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EXPERIMENTAL RESEARCH OF THE DUPLEX STAINLESS STEEL WELDS IN SHIPBUILDING

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Review paper

Summary

Duplex stainless steel is used in shipbuilding increasingly because of its good mechanical properties and marked corrosion resistance. This steel has a two phase structure (austenite-ferrite) which is sensitive on heat input during welding because of the possible ferritisation appearance, that is, increase in ferrite content in the area of heat effected zone (HAZ) which can lead to loss of mechanical and corrosion properties. Work with duplex stainless steel requires special attention in every phase of production process, from storage, material handling, up to welding and welded joint surface treatment, in order to achieve a high quality welded joint and assure long-lasting corrosion resistance of the structure. In the beginning, this paper explains basic characteristics of the duplex stainless steel. In the experimental part, macrostructure, microstructure and corrosion resistance testing of butt welds, fillet welds and welded studs were performed. Results of the research are a basis for conclusions and suggestions for successful applications of duplex stainless steel in shipbuilding.

Key words: *duplex stainless steel; corrosion resistance; welded joints; shipbuilding;*

1. Introduction

The corrosion is, by definition, a process of unintentional deterioration of material caused by physical, chemical and biological agents. It is a spontaneous process which causes great damage to the entire economy. Therefore, quality and timely corrosion protection becomes of paramount importance [1, 2]. Different methods are used in corrosion protection and one of them is choosing corrosion resistant materials which are increasingly represented in all branches of industry. Stainless steels have been used over the last 100 years and are still developing. There are several types of stainless steels divided in groups according to their chemical composition and structure. One group is dedicated to a duplex stainless steel with two characteristic phases - austenite and ferrite [3].

Duplex stainless steel is used in shipbuilding for building tanks for aggressive media transport or transport of different kinds of chemicals because of its good physical and mechanical properties, corrosion resistance and easy maintenance.

Also, duplex stainless steel is widely used in the food industry and transport of victuals. In general, it can be used in many corrosive environments within the temperature range of approx. -50 ºC to less than 300 ºC [3, 4]. Croatian shipyards built ships for chemicals transport and food transport with duplex stainless steel cargo tanks shown in Fig. 1. A characteristic cargo tank is presented in Fig. 2.

Fig. 1 Tanker for chemical, oil and oil products

Fig. 2 The cargo tank bulkhead and the bottom of the tanker for chemical, oil and oil products

Work with duplex stainless steel requires good knowledge of material physical and mechanical characteristics, weldability, and corrosion resistance in order to qualitatively prepare the technological documentation in the production process. Inadequate material handling will cause additional interventions, work and costs. Price of duplex stainless steel is many times higher than mild steel price and mistakes in the production process are very expensive.

The paper contains results of the experimental research on duplex stainless steel welded joints with the aim that application of duplex stainless steel in the shipbuilding production process could be more successful.

2. Duplex stainless steel

Demands from industry for use of material with high corrosion resistance led to development of duplex stainless steel which has two phase microstructure - austenite and ferrite, in equal proportion (50% - 50%) in order to exhibit the best performance characteristics, illustrated by Fig. 3 [3-6].

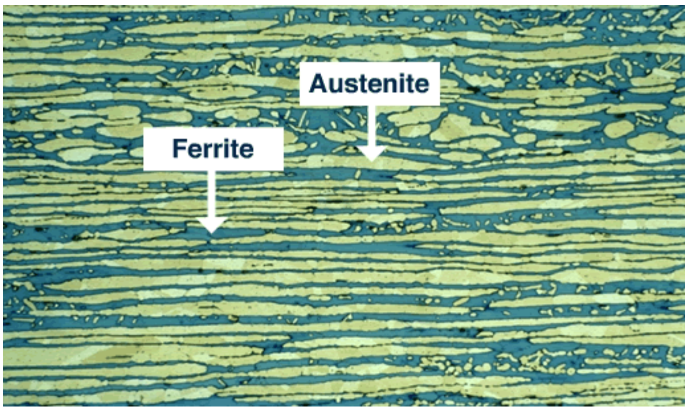


Fig. 3 The microstructure of duplex stainless steel [7]

The stabile duplex microstructure and good material properties are achieved by alloy elements influence. The most important are chromium, nickel, molybdenum, manganese and nitrogen. The chromium with minimum content of 10.5% enables formation of the passive film on the material surface [8, 9]. With the increase of the chromium content, corrosion resistance generally increases, but a high content of chromium has a negative influence on the material structure because of intermetallic phases forming. The molybdenum increases corrosion resistance too, especially in chloride environments, but its content in the alloy has to be less than 4%. These two elements help ferrite microstructure forming and their higher content has an impact on duplex (50:50) microstructure stability. The nickel is added to a duplex stainless steel for austenite stabilization and for increase of material toughness. The manganese increases wear resistance and tensile strength and the nitrogen improves corrosion resistance and tensile strength. Due to alloy elements content, different grades of duplex stainless steel were developed [3, 6-10].

Many of the duplex stainless steel grades are commonly known by a number that reflects their typical chromium and nickel contents, i.e. 2205 with 22% Cr and 5% Ni. The 2205 alloy (EN 1.4462; UNS S31803) is the most frequently used duplex stainless steel. It is a nitrogen enhanced duplex stainless steel alloy. The nitrogen serves to significantly improve the corrosion resistance properties of the alloy, which also exhibits a yield strength that is more than double that of conventional austenitic stainless steels; especially in the welded condition [3, 10]. Table 1 contains the chemical structure of duplex stainless steel 2205 and Table 2 shows values of mechanical properties.

Table 1 Duplex stainless steel 2205 chemical structure [11, 12]

Element	Duplex stainless steel 2205
Carbon	0.03%
Manganese	2.0%
Silicon	1.0%
Chromium	21 - 23%
Nickel	4.5 - 6.5%
Molybdenum	2.5 - 3.5%
Phosphor	0.03%
Nitrogen	0.08 - 0.2%
Sulphur	0.02%
Iron	uniformly

Table 2 Duplex stainless steel 2205 mechanical properties [12]

Material property	Value
Yield strength Re^h [N/mm^2]	450
Tensile strength Rm [N/mm^2]	620
Elongation ε [%]	25
Rockwell hardness [HRC]	31

The comparison of duplex stainless steels according to corrosion properties could be done by pitting index (PRE_N - Pitting Resistance Equivalent Number) calculation with next expression [3, 6, 10]:

$$PRE_N = \%Cr + 3.3 \times (\%Mo + 0.5 \times \%W) + 16 \times \%N \qquad (1)$$

There are three groups of duplex stainless steel regarding a pitting index as follows [3]:

- steels with $PRE_N < 30$ - lean steels,
- steels with $30 < PRE_N < 40$ - standard duplex steels and
- steels with $PRE_N > 40$ - super duplex steels.

Duplex stainless steel 2205 is grouped as standard duplex steel with $PRE_N = 35$ [9].

Regarding welding, it is necessary to point out that all conventional welding methods could be used for duplex stainless steel. A problem in duplex stainless steel welding is that visual control of welds is not appropriate because mistakes cannot be seen. Macrostructure analysis should be conducted. It is strongly recommended that all technological operations in the welding procedure should be done properly. The technological operations are material handling, joint preparation for welding, choice of filler material and shielding gas, preheating parameters, welding parameters, welded joint cleaning, afterward heat treatment and welded joint passivation conduction [4].

Quality weld of duplex stainless steel requires adequate welding parameters and an adequate level of heat input in the structure during the welding. If heat input is too small, the content of the ferrite will be increased in the material. Therefore, corrosion resistance and mechanical properties of the weld will decrease. Contrary, if a heat input is too high, intermetallic phases in the material could be raised [4, 8-10]. The welding parameters are prescribed according to the welding method. Choice of the shielding gas is very important because it influences the production efficiency, welded joint mechanical properties, corrosion resistance, welded joint appearance and geometry, arc ignition and stability. The filler material has to be alloyed more than the base material. The content of the nickel has to be 2-4% greater than the content of the nickel in a base material [9].

3. Duplex stainless steel welded joint corrosion resistance

In the experimental work, samples of butt and fillet joints most frequently used in shipbuilding as well as samples of stud welds used at regulating section joint in preassembly and assembly of ship hull were tested. Influence of welding on microstructure and quality of weld, heat affected zone (HAZ) and melting line were established. In addition, the effects of grinding, mechanical damage and repair on base materials properties were tested. Testing samples were plasma cut and ground before welding. Macro and micro structure assessment and pitting corrosion testing were conducted.

Material condition after welding in terms of uniformity, melting line and HAZ in the welded joint was assessed by macrostructural testing. The testing was conducted with Leica MZ6 stereomicroscope with 50x magnification. Critical points such as base material microstructure, HAZ and weld metal are additionally tested by microstructural testing.

Pitting corrosion testing is conducted according to ASTM G48 – test method A. The sample is immersed in 10% ferric chloride solution ($FeCl_3$) for 72 hours at room temperature or for 24 hours at increased temperature of 50±2 °C. After testing, the sample is rinsed with distilled water and visually controlled.

3.1 Butt welded joint corrosion resistance

Butt welded joint is made of metal sheet dimensions 300x125x13 mm. It is a V-joint with a 22.5° angle and 5 mm gap. The welding was conducted using gas shielded flux cored arc welding (FCAW) with Elga Sweden Cromacore DW 329AP 1.2 mm wire which corresponds to the base material. One-sided 4-pass welding on ceramic backing in vertical position was used as shown in Figure 4. Welding parameters are given in Table 3.

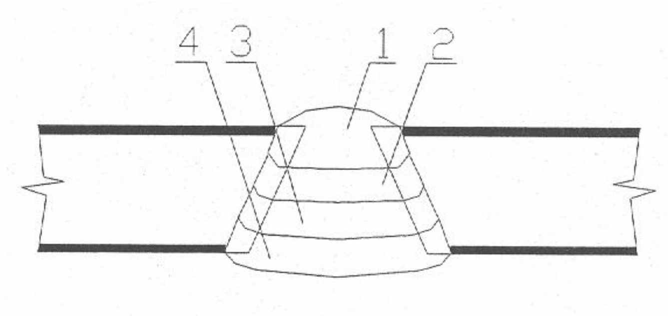


Fig. 4 Four passes butt welded joint

Table 3 Butt joint welding parameters

Weld number	Wire	Wire diameter [mm]	Voltage [V]	Current [A]	Wire speed [m/min]	Welding speed [cm/min]	Heat input [kJ/cm]
1.	DW329AP	1.2	24	145	4.5	12	13.9
2.	DW329AP	1.2	24	145	4.5	13	12.8
3.	DW329AP	1.2	24	145	4.5	13	12.8
4.	DW329AP	1.2	24	145	4.5	14	11.9

One part of the tested sample was mechanically damaged and subsequently repaired by welding, i.e. simulation of real damage occurrence during shipbuilding (Figures 5a and 5b).

Fig. 5a Mechanical damage of material surface

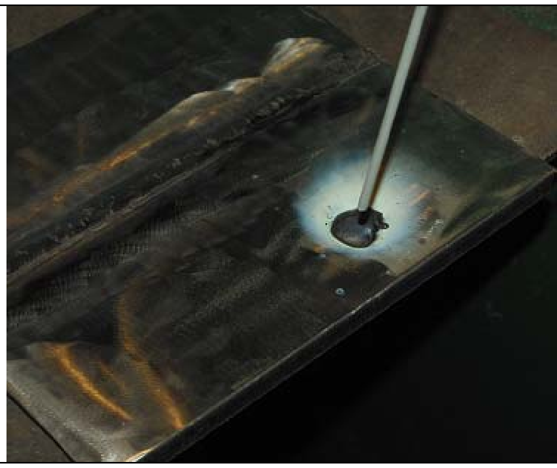


Fig. 5b Damage repair by welding

Samples in the form of strips cut out from the welded plate as shown in Figure 6 were used.

Fig. 6 Testing strips cutting scheme

After cutting, macrostructural testing was conducted first. An overview of melting line and HAZ width is shown in Figure 7. In weld metal, dendritic structure due to cooling and austenitic-ferritic structure crystallisation is visible. This results in ferritisation which negatively affects mechanical properties and leads to lower corrosion resistance. The ferritised section of the structure is the most critical part of the duplex welded joint.

Fig. 7 Macrostructure of the welded joint

Microstructural testing conducted at 7 different locations starting from weld metal, HAZ up to base material is shown in Figure 8. Face, centre and root of the weld metal were analysed at locations 1, 2 and 3, HAZ at locations 4, 5 and 6, and the base material at location 7.

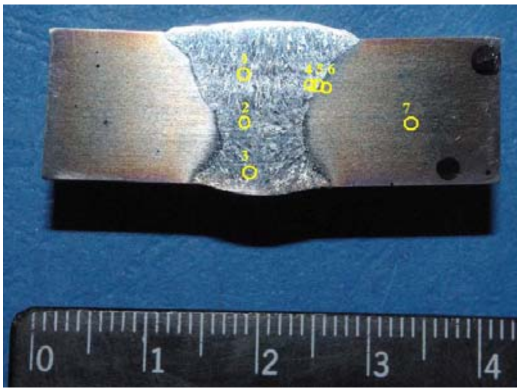


Fig. 8 Butt weld joint microstructural locations testing

Face and centre of the weld metal microstructure with the ferrite grain of irregular shape and regular orientation is shown in Figure 9. It was noticed that the appearance of ferrite grain is more frequent on the face of the weld metal rather than on the centre and root. Since the face of the weld metal is the last welding pass, it cools faster and this promotes the formation of ferrite microstructure.

Heat affected zone is characterised by highly irregular microstructure, whereas the base material features an equal austenite and ferrite structure typical for duplex stainless steels (Figure 9b).

Fig. 9a Microstructure of the weld metal centre, location 2

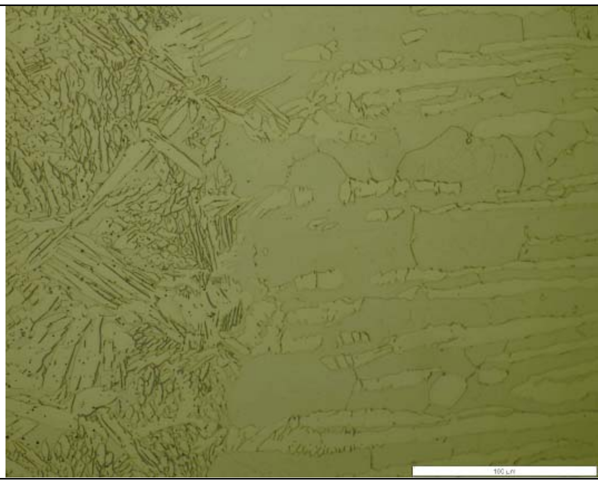


Fig. 9b Microstructure of the sample in the weld metal/HAZ area, location 5

For pitting corrosion resistance testing, three samples were cut from welded joint area and two from mechanically damaged and subsequently repaired area as shown in Figure 10. The weld samples were degreased and one half was pickled. This was followed by pitting corrosion resistance testing at room and elevated temperature.

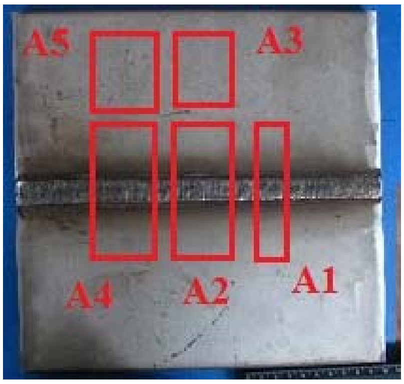
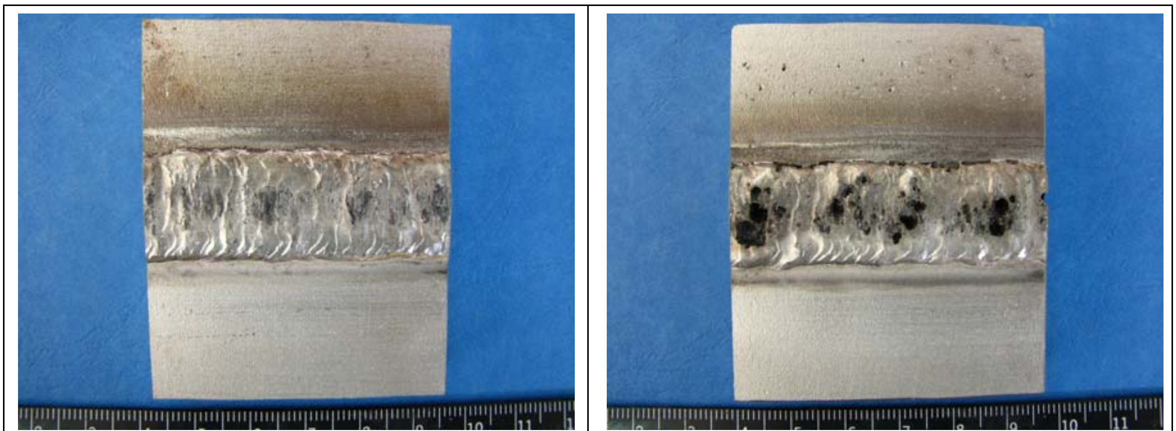


Fig. 10 Cut samples locations for pitting corrosion resistance testing

After testing at room temperature (Figure 11a), no corrosion was visible, whereas testing at elevated temperature gave significantly different results (Figure 11b). In fact, the chemical treated surface (lower part of the sample) showed no corrosion, compared to the upper and not treated part where pitting corrosion occurred. This leads to the conclusion that surface treatment – cleaning after welding must be performed to maintain corrosion resistance properties of duplex stainless steels, especially at elevated temperatures.



a) b)

Fig. 11 Samples after pitting corrosion testing; a) room temperature, b) elevated temperature

On the mechanically and subsequently repaired sample, which was not chemically treated, strong pitting corrosion occurred (Figure 12).

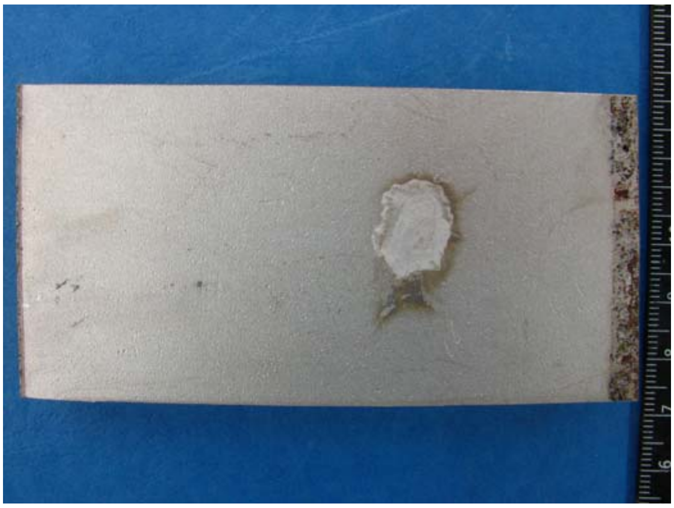


Fig. 12 Pitting corrosion on repaired part of the material – elevated temperature

3.2 Fillet welded joint corrosion resistance

As for the butt welded samples, welding of fillet joints was conducted using gas shielded (mixture of Ar and CO_2) flux cored arc welding (FCAW). Single-pass fillet joint is shown in Figure 13 and the welding parameters are given in Table 4.

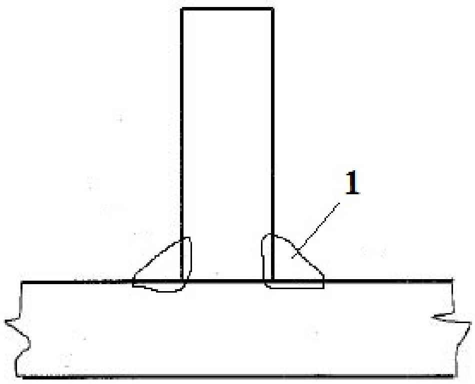


Fig. 13 Fillet joint scheme

Table 4 Fillet joint welding parameters

Weld number	Wire	Wire diameter [mm]	Voltage [V]	Current [A]	Wire speed [m/min]	Welding speed [cm/min]	Heat input [kJ/cm]
1.	DW329AP	1.2	26	190-200	8	23	10.5

Macrostructural testing from weld metal to base material were conducted for both sides of fillet joint. The observations are similar to those established in the case of butt welds, that is, in HAZ strong ferritisation occurs.

Microstructural testing was conducted according to the scheme shown in Figure 14. Six locations were analysed: location 1 at the weld metal, locations 2, 3 and 4 in HAZ specifically in weld metal to base material transition, and locations 5 and 6 on the base material.

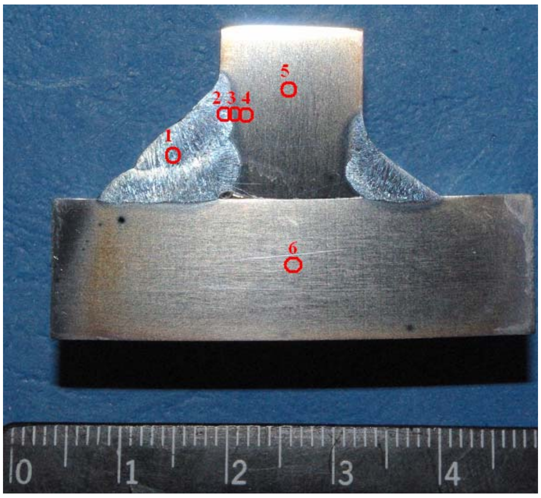


Fig. 14 Locations (1-6) for fillet joint microstructure testing

Microstructure at location 1 in weld metal is irregular but with regularly orientated grains which lack the shape of the base material. It was expected that weld structure would be similar to base material because the welding wire corresponds to the base material chemical properties. However, welding and heat input changed its structure. Microstructural images in HAZ show the appearance of ferritisation (like in butt welded joint) which make this part of the welded joint the most critical. Moving towards the base material in locations 2, 3, 4, the grains assume a more regular and oriented shape, that is, a characteristic structure of duplex stainless steel.

The fillet joint samples were tested against pitting corrosion too. Only left side of the fillet weld joint was chemically treated (pickled). Samples exposed to ferric chloride solution at room temperature did not corrode. However, samples not chemically treated and exposed to elevated temperature testing show significant corrosion appearance as shown in Figure 15. Similar testing results were obtained for butt welded joint and the conclusion is the same. The surface treatment – cleaning after welding must be performed to maintain corrosion resistance properties of duplex stainless steels, especially at elevated temperatures.

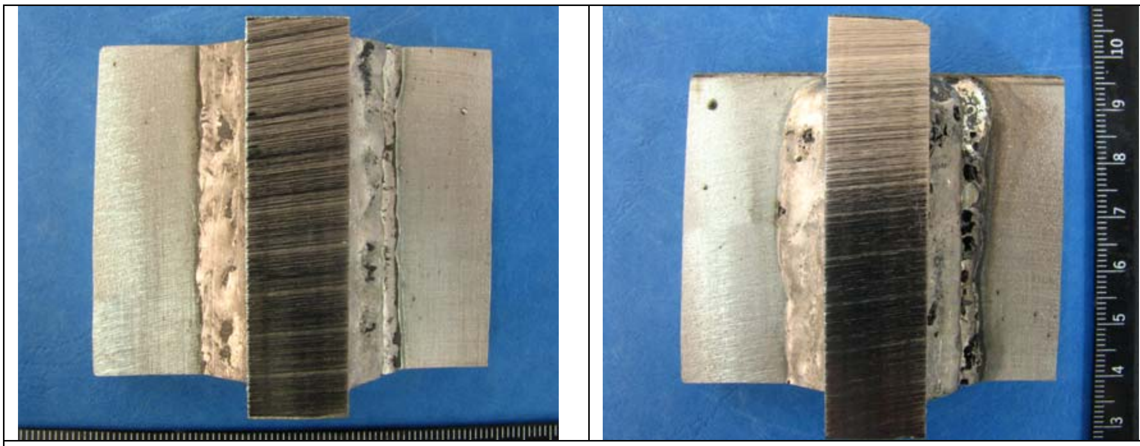


Fig. 15 Pitting corrosion testing samples (left – room temperature, right – elevated temperature)

3.3 Welded stud corrosion resistance

In shipbuilding, studs are used in the reassembly and hull assembly stages in section joints regulation to bring the joint in the required position thus enabling quality welding. Drawn arc stud welding is usually used as in this experiment. The arc melts the end of the weld stud and the base material below. The arc shield (ferrule) concentrates the heat below the weld stud and contains the molten metal within the weld zone (Figure 16).

Fig. 16 Drawn arc stud welding

Testing sample is made of duplex stainless steel base material on which the austenitic stainless steel stud is welded. By macrostructural analysis the sample was tested as shown in Figure 17. The appearance of ferritisation in HAZ is observed.

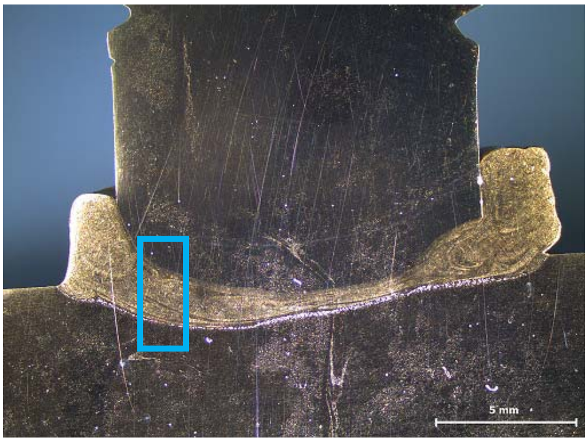


Fig. 17 Stud macrostructural testing area

Microstructural analysis was conducted in the following locations: stud, base material and melting lines. On the base material/weld metal, melting line ferritisation appeared showing a possible weaker corrosion resistance. Microstructural testing of both stud and base material did not show any changes. The microstructure appearance is as expected.

Pitting corrosion testing was conducted after removing the stud form the base material, where one sample was chemically treated and the other not. The samples were tested in ferric chloride solution for 72 hours at elevated temperature of 50 °C. Both samples showed strong pitting corrosion as shown in Figure 18. It can be concluded that welding resulted in significant heat input which irreversibly damaged material structure at the surface.

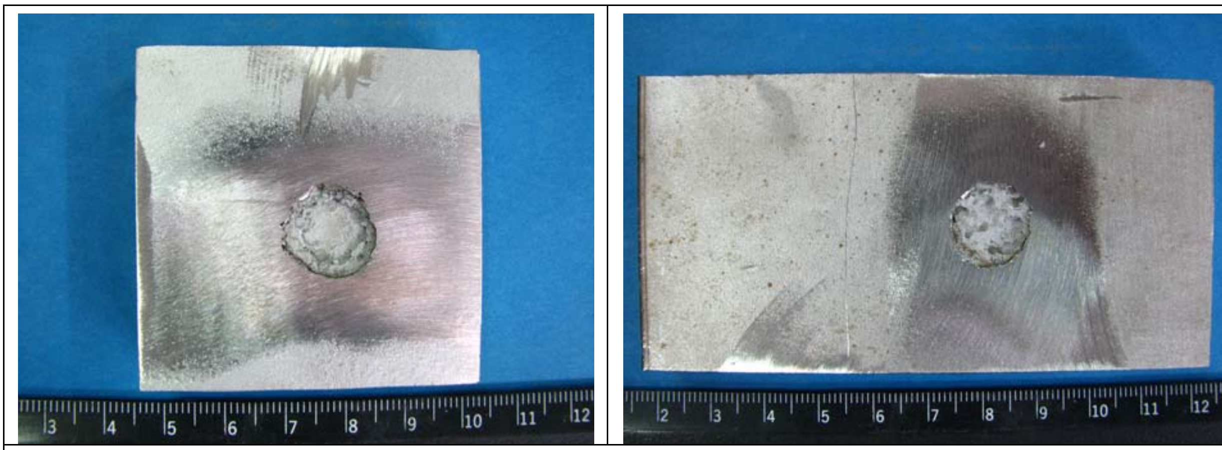


Fig. 18 Strong corrosion damage at stud welding location

4. Recommendations for duplex stainless steel application in shipbuilding

After the experimental research was done, results are used for the recommendations for duplex stainless steel application in all stages of the shipbuilding production process. At the beginning of the production process in the stage of material storing, it is necessary to separate duplex stainless steel from mild steel or high tensile steel. Besides that, duplex stainless steel plates and bars have to be transported carefully without mechanical damages of the material. A mechanical damage destroys passive film on the duplex stainless steel surface and the material becomes prone to corrosion.

The recommendations for duplex stainless steel welding are as follows:

- a welding method with a lower current intensity should be used; this results in low heat input in the structure. A high level of heat input in the material causes ferritisation in the melting line and in the heat affected zone (HAZ) which than become the weak points of the welded joint.
- a filler material should be chosen in accordance with the base metal. The filler material for duplex stainless steel welding has to have a nickel content 2-4% greater than the base metal and nitrogen content slightly lower than the content in the base metal.
- the maximum interpass temperature should be lower than 150 °C.
- after welding, welded joints have to be grinded with hand tools for duplex stainless steel application. Grinding has to be done carefully because mechanical damages caused by grinding have an adverse effect on material corrosion resistance.
- one side welding with ceramic pad is recommended in order to obtain a quality root weld.
- it is necessary to conduct chemical cleaning and passivation of the welded surface after welding with a view to increase corrosion resistance.

The recommendations for proper application of duplex stainless steel in subassembly and hull assembly stage related to welding procedure of the studs used for section joint regulations are as follows:

- material of the studs have to be chosen depending on the base metal,
- studs have to be welded on the outer side of the cargo tank and the welding area needs to be chemically treated and painted after stud grinding.

5. Conclusion

Shipyards in Croatia are oriented towards building sophisticated ships often made of or containing special materials such as duplex stainless steels and this requires good preparation and a higher level of knowledge. This experimental work was done in collaboration with one of the shipyards for a potential job offer for the construction of a duplex stainless steel vessel. The results from this study served for preparing work guidelines. Work with duplex stainless steel demands adequate handling and strict observance of all technological instructions in order to maintain passive chromium oxide Cr_2O_3 film on the surface and a stable two phase structure. Negative influence of mechanical damage and welding on material corrosion resistance was demonstrated. As a result, welding methods with low heat input are recommended. A two phase (austenitic - ferritic) structure is sensitive to higher temperature changes and consequent appearance of ferritisation in the welded joint.

Welded joints have to be cleaned in order to remove thermal oxides (heat tints) incurred by welding and passivated to decrease the possibility of pitting corrosion occurrence.

Special attention should be given to stud welding, because of determined corrosion problems in the weld area. It is necessary to make a correct choice of the stud material and proper welding parameters as well as to conduct surface treatment after stud removal.

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