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Corrosion Resistance of TIG Welded Joints of Stainless Steels  
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**Abstract.** The aim of this work was to analyze the performance of joints made by TIG (Tungsten Inert Gas) welding process in austenitic and duplex stainless steels with special regards to their corrosion resistance. Three different types of stainless steel were butt welded with TIG method. Ferric-chloride test and electrochemical treatments revealed how does the TIG process affects the corrosion resistance depending upon the alloy used for welding the joint. This work focuses on the weldability of the 2304, 2404 and 304 type stainless steel heterogeneous welds.

## Introduction

Stainless steels are an important class of engineering materials that have been used in a variety of industries and environments due to their high corrosion, oxidation and fatigue resistance in corrosive media as well as their good resistance against stress corrosion cracking. They are alloyed with at least 12% chromium and become corrosion resistant by formation of a passive film on the surface. The austenitic, ferritic and ferritic-austenitic (duplex) groups are the most commonly used in several industrial areas such as steam-power generation, automotive engineering, biotechnological, chemical, transportation, nuclear and aerospace industries [1].

The austenitic group of steels includes the most widely used stainless chromium-nickel steels. They are general-purpose grades with good resistance against atmospheric corrosion and too many organic and inorganic chemicals. They are suitable for processing, storing and transporting foodstuffs and beverages. This, together with their good formability and varied surface treatments providing wide range of functional and aesthetic surfaces, makes them suitable for use in a large-scale of applications [2]. The ferritic-austenitic stainless steel group, also referred to as duplex stainless steels, combines many of the beneficial properties of ferritic and austenitic steels [3]. Duplex stainless steels can be very attractive alternatives to austenitic grades due to their almost double strength while their pitting corrosion resistance is, at least, at the same level or even better.

Inert gas shielded, tungsten arc (TIG) welding is an essential part for developing and commercializing duplex stainless steels. It is important to show that they have good weldability and corrosion resistance, however at the same time it is also important to be aware of their limitations [4].

## Experimental procedure – TIG welding

Three different grades of stainless steel were butt welded using tungsten inert gas method. Two of the used materials were duplex (X2CrNiMnMoCuN24-4-3-2, marked at Outokumpu Stainless AB as LDX 2404 and X2CrNiN23-4, marked 2304) and the third one was austenitic grade: X5CrNi18-10, marked as AISI 304. The corrosion resistance of heterogeneous joints constituted by the austenitic and one of the duplex grades were also investigated.

The materials were welded using a single-sided square butt joint, where the two opposite surfaces were flat and parallel to each other. The plates that had been used for making welded couples (304-304, 2304-2304, 2404-2404 and one heterogeneous 304-2404) are shown in Table. The used filler material was E309L type for the duplex and heterogeneous weld and E308L for the austenitic couple. In this condition, current is conducted through plasma, partially by ions and electrons which are mainly emitted by the tungsten cathode [5].

Table 1 Welding process parameters.

Sample		Current (A)	Welding speed (mm/s)	Grade 1	Grade 2	Shielding gas	Flow rate (L/mm)
T 1	2304	75	1,46	2304	2304	Ar	6
T 2	2404	75	1,46	2404	2404	Ar	6
T 3	304	90	3,33	304	304	Ar	6
T 4	2404-304	85	1,46	304	2404	Ar	6

### Microstructural investigation

Transverse sections of welds were examined by metallographic method with the aim of determining the general microstructure of the weld metal and heat affected zones (henceforward HAZ). Metallographic preparation included cutting transverse sections through the welds, followed by grinding and polishing up to 0.05  $\mu\text{m}$  alumina and silica powders. Microstructural features of the different regions of weldments were characterized by conventional metallographic practices using appropriate etchants for the respective areas. Kalling'2 reagent, composed from 100 ml ethanol ( $\text{C}_2\text{H}_6\text{O}$ ), 100 ml hydrochloric acid ( $\text{HCl}$ ) and 5 mg cupric chloride ( $\text{CuCl}_2$ ), attacks ferrite and slightly affects austenite.

The different welding zone of austenitic steel could be studied well after etching with Kalling'2 reagent to 1-2 minutes. Beraha-type etchant for duplex stainless steels is composed from 85 ml water, 15 ml  $\text{HCl}$ , 1 g  $\text{K}_2\text{S}_2\text{O}_5$  (potassium pyrosulfite) and it had to be mixed fresh. This was used by immersion until the surface faded. The ferrite changed its color but it did not happen to austenite. Beraha reagent was used to enable a quantitative analysis of the microstructure consistence because it provides a sufficiently high contrast of the ferrite and austenite. The microstructure and phases in the weld metal were analyzed by optical and stereo microscopy.

### Optical microscopic investigation

Characteristic zones of 304 type austenitic steel's weldment are presented in Fig 1. a-c. In the heat affected zone the grain size increased, near to the fusion line ferrite segregation is to be seen in its original rolling direction. The weld metal is homogenous.

The welding of austenitic and duplex 2404 type duplex grade results a sophisticated weldment. In case of this heterogeneous joint, ferrite appeared between austenite arms in the weld metal (Fig. 1. d, e, f). In the HAZ of the sample equiaxed grains are visible at each side, but in the HAZ of duplex steel grain size is higher than 100  $\mu\text{m}$ , and the ferrite content is significantly increased. In the austenitic HAZ, near to the fusion zone, no segregation can be observed and the grains are fine (Fig. 1. f).

In the HAZ of the 2404 type duplex steel equiaxed grains can be seen. There are acicular austenite at the boundary of large ferrite grains. In the weld metal the ferrite content increased as well (Fig. 1. g, h, i).

The weldment of 2304 type steel differs from that of 2404 type steel. Similarly, the grain size in the HAZ is higher than in the base material, which means that a recrystallization process could take place because of the welding heat cycle, but the secondary austenite precipitates at the ferrite grain boundaries were thinner compared to the 2404 type steel. In the weld metal thin austenitic grain boundaries and thin Widmanstätten-like austenite within the ferrite grains present as shown in Fig. 1. j, k, l.



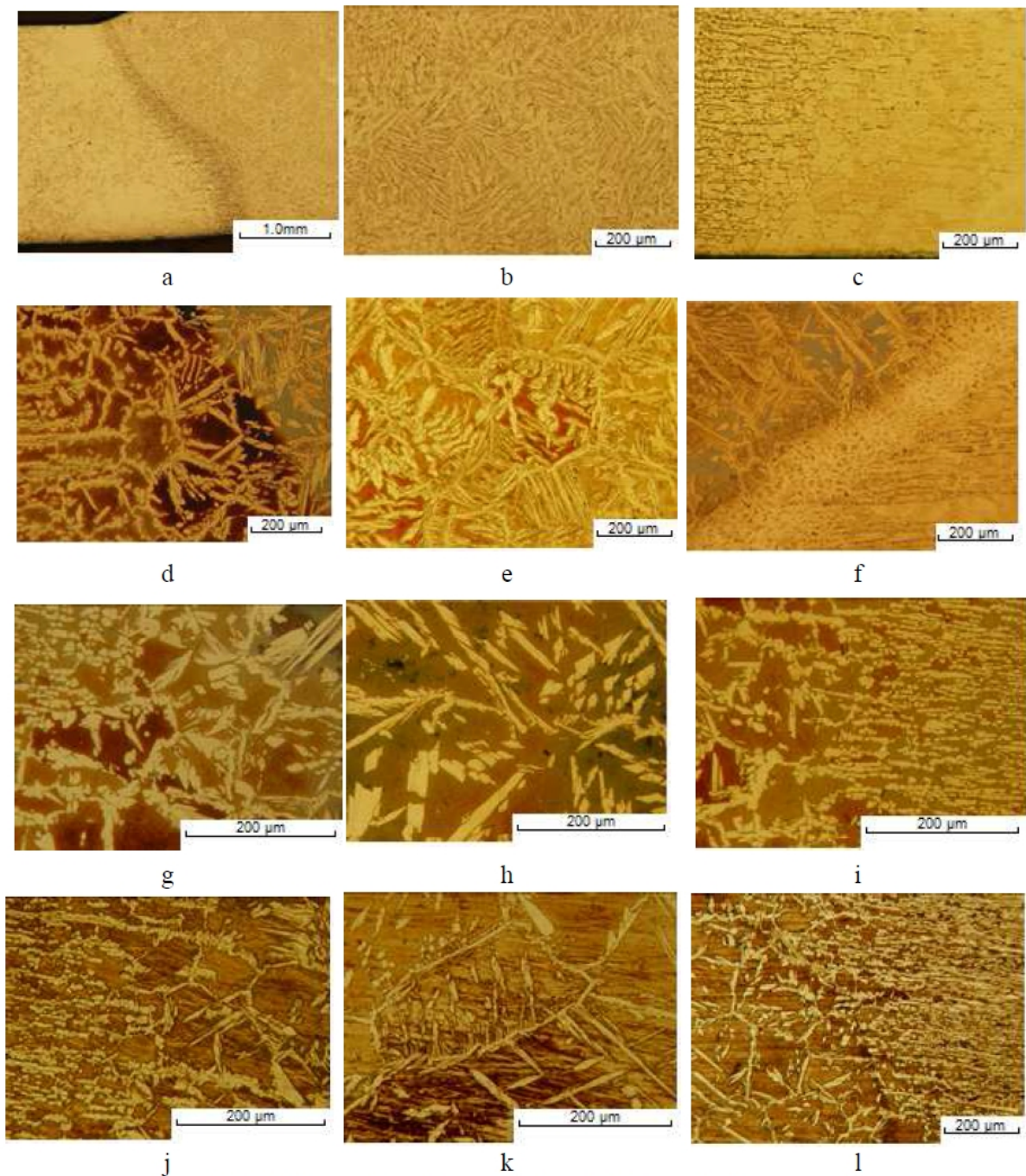


Fig.1 Micrographs of the most characteristic welding zones

- a) HAZ of 304 steel at left side, 25×; b) 304 weld metal, 100×; c) HAZ of 304 steel at right side, 100×; d) HAZ of heterogeneous weldment at 2404 steel side, 100×; e) weld metal at heterogeneous weldment, 100×; f) HAZ of heterogeneous weldment at 304 steel side 100×; g) HAZ of 2404 steel at left side, 200×; h) HAZ of 2404 steel after Beraha, 200×; i) HAZ of 2404 steel after Kalling, 200×; j) HAZ of 2304 steel at left side, 200×; k) weld metal of 2304 steel at left side 200×; l) HAZ of 2304 steel at right side, 100×.

### Ferric chloride pitting corrosion test

After the welding processes, formation of oxides could be observed on the weld beads. In order to promote good performance of the tests, a pickling treatment of the specimens was performed with pickling paste to remove heat tinted layers from the surface of stainless steel joints.

A suitable cut-off wheel was used with water-cooling to avoid any change in the metallurgical structure of the materials and then the joints were clamped mechanically in samples the dimensions of 10×25 mm. The samples were put separately into glasses which contained 100 g of ferric chloride hexahydrate ( $\text{FeCl}_3 \times 6\text{H}_2\text{O}$ ) in 900 ml of distilled water, according to ASTM G48 (The “A” practice Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys). The results may be used for ranking alloys in order of increasing resistance to pitting and crevice corrosion initiation under specific conditions of these methods [6].

The changes endured by the samples were monitored at intervals of 24, 48 and 72 hours. During the experimental time, the weight changing was measured and photos were taken of the welded surface using stereo microscope Olympus SZX16. The results of the weight measurements are shown in Table 2 below.

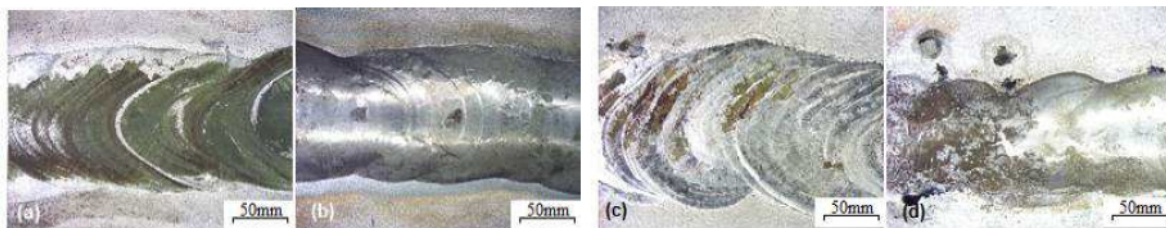
Table 2 Weight changes and mass loss in each time interval.

TIG weld	Sample	Initial (g)	24 hours	48 hours	72 hours	Mass loss ( $\text{g}/\text{cm}^2$ )
T1	1	10.3854	10.3795	10.3756	10.3678	0,00282
	2	11.0234	11.0177	11.0105	11.0086	0,00237
T2	1	15.0598	14.9485	14.8853	14.8767	0,02929
	2	13.9944	13.8730	13.7639	13.6982	0,04739
T3	1	12.9670	12.8257	12.7510	12.7189	0,04962
	2	30.6418	30.3202	30.1615	30.1282	0,03735
T4	1	10.5113	10.3232	10.1841	10.0103	0,08016
	2	11.8114	11.6159	11.4386	11.1981	0,09813
	3	19.0882	18.6286	18.4479	18.2835	0,12875

Among the duplex steels, the 2304 type lost the least mass. Furthermore, it can be seen that the heterogeneous weld showed a significant weight loss, which implies that it has a higher tendency for localized corrosion. This data shows that the parameters used for welding must be carefully defined for this special type of joint in order to increase or keep corrosion resistance.

### Stereo microscopic investigation

The heat affected zone was not damaged at the face of the 2404 steel (Fig. 2. a). In the root of the 2404, a good performance appeared after 72 hour (Fig. 2. b). On the face of 2304 a hole appeared in the HAZ (Fig. 2 c), although in the root number of pits was higher in the HAZ (Fig. 2. d). In Fig. 2 e, f few holes can be seen in the weldment of 304 type steel. The presence of pits was considerable in heterogeneous weld even both in the face and in the root (Fig. 2. g, h).





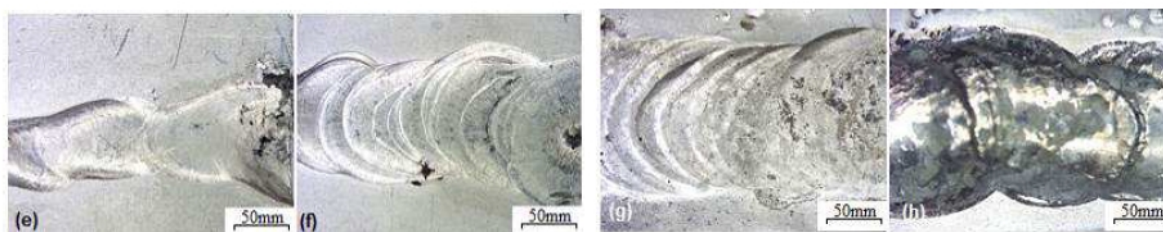


Fig. 2 Stereo micrographs after 72 h pitting corrosion test at TIG welded joints. a) steel 2404 face; b) steel 2404 root; c) steel 2304 face; d) steel 2304 root; e) steel 304 root; f) steel 304 face; g) heterogeneous weld metal face; h) heterogeneous weld metal root.

### Electrochemical corrosion test

The corrosion tests were performed by using Zahner IM6e potentiostat (Zahner, Germany). During the electrochemical measurements we used conventional three-electrode cell in which the working electrode was the welded sample. Platinum net and Ag/AgCl/KCl<sub>sat</sub> electrodes were used as counter electrode and reference electrode, respectively. The potentiodynamic polarization curves were recorded with 5 mV/s scanning rate. A 0.5 M NaCl solution was used as an electrolyte for all the electrochemical experiments.

The welded couples were painted around the welded surface with lacquer in order to ensure that only the welded contacts get in contact with the electrolyte solution. The corrosion currents and corrosion potentials of samples can be drawn from the Tafel curves (Fig. 3). It is visible that the most negative corrosion potential ( $E_{\text{corr}}$ ) and highest corrosion current density ( $j_{\text{corr}}$ ) belong to sample 2404, -217 mV and 10 mA/cm<sup>2</sup>, respectively. On the other hand, sample 2304 has the lowest corrosion current density, 790  $\mu\text{A}/\text{cm}^2$ , which can refer to its highest corrosion resistance. According to the shapes of the curves recorded on welded joints, the cathodic branch of Tafel curves implies kinetic control of cathodic reaction while the anodic branches refer mainly to mixed kinetic and diffusion controlled processes for anodic dissolution.

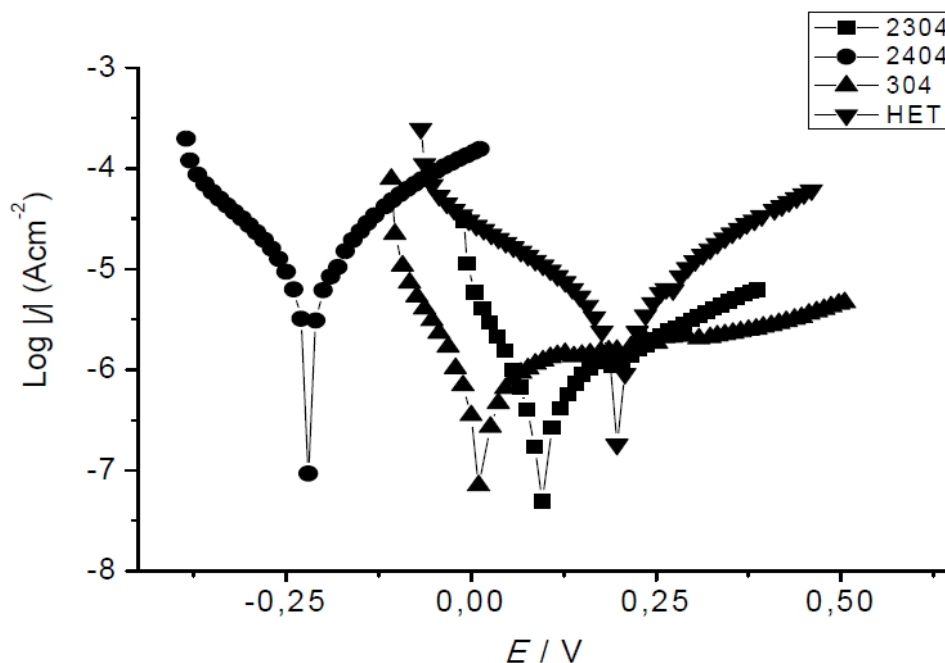


Fig. 3 Potentiodynamic curves recorded on different TIG welded samples after 72 hours of immersion in 0.5 M NaCl solution. The applied potential scanning rate is 5 mV/s.

It is generally considered that the development of passivity in iron-chromium alloys occurs virtually as a step change as chromium level is increased: below some 10% Cr, the material remains active in normal aqueous media, while above 12% Cr, a passive film develops and corrosion rate is greatly decreased. While this is essentially true, the influence of the environment must be clearly recognized in terms of redox potential and content of specific anions such as chlorides [7].

When 2404 type duplex steel is combined with 304 stainless steel, there is the possibility of a galvanic (dissimilar metal) reaction when the couple is exposed to the oral environment [8]. An important factor in galvanic corrosion is the effect of the ratio of the cathodic and anodic areas. An unfavorable area ratio consists of a large cathode and a small anode. For a given current flow in the galvanic cell, a smaller anode results in a greater current density and hence has a greater corrosion rate.

## Conclusion

The TIG welding process allows a high degree of control and low oxygen content in the weld metal, which results in excellent notch toughness characteristics. Otherwise TIG welding with argon as shielding gas results in a loss of nitrogen from the weld pool. This resulted in a ferrite rich weld metal with poor corrosion properties.

Compared to the base metals the ferrite content of duplex steels was relatively higher in both weld metals and HAZs. The highest amount of ferrite appeared in the heat affected zone of the 2304 type material which was the most sensitive to pitting corrosion, but regarding the weld metal, this type of steel showed the best corrosion resistance in electrochemical test, and similarly, the least mass loss was measured at these samples.

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