrosion resistance test was performed on the basis of ASTM G48 Method A. The test objective was to determine the susceptibility of each of the four specimens to pitting corrosion. An environment containing the high concentration of Cl⁻ ions is aggressive for stainless austenitic steels and welded joints. An increase in temperature is accompanied by an increase in the susceptibility of austenitic steel AISI 304 to pitting corrosion. For this reason, the corrosion resistance test was performed at a temperature exceeding 60°C in the solution composed of 60 g FeCl₃ and 540 ml deionised water (iron chloride solution). The test was 24h in duration. The specimens were cut mechanically out of the joints. Figure 5 presented the dependence of temperature in the function of test duration. The weight of the specimens before and after the test is presented in Table 4 along with calculated mass depletion.

Table 3. Chemical composition on the areas of temper colours

| Tested area | Chemical composition, % by weight | | | | | | | | |
|----------------------|-----------------------------------|------|------|------|------|-------|------|------|------|
| | Fe | Mn | P | S | Si | Cr | Ni | Mo | Ti |
| straw-coloured | 70.92 | 1.28 | 0.06 | 0.10 | 0.63 | 18.82 | 8.00 | 0.00 | 0.03 |
| yellow | 71.09 | 1.45 | 0.06 | 0.08 | 0.67 | 18.54 | 7.96 | 0.00 | 0.02 |
| dark navy blue | 70.83 | 1.40 | 0.05 | 0.10 | 0.59 | 18.62 | 8.19 | 0.00 | 0.00 |
| under temper colours | 71.05 | 1.47 | 0.04 | 0.08 | 0.59 | 18.48 | 7.99 | 0.01 | 0.03 |

Table 4. Corrosion resistance test results

| Specimen no. | Specimen weight before the corrosion resistance test [g] | Specimen weight after the corrosion resistance test [g] | Mass depletion [g] | Mass depletion [%] |
|--------------|--|---|--------------------|--------------------|
| 1 | 40.1772 | 39.6407 | 0.5365 | 1.34 |
| 2 | 36.7064 | 35.8141 | 0.8923 | 2.43 |
| 3 | 42.3049 | 41.2485 | 1.0564 | 2.50 |
| 4 | 44.8798 | 42.856 | 2.0238 | 4.51 |

The comparison of results in relation to each of the test specimens is presented in Figure 10; the weld face and weld root surfaces after the corrosion resistance test are presented in Figures 6÷9.

Because of the various initial weights of the specimens, the mass depletion in relation to the initial weight expressed in percentage was used as

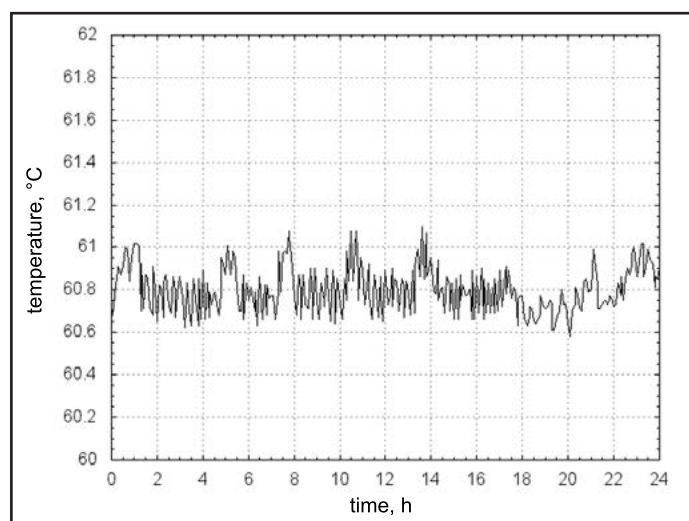


Fig. 5. Dependence of temperature in the function of corrosion resistance test duration

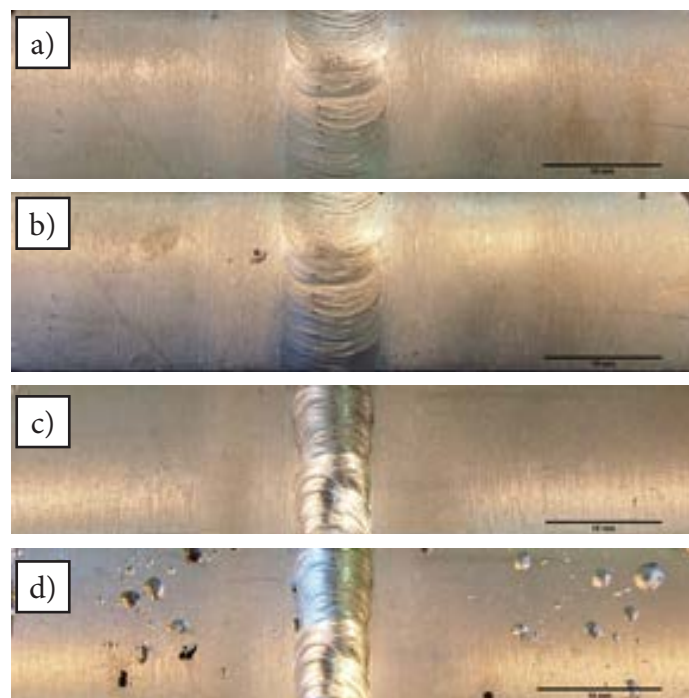


Fig. 6. Specimen no. 1, where temper colours were removed through cleaning and passivation: a) weld face before the corrosion resistance test, b) weld face after the corrosion resistance test, c) weld root before the corrosion resistance test, d) weld root after the corrosion resistance test

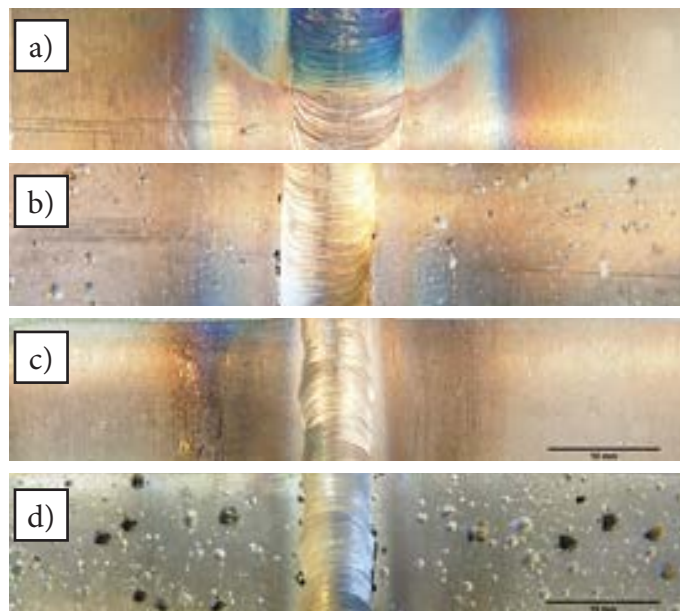


Fig. 7. Specimen no. 2, where temper colours were not removed: a) weld face before the corrosion resistance test, b) weld face after the corrosion resistance test, c) weld root before the corrosion resistance test, d) weld root after the corrosion resistance test

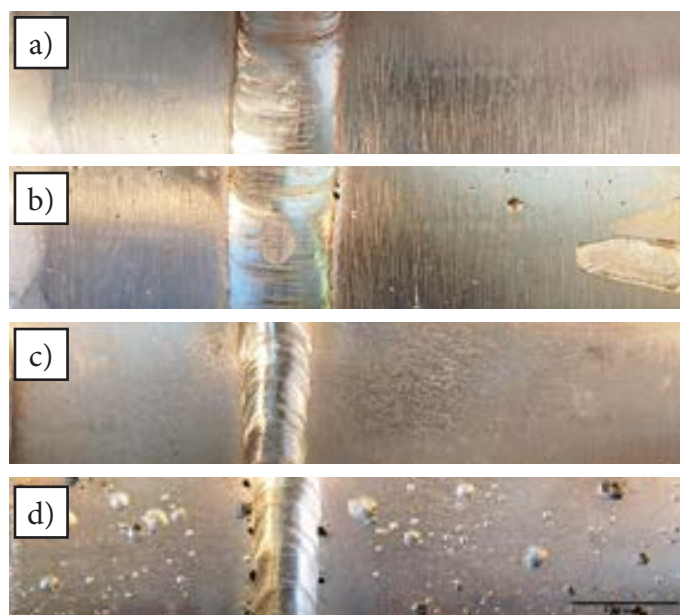


Fig. 8. Specimen no. 3, where temper colours were removed mechanically: a) weld face before the corrosion resistance test, b) weld face after the corrosion resistance test, c) weld root before the corrosion resistance test, d) weld root after the corrosion resistance test

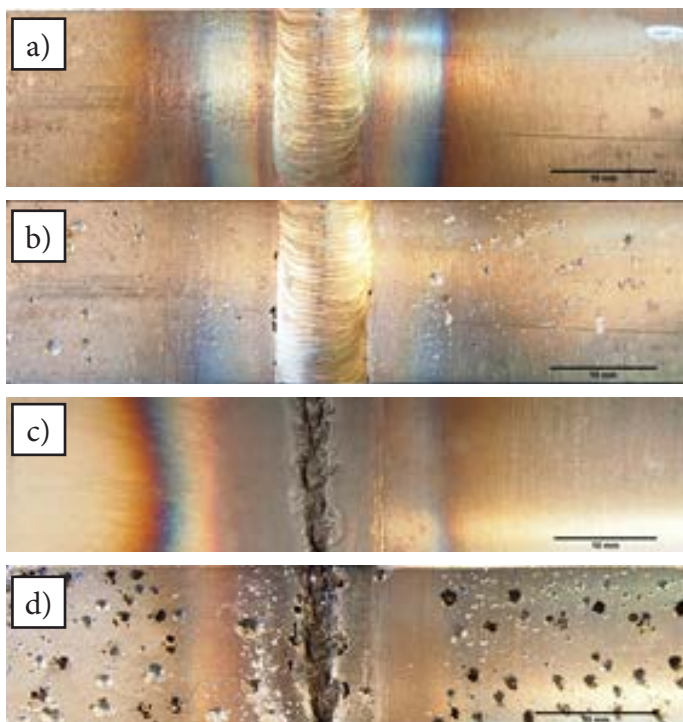


Fig. 9. Specimen no. 4, made without the use of forming gas on the weld root side and where temper colours were not removed: a) weld face before the corrosion resistance test, b) weld face after the corrosion resistance test, c) weld root before the corrosion resistance test, d) weld root after the corrosion resistance test

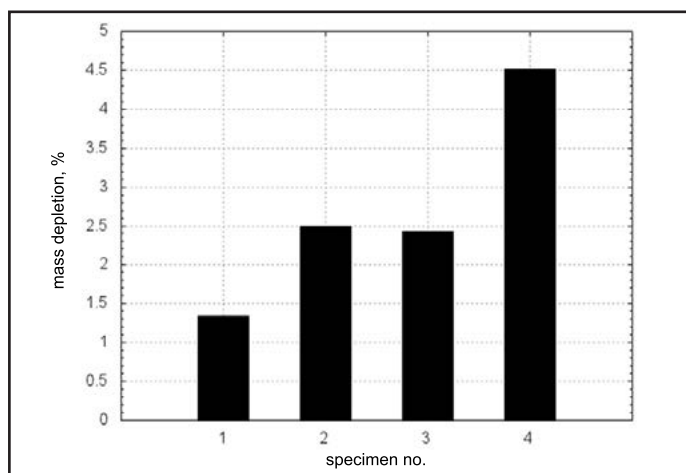


Fig. 10. Test results concerning relative corrosion resistance

the measure depicting the susceptibility of the specimens to corrosion. The above-presented approach enabled the comparison of test results in relation to all of the joints (Fig. 10).

The obtained test results (Table 4, Fig. 10) revealed that, as regards AISI 304 steel subjected to tests in a very aggressive environment, the highest corrosion resistance was that of the specimen made properly, using root-forming gas and subjected to properly combined

surface cleaning and passivation procedures. The highest mass depletion was found in the specimen made without the use of the forming gas and without the removal of temper colours. The foregoing demonstrated the importance of the shielding of the root during the one-sided welding of stainless austenitic steel. Failure to remove temper colours and the mechanical removal of temper colours involving the use of abrasive cloth provided similar results.

Summary

The tests revealed that a method applied when removing temper colours from welded joints significantly affects the corrosion resistance of stainless austenitic steel AISI 304. The process of passivation proved to be the best method enabling the obtainment of the highest corrosion resistance (obtainable) in relation to a given stainless steel grade.

In spite of its high weldability and resistance to intergranular corrosion, AISI 304 steel should not be used as a structural material exposed to operation in an environment characterised by the high concentration of Cl⁻ ions.

Even in properly made joints, failure to remove the layer having the reduced content of chromium and located under the thickened layer of oxides combined with the surface not subjected to re-passivation may lead to a significant decrease in the corrosion resistance of the joint. Improper joints made of stainless steel, the surface of which reveals the presence of welding imperfections and temper colours are particularly exposed to fast pitting corrosion leading to the failure of an element before reaching the designed (calculated) service life limit. It can also be assumed that, in cases of certain material-operation combinations, the proper removal of temper colours and the rebuilding of passive layers may not provide desired long-lasting and failure-free operation if the base material was selected improperly.

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