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Ph.D. THESIS *Summary*

CORROSION RESISTANCE FOR WELDED
JOINTS WHICH ARE MADE OF 304 AND 316L AUSTENITIC
STAINLESS STEEL

REZISTENȚA LA COROZIUNE A ÎMBINĂRILOR
SUDATE REALIZATE DIN OȚELURI INOXIDABILE
AUSTENITICE 304 ȘI 316L

Author: Ing. Alaa Abou Harb

Coordinator: Prof. Dr. Ing. Ion Ciucă

COMISIA DE DOCTORAT

President	Prof. Univ. Habil. Dr. Ing. Antoniac Vasile Iulian	From	University POLITEHNICA of Bucharest
PhD Coordinator	Prof. Univ. Dr. Ing. Ciucă Ion	From	University POLITEHNICA of Bucharest
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INTRODUCTION

The page of Acknowledgments expressed on the author's gratitude to those who contributed, to the moral support, to carry out the finalization of the doctoral thesis.

The Introduction presented the problems of corrosion for austenitic stainless steel, the objectives of the doctoral thesis and its general presentation.

The choice of the topic is emerged from the need for the continuous completion of the data regarding for 304 and 316L austenitic stainless steels, in terms of the structures and properties of these steels influenced with the welding procedures, as well as in the electrochemical corrosion behavior of the different types of welding in chlorinated environments.

The doctoral thesis is divided into seven chapters and is organized into two parts: theoretical study and experimental research.

The first part of the doctoral thesis is entitled "**General notions on the corrosion of austenitic stainless steels alloys**", and included an extensive study for this class of metallic materials. it consisted of three chapters, as follow:

The first chapter is entitled "**Overview of corrosion, its types, and protection from it**". This chapter presents the main corrosion phenomena which specified to stainless steels, it makes a classification of the corrosion forms, the methods of measuring the corrosion speed and the methods of corrosion protection such as, the control of corrosion by coating methods for the surfaces, as well anodic and cathodic protection.

The second chapter is entitled "**Welding for 304 & 316L austenitic stainless steel, its types and its effect on corrosion**". In a correct and concise graphic presentation, seven types of welding are presented briefly. As well as the influence of various factors on weldability for alloys 304 and 316L.

The third chapter is entitled "**Stress corrosion cracking behavior for welded stainless steel**". After presenting the factors that can determine the stress corrosion cracking, the main corrosive media (halides media, ambient temperature media, high-temperature high-pressure aqueous media, sulfur media and caustic media) are presented, as well as the main factors that effect on SCC (chemical composition, grain boundaries, hydrogen and the residual stresses).

The second part of this Ph.D. thesis is entitled "Experiments, studies, analyses, results, results interpretation, conclusions and results dissemination.

The fourth chapter is entitled "**A study of the effects of some types of welding on the mechanical properties for 304 and 316L austenitic stainless-steel sheets**". The experimental program of these investigations, the types of material, mechanical tensile test, Welding test and hardness test are presented, as well as comparative results on the tensile and hardness tests. Here, it should be referred to the appropriate way of presenting the results, which allowed making relevant conclusions with the mechanical behavior of welded joints.

The fifth chapter is entitled "**A study of the effect of tig welding on the corrosion behavior for alloys 304 and 316L sheets in chlorine solutions**". as in the previous chapter, the research material and methodology used in these investigations are presented both separately and comparatively. Corrosion behavior in chlorinated solutions of the different areas of 304 and 316L austenitic stainless steel are investigated by using AUTOLAB Potentiostat/ Galvanostat.

The sixth chapter is entitled "**A study of the effect of welding on the corrosion behavior for u- bend samples of 316L and 304 stainless steel in saline solution**". Similar to the previous chapter, the research material and methodology used in these investigations are presented both separately and comparatively, the results of corrosion testing tested by using a PARSTAT 4000 model Potentiostat/ Galvanostat, with the measurement of the corrosion potential variation over

time, as well as by building potential curves - current density. By the type of steel, test and welding conditions, and comparative, the results presented, which facilitates the highlighting of the corrosion resistance status in detail. Also, the observations regarding the resistance to the electrochemical corrosion are complemented by the investigation at the SEM and stereomicroscope. The investigations are completed with 3D images, which facilitate highlighting the most representative topographic aspects of the corroded surfaces.

The third part consists of the **seventh chapter**, that is intended for the conclusions of experimental research. The Chapter ends with the formulation of future research directions.

The bibliography consulted includes reference works from the Romanian and the foreign studied fields.

The annexes refer to the list of figures and the list of tables.

PART I: THEORETICAL STUDY

CHAPTER 1

1 OVERVIEW OF CORROSION, ITS TYPES, AND PROTECTION FROM IT

1.1. OVERVIEW OF CORROSION

It is known for the industrialists that equipment does not remain the same when it is entering manufacturing processes. It may be exposed to degradation over time, which may take hours, minutes, or even seconds depending on the applying conditions, if they were not studied carefully.

In general, latest studies show that corrosion is the most important problem facing the global public and industrial sectors.

It is a degradation of a metal by electrochemical changes that occur with the existence the surrounding environment which helps the occurrence of the corrosion, all of that leads to a change in the mechanical properties of metal.

This economic report confirms that by controlling the corrosion well, we can save up to 35% of the cost of corrosion, the equivalent of 875\$ billion. [2]

Figure 1.1 indicates to the chart of the global cost of corrosion in the entire world, we notice that the higher ratio of cost of corrosion is in the USA, European region and China. Contrary observations apply in Japan that has a lower ratio.

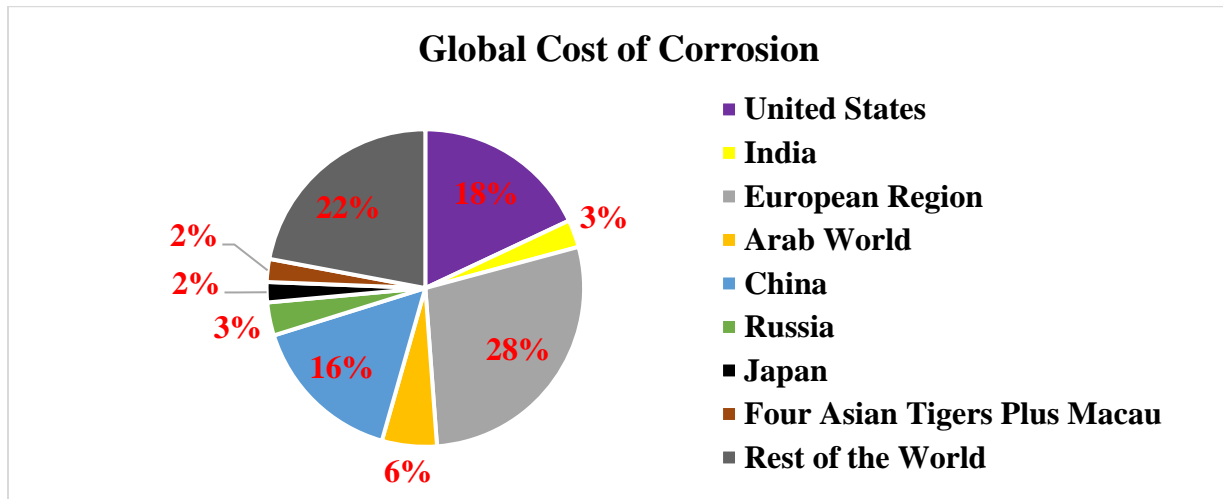


Fig. 2.1 The global cost of corrosion

1.2. CORROSION OF STAINLESS STEELS

The latest studies show that stainless steel is characterized by corrosion resistance, but is not immune from the occurrence of corrosion, and this depends on the environments and their specifications (the chemical composition of the corrosion environments and the specifications of elements which are present in them).

So, corrosion of stainless steels can be divided into corrosion in wet environments (aqueous corrosion) and corrosion in high-temperature (gaseous corrosion). [1]

Corrosion usually begins on the stages which can be shortened by the following steps:

1. Interaction between the base metal and the corrosive environment.
2. Growth of oxidation layer and its penetration in the base metal. [4]

1.3. TYPES OF THE CORROSION

The latest studies indicate that the corrosion is caused by the interaction between the base metal and the environment surrounding it, therefore there are many types of corrosion which refer to the form of corrosion, and these multiple types lead to different forms of deterioration in the mechanical properties of the base metal. [5]

There are several types of corrosion as a result of oxidation.

1.3.1. According to the corrosion environment

According to that, corrosion can be divided into two types: dry and wet. Therefore, it is necessary to have a liquid or moisture to corrosion of the wet type, the example that is common to this type is the corrosion of stainless steel in the water.

In contrast, the dry type does not require the presence of liquids or moisture. Typically, it occurs at high temperatures, as what happens in some chimneys. [4]

1.3.2. According to the mechanism of corrosion

Corrosion is divided into two types:

- Chemical corrosion: the destruction of the metal happens as a result of direct interaction with the surrounding environment that is not an electrolyte.

- Electrochemical corrosion: it happens in the electrolyte environment that surrounds the whole metal or partially, and that is as a result of electrochemical reactions on the surface of the metal. [4]

1.3.3. According to the appearance of metal corrosion:

Corrosion is divided into two types:

- Uniform corrosion: The corrosion rate is equal in the metal surface as a whole.

- Localized corrosion: Corrosion is concentrated in specific areas for the metal. [4]

1.4. FORM OF CORROSION

The latest studies show that metal structures corrode in different ways, and that depends on the properties of the metal, the environment of corrosion and working conditions (variations in temperature, contact with another metal, the existence of oxygen and vibrations). So, we can choose the main types of corrosion which benefit us to know the form of corrosion that can occur for the stainless steel which can be as follows: Uniform corrosion; Galvanic corrosion; Crevice corrosion; Pitting corrosion; Stress corrosion cracking; Intergranular corrosion.

1.5. CORROSION CONTROL

There are numerous ways to control and impede corrosion, but for one special practical process, there are only some specific ways in which they can be applied. Therefore, the first thing that an engineer has to do is to identify all the ways in which they can give better results concerning reducing the rate of corrosion, and taking into account the economic angle. [15]

The most common ways of impeding the corrosion are:

1. Consideration of the proper engineering design and abide by the rules;
2. Controlling corrosion by coating;
3. Confronting corrosion by cathodic and anodic protection;
4. Facing corrosion by using corrosion inhibitors.

CHAPTER 2

2 WELDING FOR 304 & 316L AUSTENITIC STAINLESS STEEL, ITS TYPES, AND ITS EFFECT ON CORROSION

2.1. WELDING PROCESSING FOR ALLOYS 304 AND 316L AUSTENITIC STAINLESS STEEL

Reference studies show the presence of two methods for welding stainless steel. The first one is fusion welding and the second one is resistance welding. However, the most common method is fusion welding between the electrode welding and the piece to be welded.

Through generating an electrical arc with a high voltage, fusion welding is divided into several types, every type is different from the other in the way it generates the electrical arc.

Those types are: Shielded metal arc welding (SMAW) ;Gas tungsten arc welding (GTAW) or (TIG); Gas metal arc welding (GMAW) or MIG/ MAG welding; Submerged arc welding (SAW); Plasma arc welding (PAW); Electron beam welding (EW); Laser beam welding (LW).

2.2. THE INFLUENCE OF VARIOUS FACTORS ON WELDABILITY FOR ALLOYS 304 AND 316L

2.2.1. The effect of alloying components

Based on the studies that have worked in this field, we note the existence of two types of elements that form the ferrite (such as chromium, molybdenum, silicon, and niobium), or that form the austenite (such as nickel, manganese, carbon, and nitrogen), according to the temperature changes.

The effects of these elements on the nature of the welding zone can be great as shown in previous studies. [30]

2.2.2. Effect of elements in the weld zone

The latest studies show that the most important element in the welding stainless steel is chromium, which tends to union with oxygen and carbon, so it has to be taken into account during the welding of stainless steel.

As for the other elements also effect on the properties of steel welded, oxygen in the air binds with the molten metal to form a thick layer of oxide.

Carbon interacts with chromium and that can lead to carburization. This process reduces the corrosion resistance in welded metal. Hydrogen Causes porosity in the welding zone, while copper and lead can lead to brittleness in the basic metal. [37]

2.2.3. Effect of alloying elements

Studies reveal that the steel consists of alloying elements which are aluminum, silicon, sulfur, phosphorus, selenium, nickel, manganese and molybdenum; they cause effects on the base metal. for example, the presence of silicon leads the metal to melt and make it more flow. Sulfur, phosphorus, and selenium added to steel to improve the mechanical properties but that leads to the decreasing of weldability and increasing the porosity. [37]

2.2.4. Effect of alloying elements on weld structure

The latest studies show that it is possible to control the structure of stainless steel through the basic components of the elements of alloys which are used in the alloy they help to stabilize the austenite, which is important to maintain the strength of the metal after welding. The elements that help to stable austenite such as chromium, molybdenum and nickel, carbon, nitrogen, and manganese. [37]

2.2.5. Welding properties of 304 and 316L

Latest studies show that during the welding of stainless steel, the temperature of the metal take levels that affects to the crystal structure near the welding zone of the elements, all of which affect the final shape of welding, mechanical properties and corrosion resistance which relies on a range of factors, including the alloy content, thickness, and metal fillers, etc.

But there are three main zones that determine the welding zone: The region containing the weld metal and basic metal, heat-affected zone, and the area affected or not by the heat from the base material. [37]

CHAPTER 3

3 STRESS CORROSION CRACKING BEHAVIOR FOR WELDED STAINLESS STEEL

3.1. ENVIRONMENTS AFFECTING STRESS CORROSION CRACKING

Environments causing stress corrosion cracking of austenitic stainless steels are divided into many types that are detailed below:

- Environment of halide;
- Ambient temperature environments;
- High-temperature high-pressure aqueous environments;
- Environment of sulfide;
- Environment of caustic.

3.1.1. Environment of halides

The latest studies showed that halides are the most affecting environments for materials causing SCC corrosion. Ions of chloride are the most effective ions compared with ions of bromide, fluoride, and iodide.

Chloride ions cause transgranular stress corrosion cracking; one study showed that SCC occurs for 316 and 304 stainless steel in solution 55% lithium bromide at (120 °C – 140 °C) in 388 h at a PH values of 6 up to 8, tested at high applied load of 426 MPa, but showed less SCC when a PH of 11.6. [60]

Studies have shown that use boiling solutions can be used to test the susceptibility to SCC, e.g. Magnesium chloride, sodium chloride, and calcium chloride.

The most aggressive solutions are magnesium chloride and calcium chloride compared with sodium chloride, therefore the rate of cracks growth in boiling 22% chloride solution for type 304/304L stainless steels was 10-8 m/s. [61]

In our experimental study, we will use bending tests to determine SCC for 304 and 316L austenitic stainless steel in halides solution.

3.1.2. Ambient temperature environments

One of the most aggressive environments in ambient temperature is the coastal environment causing transgranular SCC. [62][63]

Type 304L stainless steel is undergone SCC in an aqueous solution at room temperature overnight.

The latest studies have shown that austenitic stainless steels underwent SCC in hydrochloric acid vapors solution at -4 °C. [63]

As well as austenitic stainless steels exposed to SCC at ambient temperature in marine environments. [64]

3.1.3. High-temperature high-pressure aqueous environments

It is known that stainless steel is subjected to SCC in a high-temperature aqueous environment.

The presence of oxygen dissolved in distilled water makes it more prone to oxidation which leads austenitic stainless steel to become more prone to SCC. [65][66] Also, it increases the electrochemical potential in stainless steel. [67]

Researches have shown that adding nitrogen can increase cracks growth in the 304L at a rate of 20%. [68]

Local growth in tops of the cracks of oxidation is the reason for SCC in a high-temperature aqueous environment. [69][70]

Apparently, oxidation on tops of the cracks leads to chrome oxidation and the formation of an area rich in nickel on the walls of the cracks, whereas centers of the cracks stay filled with iron. Then, it was observed later, that the formed layer of the chrome has the same density as the specimens taken from boiling water reactors.

It was also revealed in steel 304, the presence of a lower density chrome layer, that leads to observing that the passive layer is low. [71]

3.1.4. Environmental of sulfide

A study has shown the occurrence of corrosion beneath the insulating substance SCC due to the presence of sulfur in the gas pipelining of the type 304L.

Verifications have shown the occurrence of corrosion in stages (mechanism of corrosion formation). Accorded intergranular SCC and the transgranular SCC, which was formed on the external and internal surfaces.

We notice that all of this had happened due to the existence of sulfur starting from the internal surface of the tube, outwards its external surface beneath the insulating substances. Deterioration occurred on the external surface which was undergoing SCC.

All of this falls under what is called (corrosion under insulation). [72]

3.1.5. Environment of caustic

It is known that certain concentrations of caustic substances at a certain temperature, cause the SCC in stainless steels. [73]

Chemicals substances (such as sodium hydroxide which producing caustic soda) and petrochemical industries can produce caustic substances that causing SCC. Studies have shown SCC occurs with caustic soda at temperatures close to 100 °C. [74]

This can be prevented from occurring by adding phosphate which prevents forming caustic substances. [75]

Furthermore, adding chrome [76] and chloride [77] in the work environment may prevent SCC with caustic substances.

3.2. EFFECT OF CHEMICAL COMPOSITION ON STRESS CORROSION CRACKING

3.2.1. Effect of alloying elements

Recent research has shown that the increase in nickel ratio in austenitic stainless steel raises its resistance to SCC in a chlorine environment. [78][79]

Also, in another research, it has been revealed that the silicon is useful to increase resistance to SCC in a chlorine environment. This result has been proved after applying corrosion tests in boiling magnesium chloride solution. [80]

It has been verified that silicon added to the alloy, raises the growth rate of cracks in a high-temperature aqueous environment, this is likely due to silica formation and its tendency to disintegrate in such environments. [81]

Furthermore, we find that the effect of molybdenum in alloys depends on the used test, where chloride tests showed that molybdenum, at first lowers the resistance to SCC, then it rises it. [82]

On the other hand, it has been found also in sodium chloride tests, that the increase in molybdenum increases resistance to SCC in austenitic stainless steel. [83]

3.2.2. Stress corrosion cracking (SCC) of types 304 and 316L austenitic stainless steel

The most prone type to SCC is type 304 in chloride solution, especially in a solution of boiling sodium chloride. [84][85]

Type 304 showed extension and expansion of TGSCC at the exposure of 144 hours to the test's cracks charged to IGSCC in sensitized conditions.

Type 316, was not affected after being exposed to the test in the same solution for more time 200 hours and it showed no SCC. One of the studies, however, showed a failure for types 316/316L and 304/304L in 42% boiling magnesium chloride. [86]

The main difference that we have noticed between types 304/304L, 316/316L is the addition of 2-3% of molybdenum in the last type. We noticed also that nickel content in 316 is higher than in 304, and that high content of molybdenum and nickel in 316/316L, increases its resistance to SCC compared to type 304/304L. [87]



Fig. 3.1 Stress corrosion cracking for stainless steel tube [1]

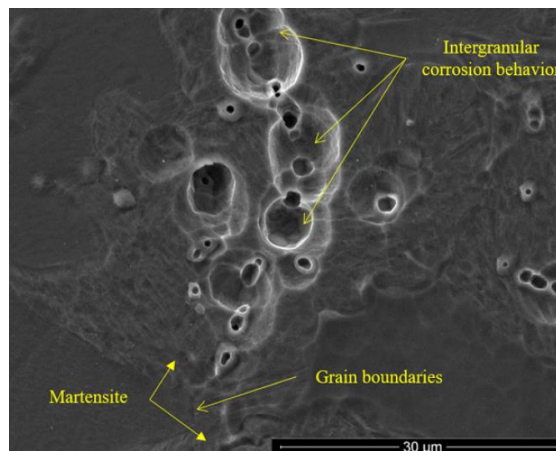


Fig. 3.2 Intergranular corrosion for ferritic Stainless steel [88]

3.3. EFFECT OF GRAIN BOUNDARY ON STRESS CORROSION CRACKING

It is known that stainless steel contains granular boundaries that are considered resistant to sensitization, and therefore resistant to intergranular stress corrosion cracking. This looks evident after applying heat treatments over it.

It was revealed also, that stainless steel's tendency to sensitization can be increased as random boundaries become larger.

A study has shown a high resistance of the granular boundaries to intergranular stress corrosion cracking in a boiling chloride solution.

It is worth mentioned here that granular boundaries whether they were random or special, could change or affect the sensitization, and as a result intergranular stress corrosion cracking takes place. Also, it was revealed that cracks grow all over the random boundaries but not on the areas with regular boundaries. [89]

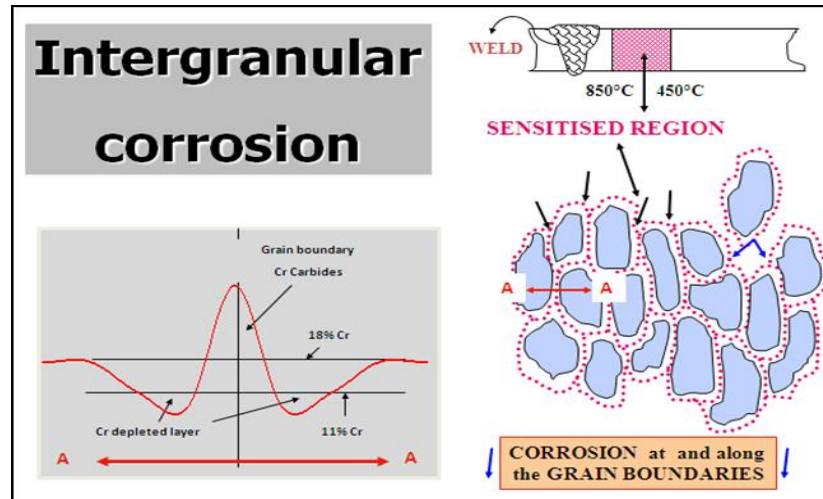


Fig. 3.3 Intergranular corrosion [90]

3.4. EFFECT OF RESIDUAL STRESSES ON STRESS CORROSION CRACKING

It is known that stress corrosion cracking causes the residual stress effects, which are stable in general, where we find that these stresses are lower than the plastic yield stress but enough to make local yielding. All these results depend on a full understanding of why the passive film collapse on the area that is under settled stresses.

And the lower value of residual stress is causing stress corrosion cracking is under the microscopic yield level, and that is in the presence of the flows in materials. [91]

3.4.1. Welding stress

It is known that the welding technique causes residual stresses in stainless steel, and the increase in temperature corresponding to a low discharge rate in stainless steel is the main cause for deterioration in the level of residual stress in the welding process. Weld pool spreads as the temperature increases, whereas low thermal discharge in stainless steel works on increasing the expansion of the welded base material.

During the cooling process, the area that surrounds the weld pool starts shrinking which results in additional load over the base material.

Furthermore, during the last phase of cooling (200 -300 °C), we notice that the area that surrounds the weld pool undergoes maximum stress so a big distortion occurs. The rate of the plastic strain was 20%. [92]

This plastic distortion takes place in temperature from (200 -300 °C) without any change or transformation in the austenitic structure. These distortions cause intergranular stress corrosion cracking without sensitization for stainless steel. [93]

Intergranular stress corrosion cracking occurs near the fusion zone that is called the heat-affected zone. This can be assigned to sensitization in this particular area.

In a chloride containing environment, the stress corrosion cracking takes the form of intergranular stress corrosion cracking. [94]

3.5. EFFECT OF HYDROGEN ON SCC (HYDROGEN EMBRITTLEMENT)

It is known that hydrogen dissolves in most material. It is a very small atom so as a result, it has the ability for penetration into the crystal structure of the metal. For example, hydrogen's permeation in ferritic stainless steel resembles the penetration of salt in the water that is in normal temperature.

Hydrogen attacks areas under stress which causes the expansion of the metallic structure. Dissolved hydrogen helps to distract the metal, which means making it easy to break. However, embrittlement of the metal takes the form of either transgranular or intergranular. Cracks can grow in a very fast rate up to 1 mm/s.

If we inspect the aforementioned crystal structure of ferritic stainless steel, we observe that its atoms take the form of a body-centered cubic. And the holes between the metallic atoms are small. The canals between them are wide. Therefore, hydrogen rapidly spreads, yet dissolves at a slow rate.

On the contrary, in austenitic stainless steel, the crystal structure of the metal takes the form of a face-centered cubic. The holes between the atoms are big, but the canals are small.

Therefore, austenitic stainless steel can embrittle but in the course of years compared to ferritic stainless steel. Thus, we concluded that austenitic stainless steel has resistance to the harmful effects of hydrogen. [95]

PART II: EXPERIMENTS, STUDIES, ANALYZES, RESULTS, RESULTS INTERPRETATION, CONCLUSIONS, RESULTS DISSEMINATION

CHAPTER 4

4 A STUDY OF THE EFFECTS OF SOME TYPES OF WELDING ON THE MECHANICAL PROPERTIES FOR 304 AND 316L AUSTENITIC STAINLESS-STEEL SHEETS

4.1. EXPERIMENTAL RESEARCH

Our aim was to observe mechanical characteristics variations on welded samples which were previously tensile tested. The tested samples, stainless steel type 304 and 316L, were obtained from cutting on the longitudinal and transverse direction with respect to the rolling direction of the steel sheet, and on each direction, two specimens were tested: one in which a 5mm hole was drilled and one full specimen.

Figure 4.1 showing the schematics of the samples used.

From the tensile tested specimens, the necked regions were cut and the specimen remainder welded together by using two methods: TIG and MMAW, then tensile tested again.

The results allowed us to compare the mechanical characteristics and find stressed regions on the test samples and decide which method would be most convenient.

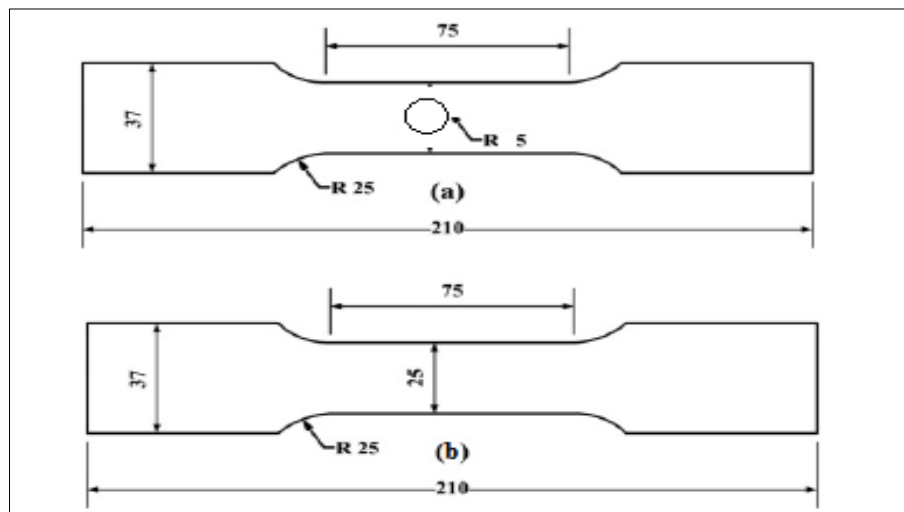


Fig. 4.1 Tensile specimens used in research: full specimen and specimens with a central 5 mm radius hole

4.2. EXPERIMENTAL PROCEDURES

4.2.1. Materials

From sheets, 2000×1000×3 mm, standard tensile specimens parallel and perpendicular to the rolling direction were cut using a laser, and on some specimens, a hole with a 5 mm radius was drilled using a conventional drilling machine in order to mimic a defect.

The material used was 3 mm thick 304 and 316L stainless steel sheets.

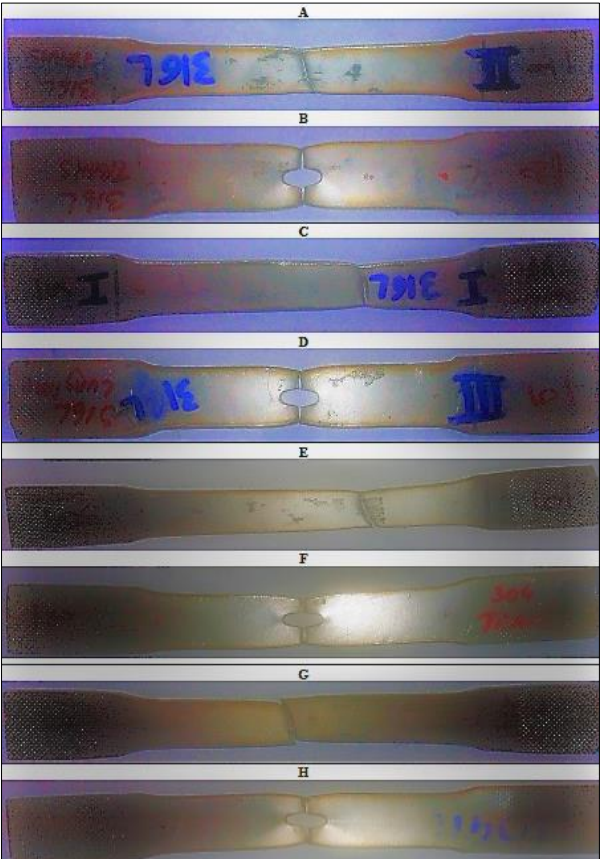

The chemical compositions of the alloys are shown in Table 4.1.

Table. 4.2 Chemical composition of the alloys (wt. %).

AISI	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
304	0.018	0.369	1.84	0.014	0.0007	18.29	8.3	0.328	0.415
316L	0.018	0.406	1.88	0.019	0.0029	17.04	9.55	1.85	0.391

4.2.2. Tensile testing

The tensile test was carried out by two stages, as follow:

The first stage	The second stage
standard tensile samples and samples containing defects were tested before welding	the necked region was removed using a metallographic cutter and the remainders of the specimens were welded together by TIG and MMAW
	
<p>Fig. 4.2 Standard tensile specimens of AISI 303 and AISI 316L austenitic stainless steels after tensile testing: (A) T316L; (B) HT316L; (C) L316L; (D) HL316L; (E) T304; (F) HT304; (G) L304; (H) HL304</p>	<p>Fig. 4.3 Welded specimens after tensile testing: (A) ELT304; (B) ELL304; (C) TIGHT304; (D) TIGHL304; (E) ELL316L; (F) ELT316L; (G) TIGHL316L; (H) TIGHT316L</p>
<p>The Load - Displacement curves of the initial specimens</p>	<p>The Load - Displacement curves of the secondary specimens</p>

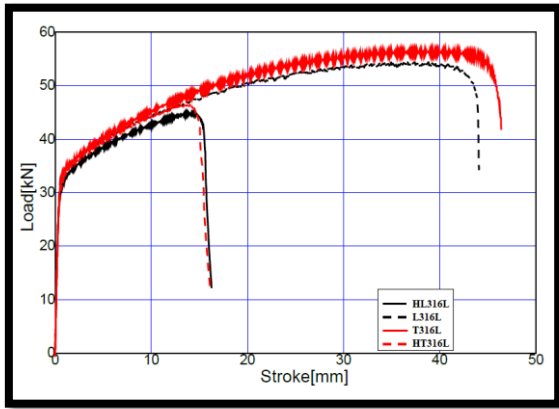


Fig. 4.4 Tensile curves for specimens 316L

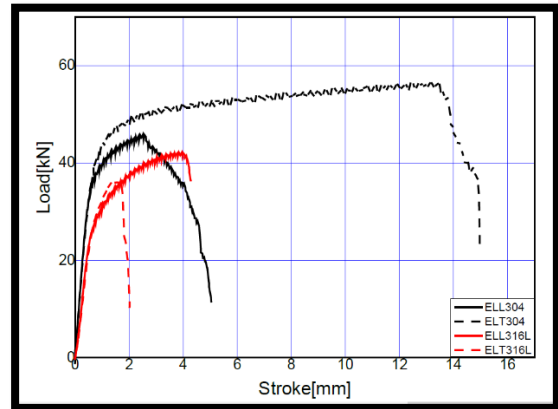


Fig. 4.5 Tensile curves for welded specimens without central holes: ELL304; ELL304; ELT316L; and ELL316L

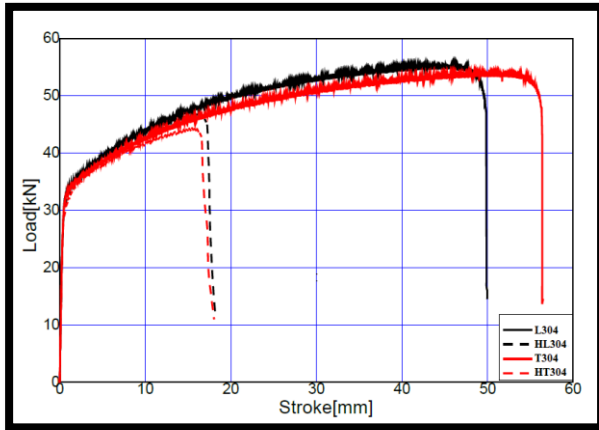


Fig. 4.6 Tensile curves for specimens 304

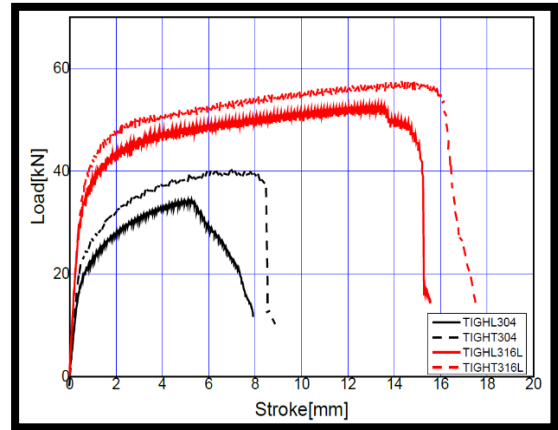


Fig. 4.7 Tensile curves for welded specimens with central holes: TIGHT304; TIGHL304; TIGHT316L; and TIGHL316L

4.2.3. Hardness testing

The Rockwell C hardness test was carried out by two stages, as follow:

The first stage	The second stage
Non-welded tensile samples were tested after tensile test	Welded tensile samples were tested after tensile test
The curves of the initial specimens after tensile test	The curves of the secondary specimens after tensile test

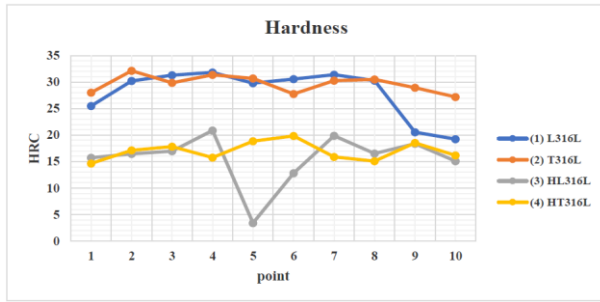


Fig. 4.8 Curves of hardness for 316L samples

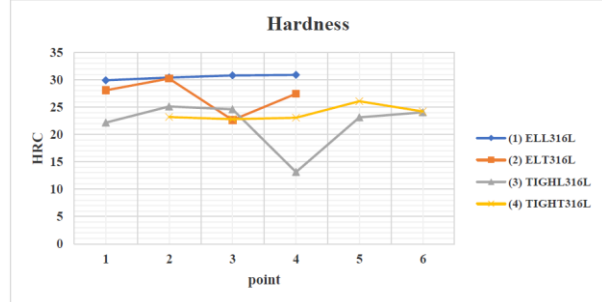


Fig. 4.9 Curves of hardness for 316L samples

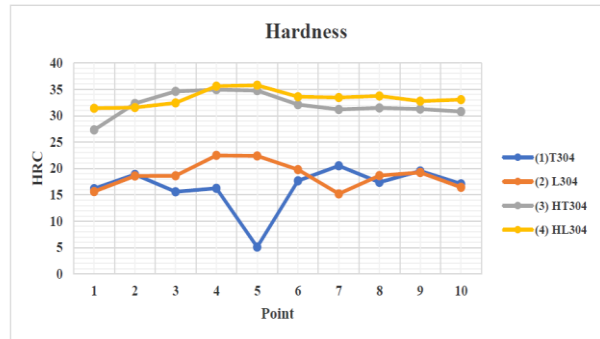


Fig. 4.10 Curves of hardness for 304 samples

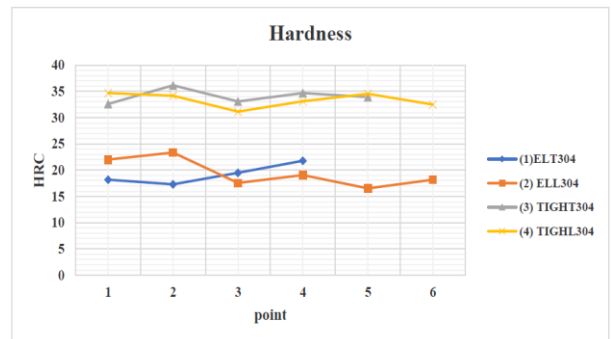


Fig. 4.11 Curves of hardness for 304 samples

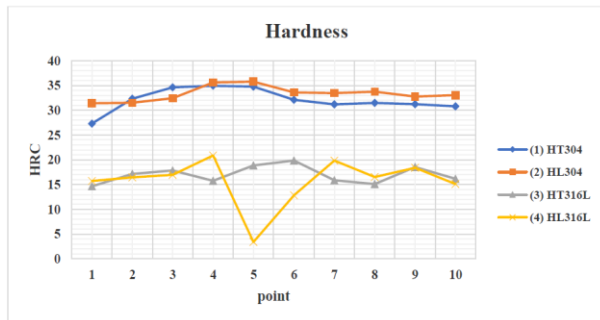


Fig. 4.12 Curves of hardness for 304 and 316L samples

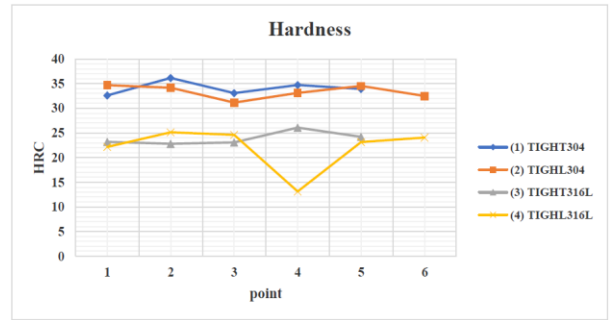


Fig. 4.13 Curves of hardness for 304 and 316L samples

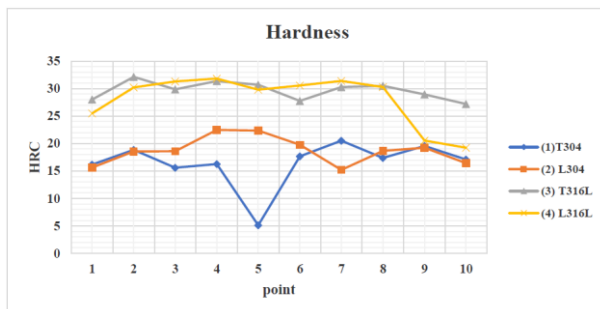


Fig. 4.14 Curves of hardness for 304 and 316L samples

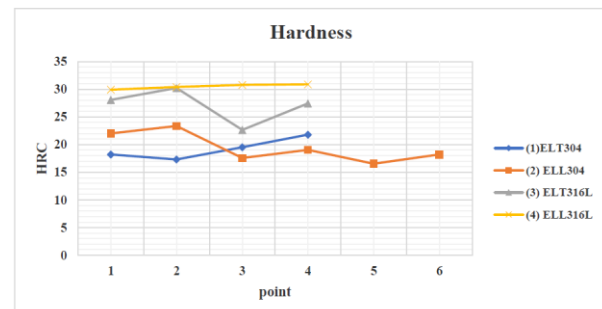


Fig. 4.15 Curves of hardness for 304 and 316L samples

4.3. CONCLUSIONS

In this research, it was used two types of austenitic stainless steel: (316L and 304) to compare mechanical properties, such as hardness and tensile properties.

Eight tensile specimens were prepared for every alloy, as follow:

- Two tensile samples for determining the effect of the cutting orientation on the mechanical properties.

- Two tensile samples for determining the effect of defects on the mechanical properties.

- Two regular samples are welded by the MMAW technique to determine the effect of WWAW on the mechanical properties.

- Two defect samples were welded by TIG technique to determine the effect of TIG on the mechanical properties when defects are existent.

The following conclusions were obtained through the results of the experimental study as follow:

For samples of Group A (T304, L304, HT304, and HL304):

According to tensile properties, it was observed that the best samples by order are: L304, T304, HL304 then HT304.

According to hardness properties: it was noticed an increase in characters of hardness for the samples with defects (HT304, HL304), and that is by making a comparison with the regular samples (T304, L304).

According to the effect of defects, it was registered that the existence of defects increased the hardness properties and decreased the tensile properties.

According to samples orientations, it was observed the increase of tensile properties for L304, by comparing it with T304, but no differences in the hardness properties had been registered.

For samples of Group B (T316L, L316L, HT316L, and HL316L):

According to tensile properties, it was observed that the best samples by order are: T316L, L316L, HL316L then HT316L.

According to the hardness properties, it was noticed an increase in characters of hardness for the regular samples (T316L, L316L), by comparing them with the samples with defects (HL316L, HT316L).

According to the effect of defects, it was registered that the existence of defects decreased the tensile properties and hardness properties.

According to sample orientations, it was observed the increase of tensile properties for T316L, in comparison with L316L, but no differences in the hardness properties had been registered.

For samples of Group C (ELT304, ELL304, TIGHT304, and TIGHL304):

According to the tensile properties, it was observed that the best samples by order are: ELT304, ELL304, TIGHT304 then TIGHL304.

According to the hardness properties, it was noticed an increase in characters of hardness for the samples with defects that were welded by TIG (TIGHT304, TIGHL304), in comparison with the regular samples that were welded by MMAW (ELT304, ELL304).

According to the welding process, the TIG welding increased the hardness properties and decreased the tensile properties. On the contrary, MMAW welding increased tensile properties and decreased hardness properties.

For samples of Group D (ELT316L, ELL316L, TIGHT316L and TIGHL316L):

According to the tensile properties, it was observed that the best samples by order are: TIGHT316L, TIGHL316L, ELL316L then ELT316L.

According to the hardness properties, it was noticed an increase in characters of hardness for the regular samples that were welded by MMAW (ELT316L, ELL316L), in comparison with the samples with defects that were welded by TIG (TIGHL316L, TIGHT316L).

According to the welding process, MMAW welding increased hardness properties and decreased tensile properties. On the contrary, TIG welding increased tensile properties and decreased hardness properties.

For samples of Group E (T304, L304, T316L, and L316L):

According to the tensile properties, no differences in the tensile properties had registered.

According to the hardness properties, the samples (L316L, T316L) have hardness properties better than the samples (T304, L304).

For samples of Group F (HT304, HL304, HT316L, and HL316L):

According to the tensile properties, no differences in the tensile properties had been registered.

According to the hardness properties, the samples (HT304, HL304) have hardness properties better than the samples (HL316L, HT316L).

According to the effect of defects, it was registered that when defects have existed, 304 alloy behavior was better than alloy 316L.

For samples of Group G (ELT304, ELL304, ELT316L, and ELL316L):

According to the tensile properties, it was noticed an increase in characters of tensile for the samples that were welded by MMAW (ELT304, ELL304), by comparison with the samples which were welded by MMAW (ELL316L, ELT316L).

According to the hardness properties, it was registered that the samples (ELL316L, ELT316L) have hardness properties better than the samples (ELT304, ELL304).

According to the welding process using the MMWA technique, it was observed that the samples (ELT304, ELL304) have tensile properties better than the samples (ELL316L, ELT316L). On the contrary, if hardness properties were compared

For samples of Group H (TIGHT304, TIGHL304, TIGHT316L, and TIGHL316L):

According to the tensile properties, it was noticed an increase in characters of tensile for the samples that were welded by TIG (TIGHL316L, TIGHT316L), in comparison with the samples which were welded by TIG (TIGHT304, TIGHL304).

According to the hardness properties, the samples (TIGHT304, TIGHL304) have hardness properties better than the samples (TIGHL316L, TIGHT316L).

According to the welding process using TIG technique, it was observed that the samples (TIGHL316L, TIGHT316L) have tensile properties better than the samples (TIGHT304, TIGHL304). On the contrary, if hardness properties were compared.

CHAPTER 5

5 A STUDY OF EFFECT OF TIG WELDING ON THE CORROSION BEHAVIOR FOR ALLOYS 304 AND 316L SHEETS IN CHLORINE SOLUTIONS

5.1. MATERIAL AND METHODS

Our aim was to observe corrosion behavior on austenitic stainless-steel specimens which were welded by the TIG technique in halide solutions such as (FeCl_3 , CaCl_2 , and MgCl_2).

The tested specimens, stainless steel type 304 and 316L, were obtained from cutting on the longitudinal direction with respect to the rolling direction of the steel sheet.

The material used was 3mm thick 304 and 316L stainless steel sheets. The chemical compositions of the alloys are shown in [Table 4.1](#).

The ultimate tensile strength, yield tensile strength, reduction in area, and elongation of the used material are presented in [Table 5.1](#).

Table 5.1 Mechanical properties of AISI 316L and AISI 304

AISI	Tensile strength R_m [Mpa]	Yield strength $R_{p0.2}$ [Mpa]	Elongation [%]	Reduction in area [%]
L 304	760	425	45	68
L 316L	774	458	41	70

Sample coding reflects the alloy, 304 or 316L and the sample orientation, L – longitudinal.

From sheets, $2000 \times 1000 \times 3$ mm, standard corrosion specimens parallel to the rolling direction were cut using a laser. Specimen's dimensions for two types of AISI 304 and AISI 316L are $200 \times 20 \times 3$ mm (two specimens for every type). After that, every two specimens of the same type were welded together by the TIG technique.

[Figure 5.1](#) indicates Standard corrosion specimens of AISI 304 and AISI 316L austenitic stainless steel.



Fig. 5.1 Standard corrosion specimens of AISI 304 and AISI 316L austenitic stainless steels

Welding parameters are shown in [Table 5.2](#).

Table 5. 2 Welding parameters used

specimens	Welding method	Welding current [A]	Shielding gas	Welding voltage [V]	Welding wire
Full specimens					
TIGL304	TIG	80	Argon	20 - 24	308L
TIGL316L	TIG	80	Argon	20 - 24	316L

Sample coding reflects the welding process used, TIG - tungsten inert gas welding, the alloy, 304 or 316L, and the sample orientation, L – longitudinal.

The chemical composition for wire welding that was used for welded specimens is shown in **Table 5.3**. Whereas 304 specimens were welded by using ER308L filler and 316L specimens were welded by using ER316L filler.

Table. 5. 3 Chemical composition for welding wire (W %) [34]

Chemical composition									
	C	Cr	Ni	Mo	Mn	Si	P	S	Cu
ER308L	0.03	19.5-22.0	9.0- 11.0	0.75	1.0 -2.5	0.30-0.65	0.03	0.03	0.75
ER316L	0.03	18.0-20.0	11.0- 14.0	2.0-3.0	1.0-2.5	0.30-0.65	0.03	0.03	0.75

5.2. CORROSION TEST

After TIG welding, the small corrosion specimens were cut by traditional shearing machine on cold, by dimensions 40×20×3 mm for welded specimens and 20×10×3 mm for non-welded specimens.

Figure 5.2 indicates to non-welded corrosion specimens of AISI 304 and AISI 316L austenitic stainless steel, and **Figure 5.3** indicates to welded corrosion specimens of AISI 304 and AISI 316L austenitic stainless steels.

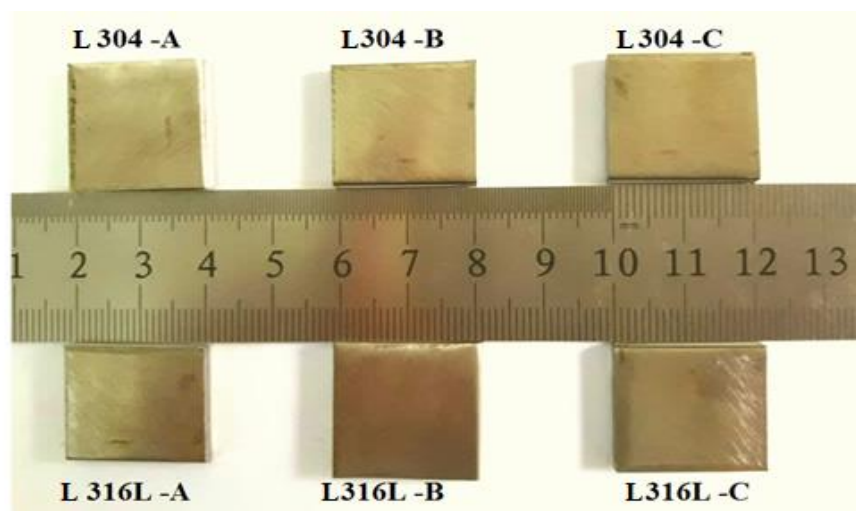


Fig. 5.2 Non-welded specimens of AISI 304 and AISI 316L austenitic stainless steels. sample coding reflects the specimen's number, A, B and C

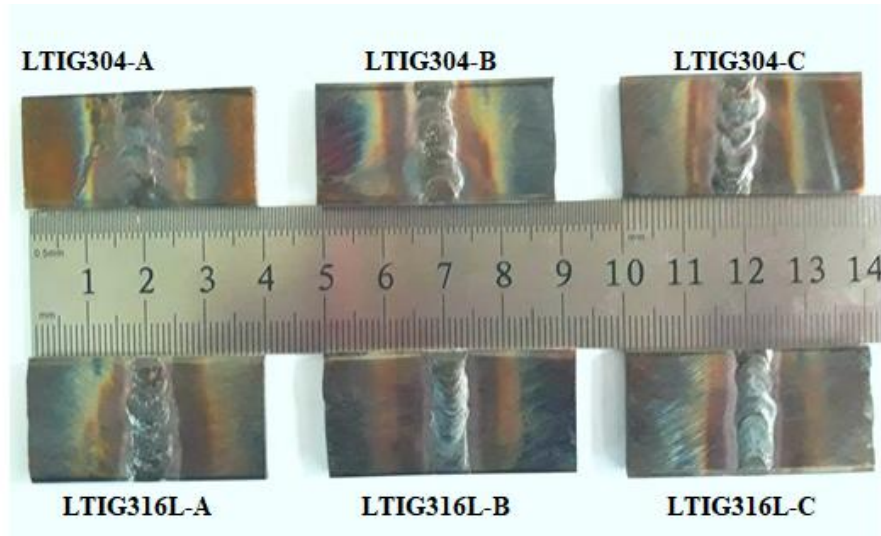


Fig. 5.3 Welded specimens of AISI 304 and AISI 316L austenitic stainless steels. sample coding reflects the specimen's number, A, B and C

To perform the tests, we used a corrosion cell consisting of a saturated calomel electrode (SCE) (Ag/AgCl) - reference electrode, a platinum electrode – counter electrode, and a working electrode consisted of specimens which are to be investigated.

Tests were performed in calcium chloride (6%CaCl₂), magnesium chloride (6%MgCl₂) and ferric chloride (6%FeCl₃), at 25 °C on 19.625 mm² for every zone in the specimen **figure 5.4**.

Before conducting the tests, the specimens were immersed in the electrolyte until stabilization the potential of an open circuit (OCP).

The polarization curves obtained after the tests which used 6%CaCl₂, 6%MgCl₂ and 6%FeCl₃ solutions for 304 and 316L specimens are shown in **Figures 5.5 – 5.10**.

The comparison of the corrosion rate obtained from the Potentiodynamic tests which used 6%CaCl₂, 6%MgCl₂ and 6%FeCl₃ solutions for 304 and 316L specimens are shown in **Figures 5.11 – 5. 13**.

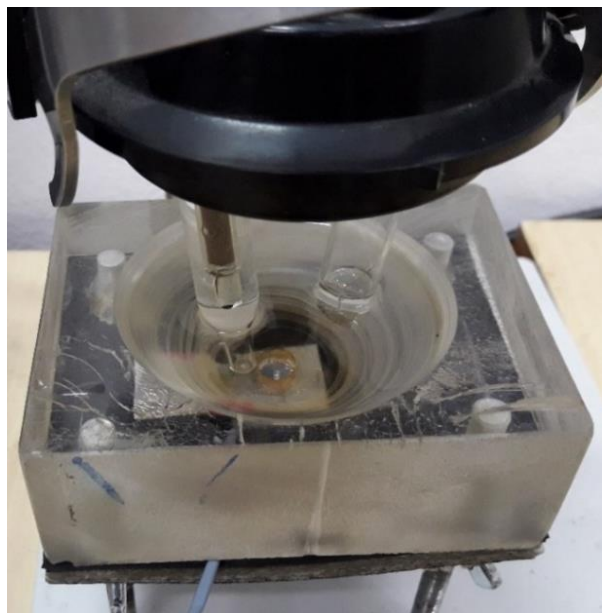


Fig. 5.4 The area where the corrosion test was performed

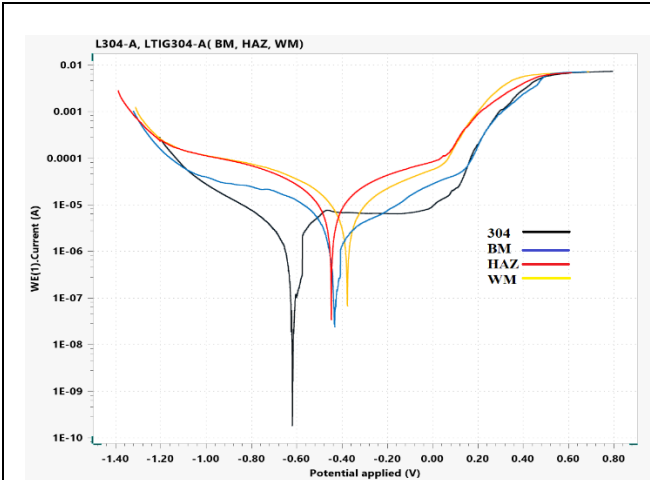


Fig. 5.5 The potentiodynamic curve that is corresponding to specimen 304 in CaCl_2 solution, with all zones (304 without welding, welded 304 BM, HAZ and WM zone)

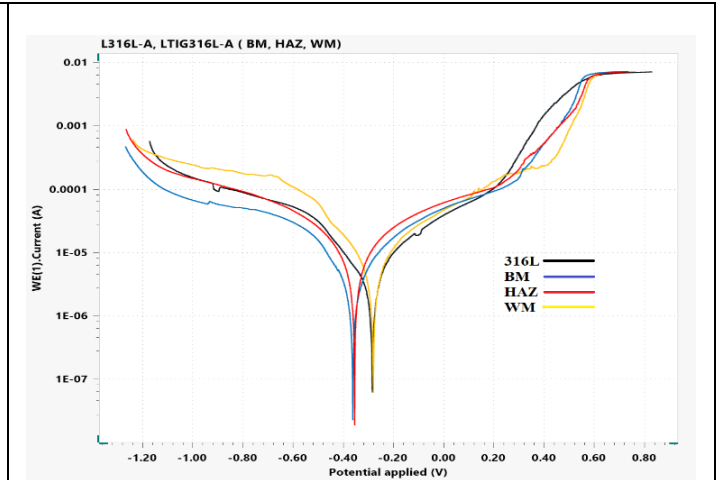


Fig. 5.6 The potentiodynamic curve that is corresponding to specimen 316L in CaCl_2 solution, with all zones (316L without welding, welded 316L BM, HAZ and WM zone)

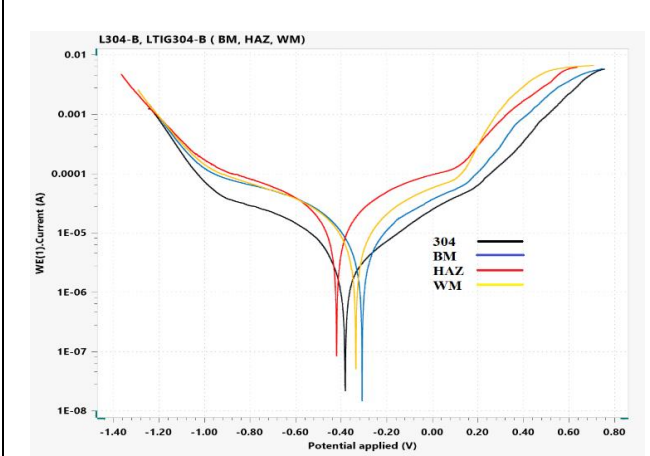


Fig. 5.7 The potentiodynamic curve that is corresponding to specimen 304 in MgCl_2 solution, with all zones (304 without welding, welded 304 BM, HAZ and WM zone)

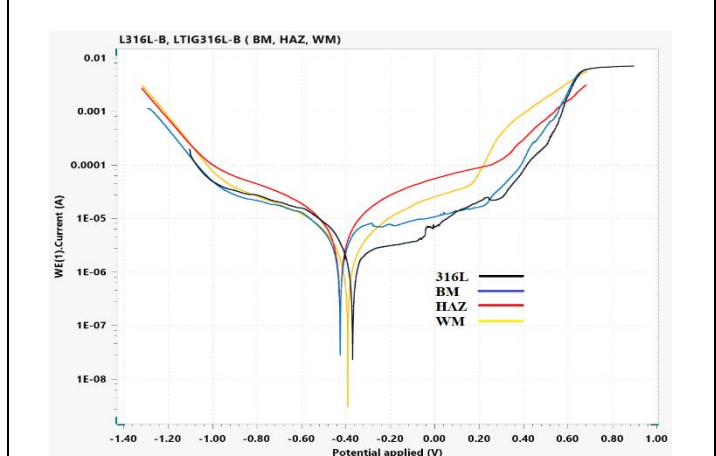


Fig. 5.8 The potentiodynamic curve that is corresponding to specimen 316L in MgCl_2 solution, with all zones (316L without welding, welded 316L BM, HAZ and WM zone)

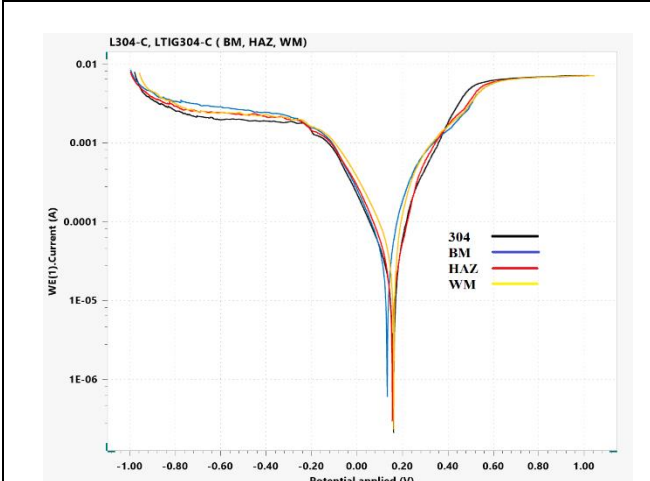


Fig. 5.9 The potentiodynamic curve that is corresponding to specimen 304 in FeCl_3 solution, with all zones (304 without welding, welded 304 BM, HAZ and WM zone)

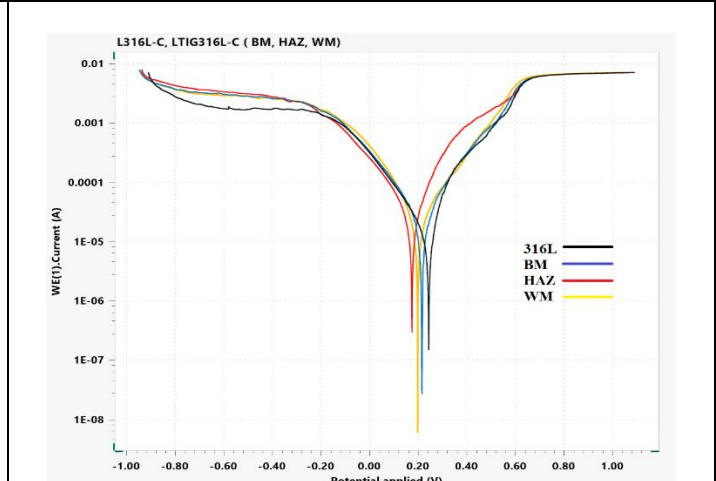


Fig. 5.10 The potentiodynamic curve that is corresponding to specimen 316L in FeCl_3 solution, with all zones (316L without welding, welded 316L BM, HAZ and WM zone)

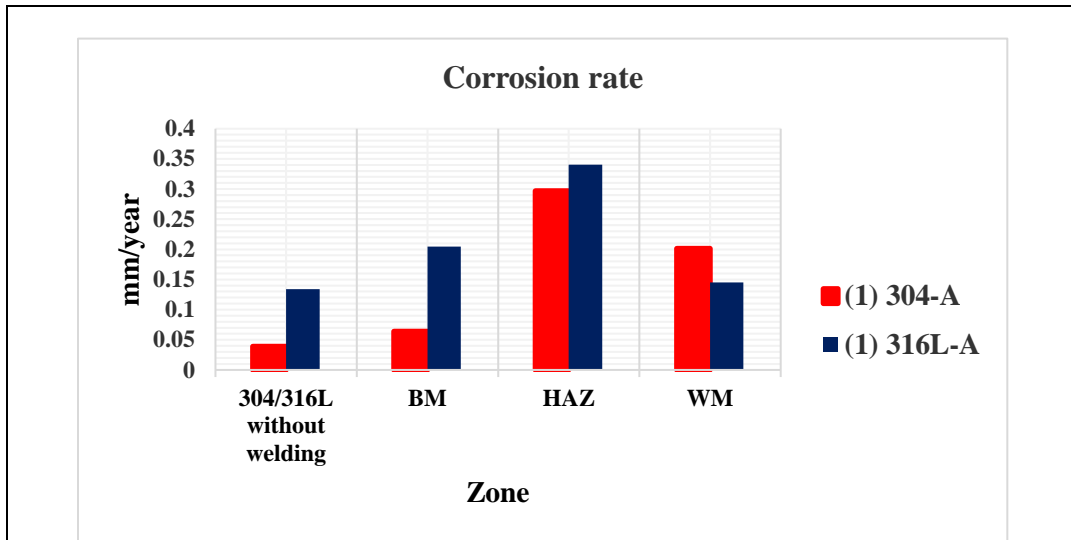


Fig. 5.11 Corrosion rate comparison for tested samples in CaCl_2 solution

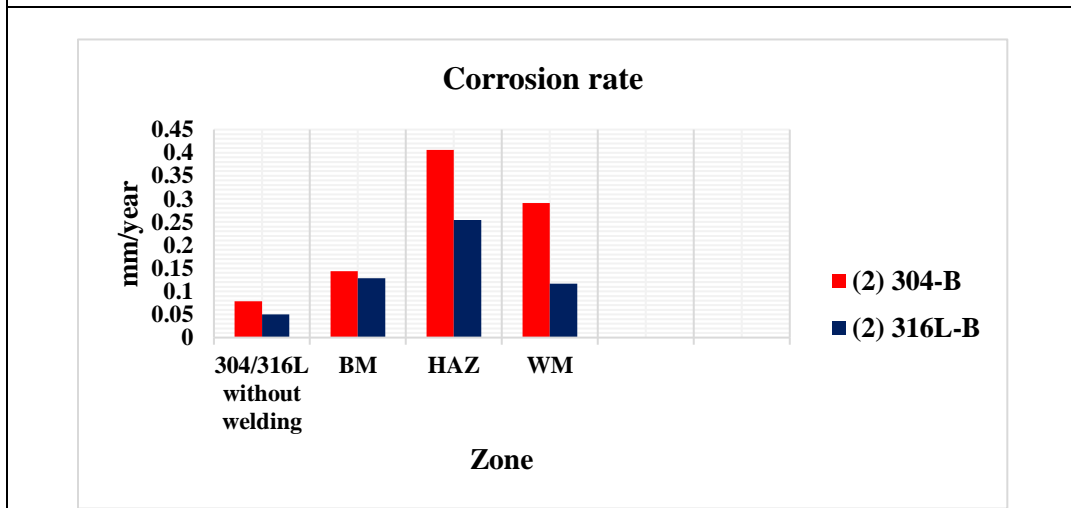


Fig. 5.12 Corrosion rate comparison for tested samples in MgCl_2 solution

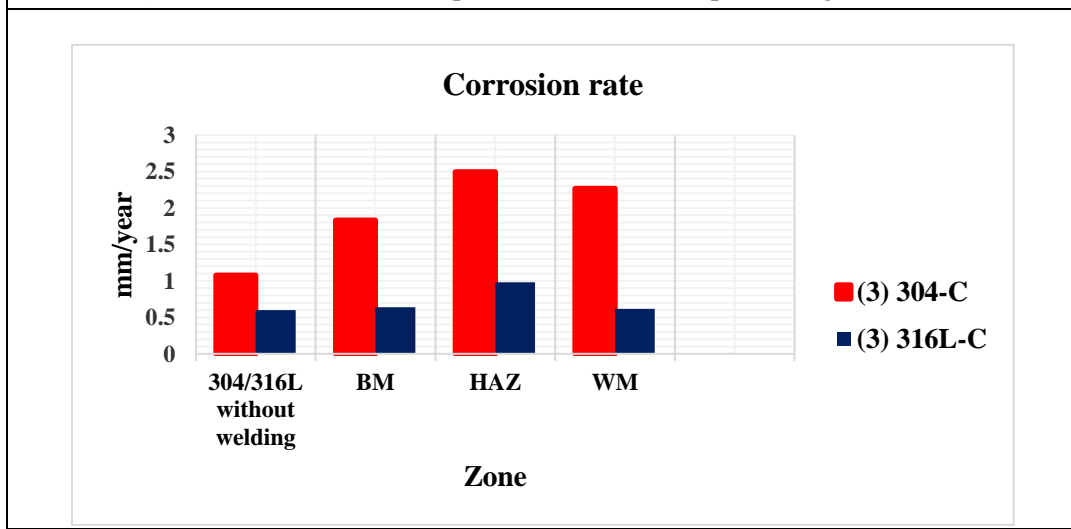


Fig. 5.13 Corrosion rate comparison for tested samples in FeCl_3 solution

5.3. SEM /EDX RESULT

5.3.1. Scanning electron microscope (SEM)

The experiments are done using a SIM device, which depends on the high power caused by an electron beam at the material surface. After the experiment, the images are processed using SIM software. In this device, the electron beam reaction with atoms that make up the surface layer give signs which show the topography of the surface.

5.3.2. Specimens

5.3.2.1. 304 & 316L austenitic stainless steels in 6%CaCl₂ solution

In this study, every welded sample was divided into three zones (heat affected zone-HAZ, base material-BM, and weld metal-WM) to perform the SEM/EDX examination, and we studied one zone for the non-welded sample to compare it with another welded samples in 6%CaCl₂ solution.

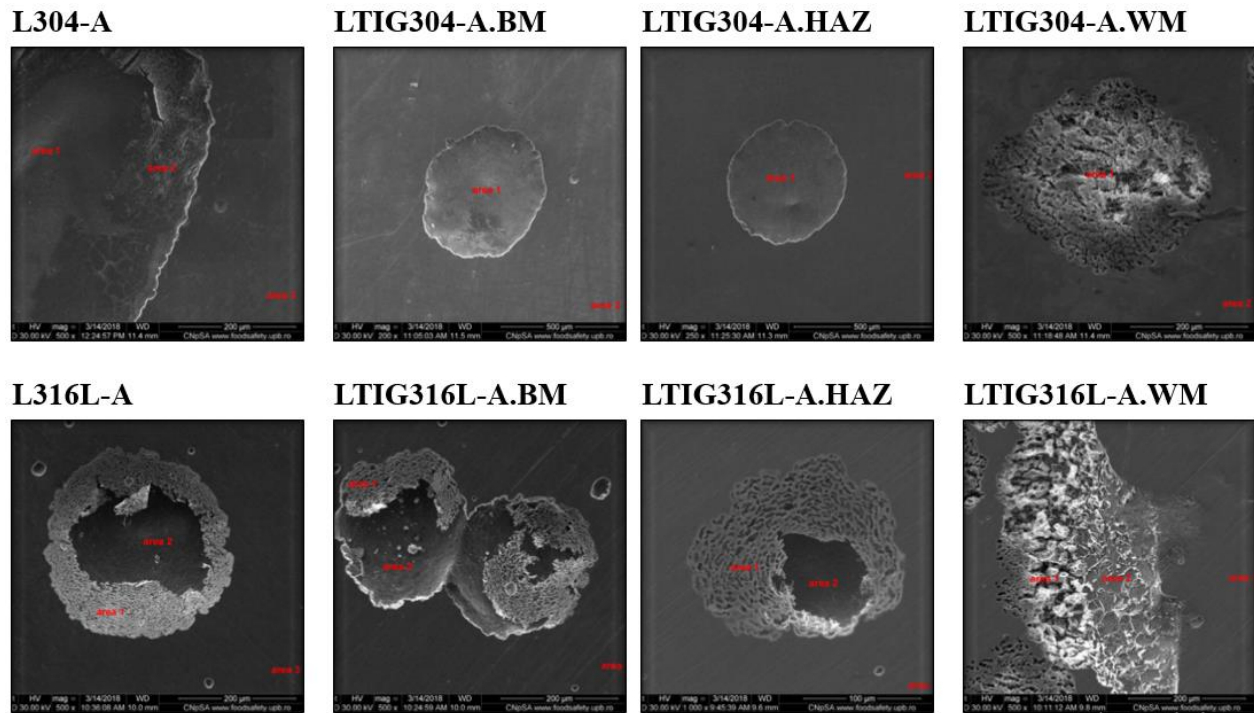


Fig. 5.14 SEM images of LTIG304-A, LTIG304-A.BM, LTIG304-A.HAZ, LTIG304-A. WM, LTIG316L-A, LTIG316L-A.BM, LTIG316L-A.HAZ and LTIG316L-A. WM specimens at MgCl₂ solution

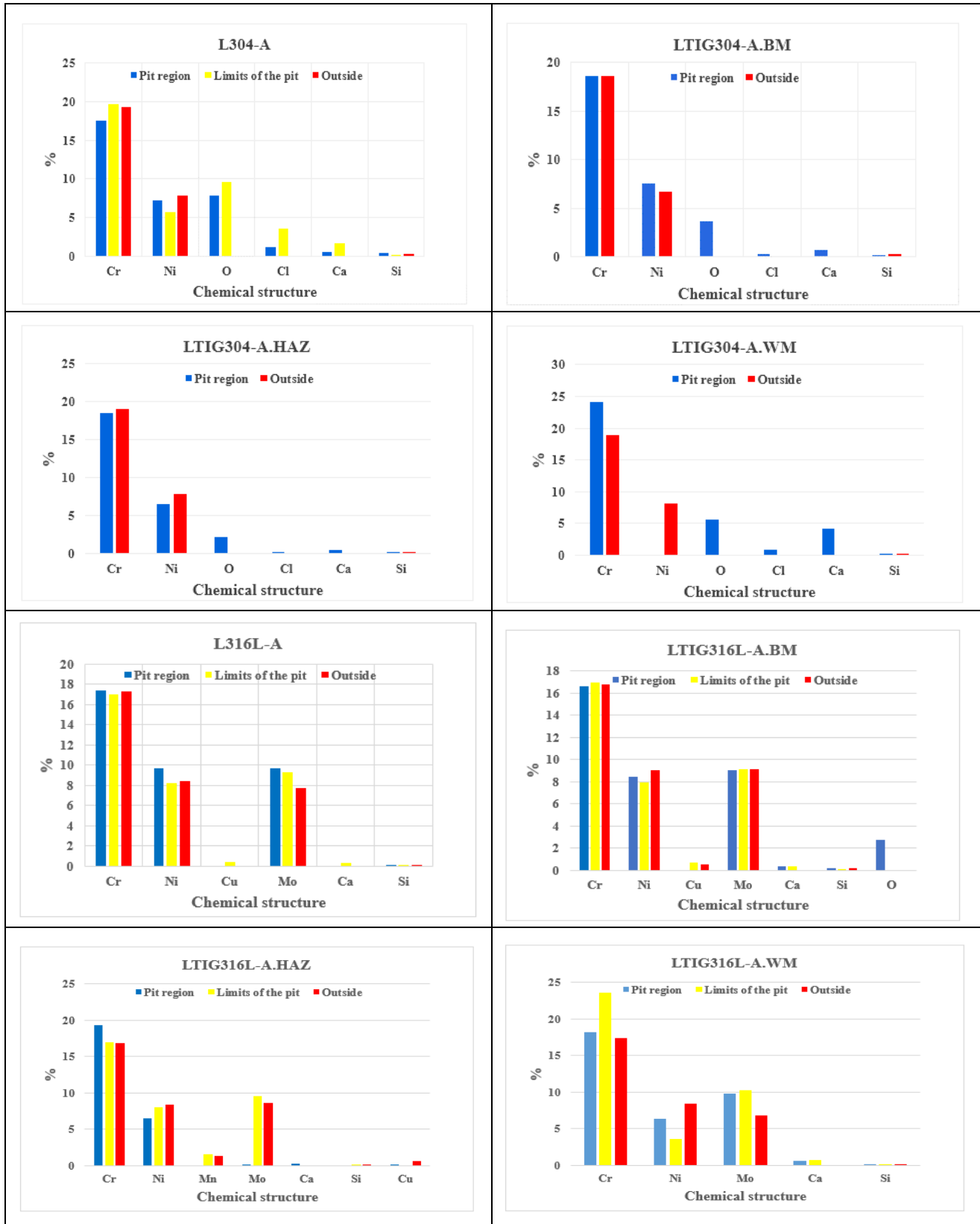


Fig. 5.15 EDX spectra results of LTIG304-A, LTIG304-A.BM, LTIG304-A.HAZ, LTIG304-A. WM, LTIG316L-A, LTIG316L-A.BM, LTIG316L-A.HAZ and LTIG316L-A. WM specimens at MgCl₂ solution

5.3.2.2. 304 & 316L austenitic stainless steels in 6%MgCl₂ solution

In this study, every welded sample was divided into three zones (heat affected zone-HAZ, base material-BM, and weld metal-WM) to perform the SEM\EDX examination, and we studied one zone for the non-welded sample to compare it with another welded samples in the 6%MgCl₂ solution

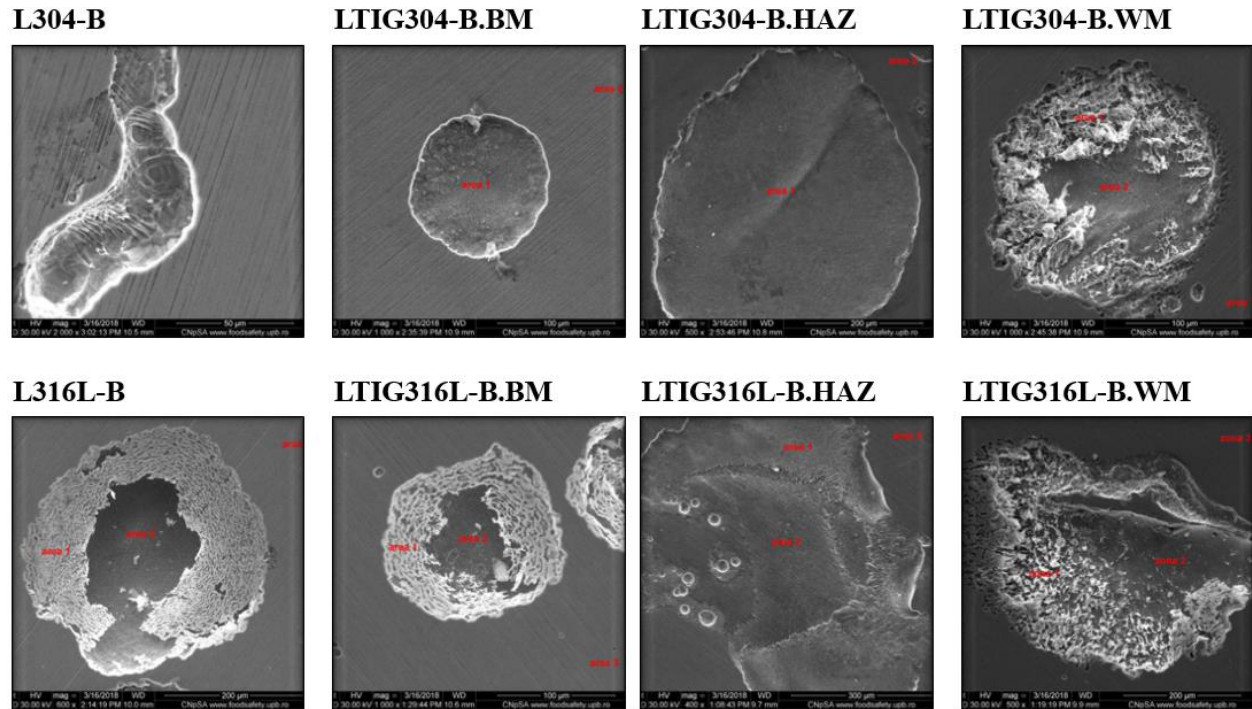


Fig. 5.16 SEM images of LTIG304-B, LTIG304-B.BM, LTIG304-B.HAZ, LTIG304-B. WM, LTIG316L-B, LTIG316L-B.BM, LTIG316L-B.HAZ and LTIG316L-B. WM specimens at MgCl₂ solution

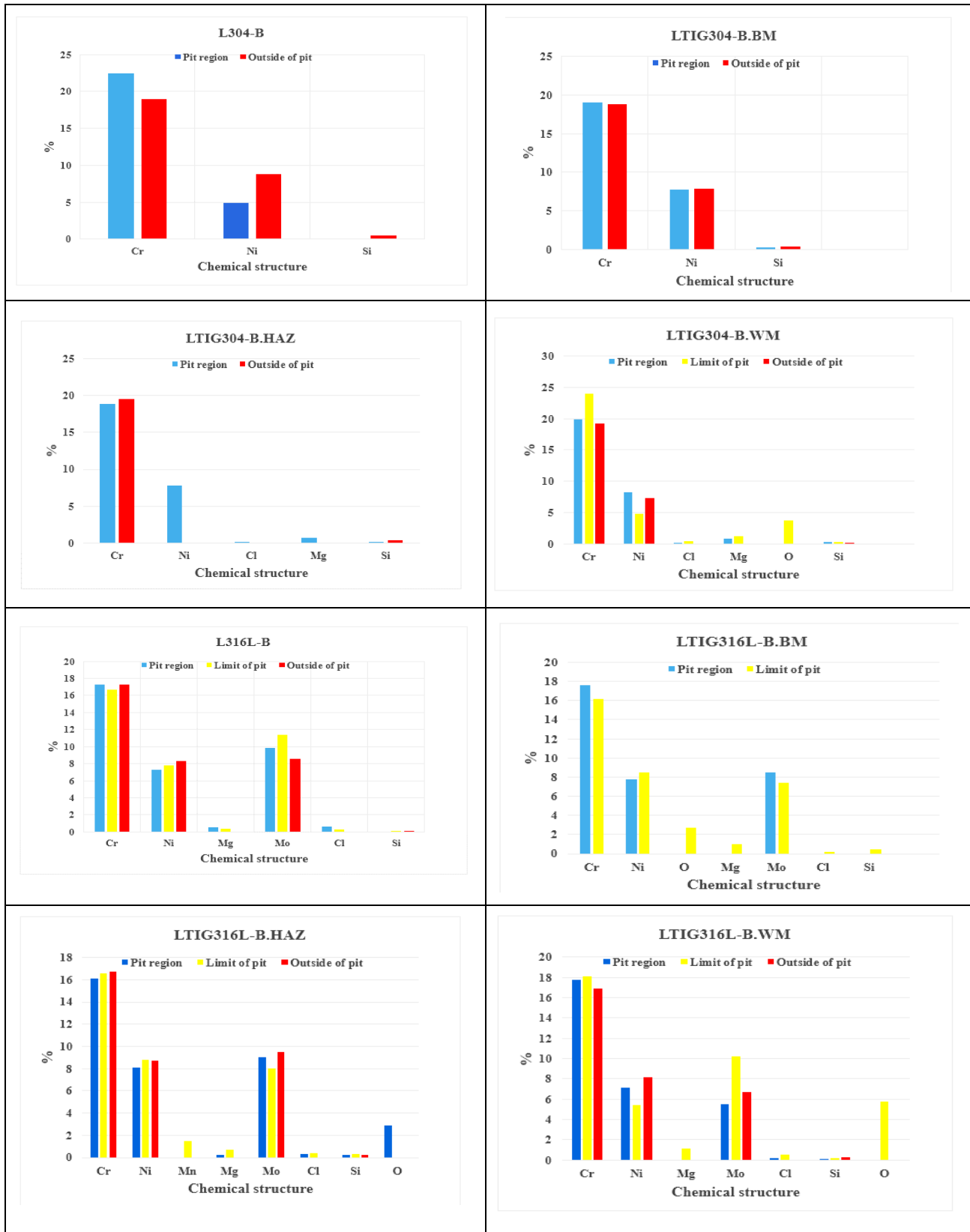


Fig. 5.17 EDX spectra results of LTIG304-B, LTIG304-B.BM, LTIG304-B.HAZ, LTIG304-B. WM, LTIG316L-B, LTIG316L-B.BM, LTIG316L-B.HAZ and LTIG316L-B. WM specimens at MgCl₂ solution

5.3.2.3. 304 & 316L austenitic stainless steels in 6%FeCl₃ solution

In this study, every welded sample was divided into three zones (heat affected zone-HAZ, base material-BM, and weld metal-WM) to perform the SEM\EDX examination, and we studied one zone for the non-welded sample to compare it with another welded samples in the 6%FeCl₃ solution.

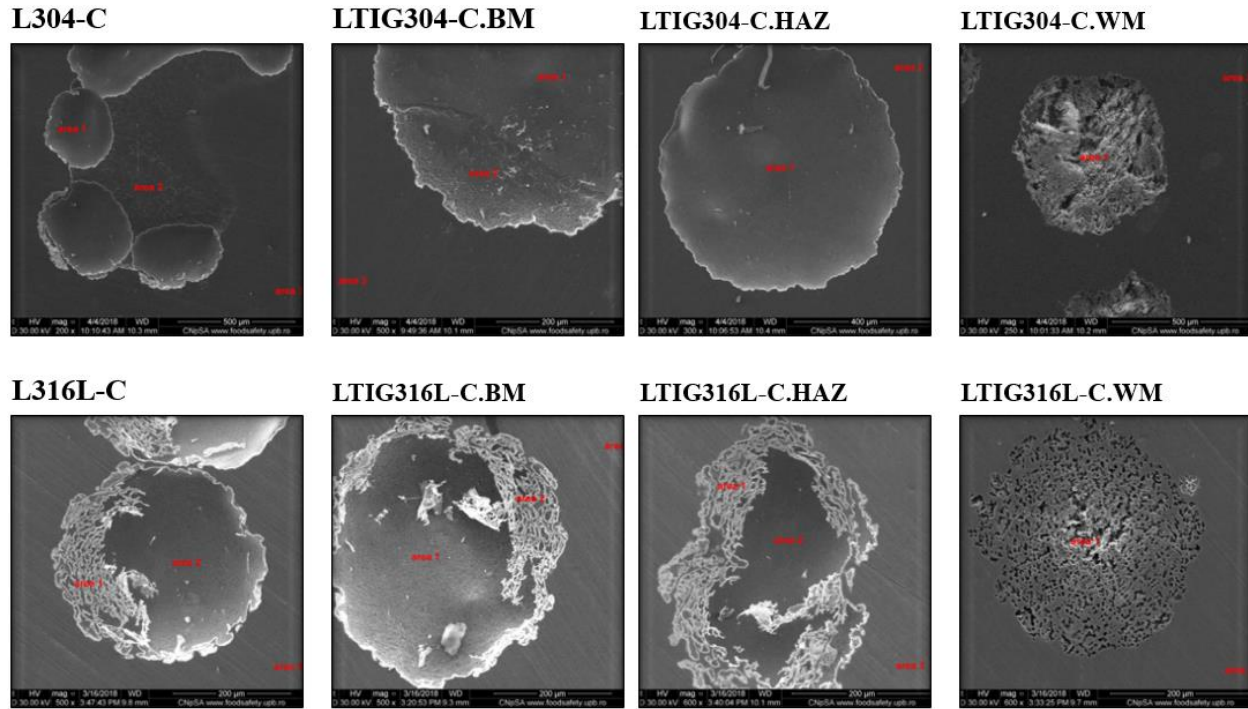


Fig. 5.18 SEM images of LTIG304-C, LTIG304-C.BM, LTIG304-C.HAZ, LTIG304-C. WM, LTIG316L-C, LTIG316L-C.BM, LTIG316L-C.HAZ and LTIG316L-C. WM specimens at FeCl₃ solution

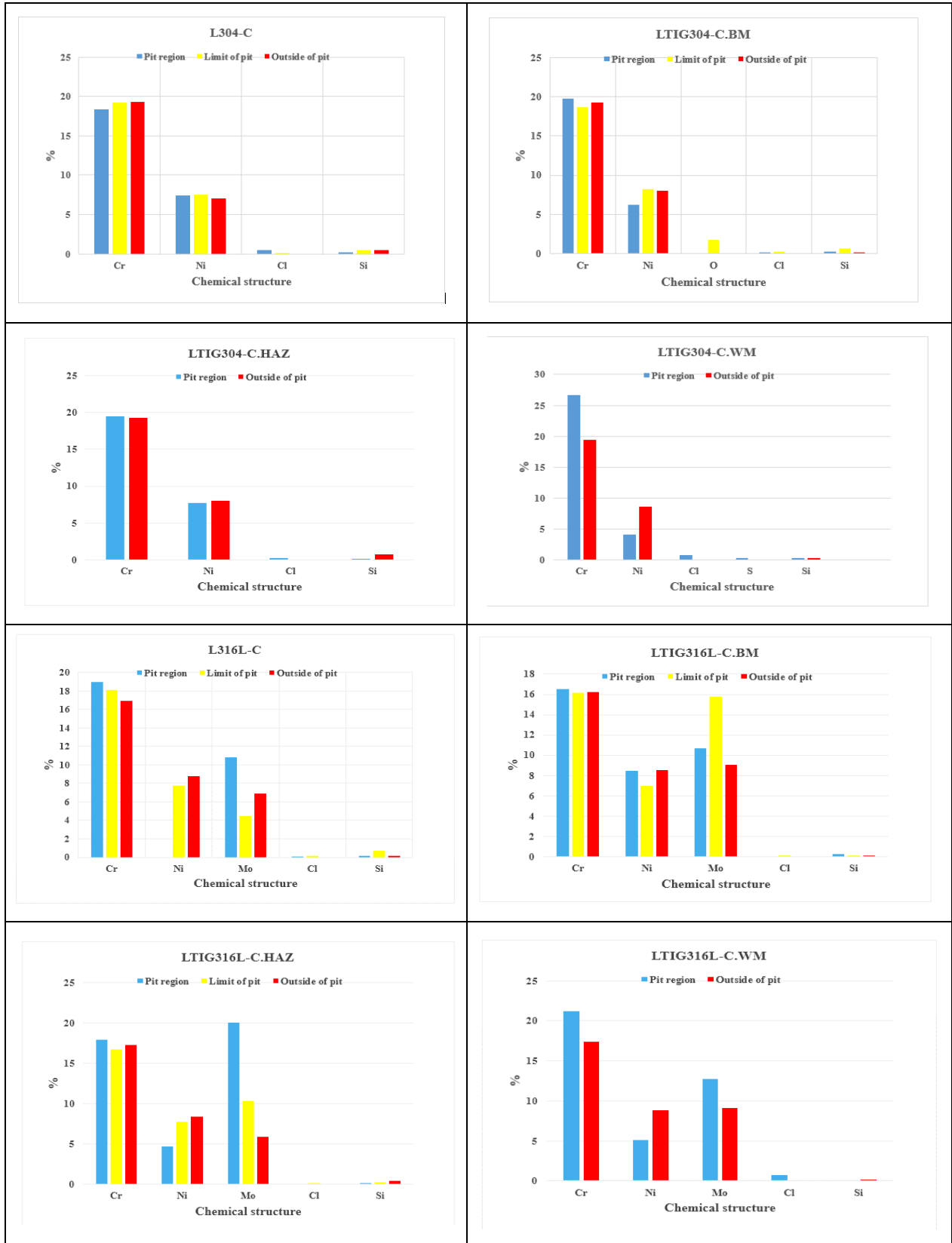


Fig. 5.19 EDX spectra results of LTIG304-C, LTIG304-C.BM, LTIG304-C.HAZ, LTIG304-C. WM, LTIG316L-C, LTIG316L-C.BM, LTIG316L-C.HAZ and LTIG316L-C. WM specimens at FeCl₃ solution

5.4. CONCLUSIONS

Our goals in this test for the welded and non-welded of 304 and 316L austenitic stainless steels were to determine the corrosion resistance on the samples that are exposed to 6% solution of calcium chloride, manganese chloride, and iron Chloride.

Electrochemical test using Potentiostat/Galvanostat AUTOLAB device shows the following conclusions, according to corrosion rate:

By comparing between 304 & 316L austenitic stainless steel (without welding, BM, WM, and HAZ zone), we noticed that the 304 stainless steel showed better results than 316L stainless steel in CaCl_2 solution, only in WM zone was showed opposite results.

By comparing between 304 & 316L austenitic stainless steel (without welding, BM, WM and HAZ zone), we noticed that the 316L stainless steel showed better results than 304 stainless steel in MgCl_2 solution. The greatest corrosion rate was observed in the HAZ zone.

By comparing between 304 & 316L austenitic stainless steel (without welding, BM, WM and HAZ zone), we noticed that the 316L stainless steel showed better results than 304 stainless steel in FeCl_3 solution. The corrosion rate increase was observed in all zones.

By comparing the zones of 316L austenitic stainless steel (Without welding, BM, WM, and HAZ zone), we noticed that the 316L stainless steel in the MgCl_2 solution showed better results followed in the CaCl_2 solution and then FeCl_3 solution. The corrosion rate increase was observed in the HAZ zone for all samples.

By comparing the zones of 304 austenitic stainless steel (Without welding, BM, WM, and HAZ zone), we noticed that the 304 stainless steel in the CaCl_2 solution showed better results followed in the MgCl_2 solution and then FeCl_3 solution. The corrosion rate increase was observed in the HAZ zone for all samples.

CHAPTER 6

6 A STUDY OF THE EFFECT OF WELDING ON THE CORROSION BEHAVIOR FOR U- BEND SAMPLES OF 316L AND 304 STAINLESS STEEL IN SALINE SOLUTION

6.1. MATERIAL AND METHODS

Our aim was to observe stress corrosion cracking behavior on austenitic stainless-steel specimens which were welded by the TIG technique in halide solutions such as NaCl.

The tested specimens, stainless steel type 304 and 316L, were obtained from cutting on the longitudinal direction in respect to the rolling direction of the steel sheet.

The material used was 3 mm thick 304 and 316L stainless steels sheets. The chemical compositions of the alloys are shown in [Table 4.1](#).

The ultimate tensile strength, yield tensile strength, Area of reduction, and elongation of the used material are presented in [Table 5.1](#).

From sheets, 2000×1000×3 mm, standard stress corrosion cracking (SSC) specimens parallel to the rolling direction were cut using a laser. Specimen's Dimensions for two types of AISI 304 and AISI 316L are 100×9×3 mm (three specimens for every type). [\[99\]\[100\]](#)

The sample dimensions used for stress corrosion cracking tests are illustrated in [Figure 6.1](#).

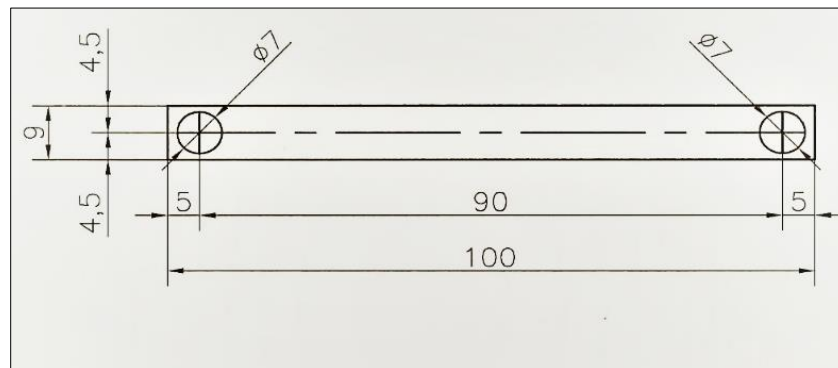


Fig. 6.1 The dimension of the samples used in stress corrosion cracking testing experiments

[Figure 6.2](#) indicates Standard non-welded SCC specimens of AISI 304 and AISI 316L austenitic stainless steel.



Fig. 6.2 Standard non-welded SCC specimens of AISI 304 and AISI 316L austenitic stainless steels

Every specimen was cut in the middle by a traditional shearing machine after that two halves were welded together by TIG.

Welding parameters are shown in [Table 6.1](#).

Table 6. 1 Welding parameters used

specimens	Welding method	Welding current (A)	Shielding gas	Welding voltage (V)	Welding wire
Full specimens					
TIGL304	TIG	80	Argon	20 - 24	308L
TIGL316L	TIG	80	Argon	20 - 24	316L

Sample coding reflects the welding process used, TIG - tungsten inert gas welding, the alloy, 304 or 316L, and the sample orientation, L – longitudinal.

The chemical composition for wire welding was used for welded specimens shown in [Table 5.3](#). Whereas 304 specimens were welded by using ER308L filler and 316L specimens were welded by using ER316L filler.

[Figure 6.3](#) indicates Standard welded SCC specimens of AISI 304 and AISI 316L austenitic stainless steel.

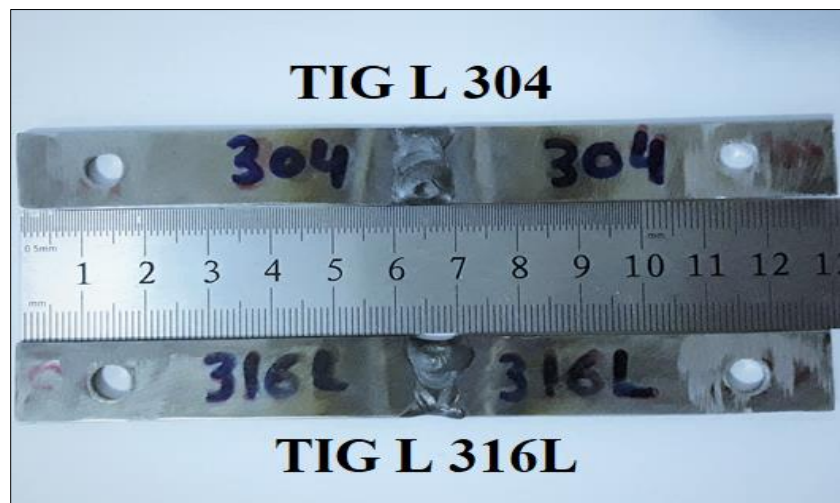


Fig. 6.3 Standard welded SCC specimens of AISI 304 and AISI 316L austenitic stainless steel

dimensions of U-bend specimens that were used for stress corrosion cracking tests are illustrated in [Figure 6.4](#) and [figure 6.5](#).

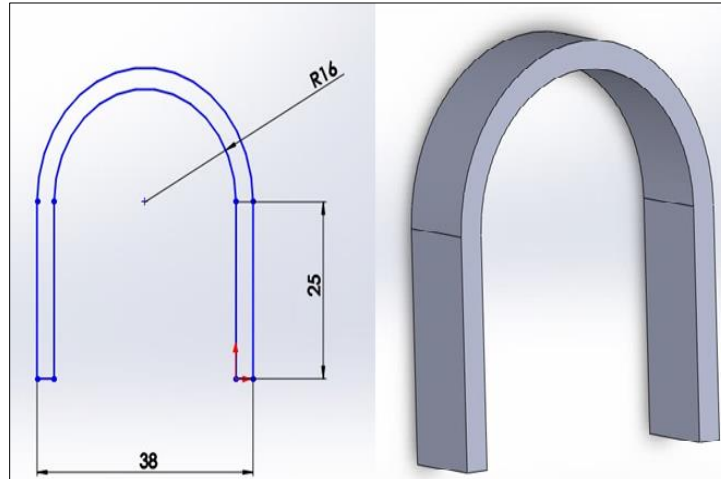


Fig. 6.4 The dimension of standard U-bend specimens used in SCC testing

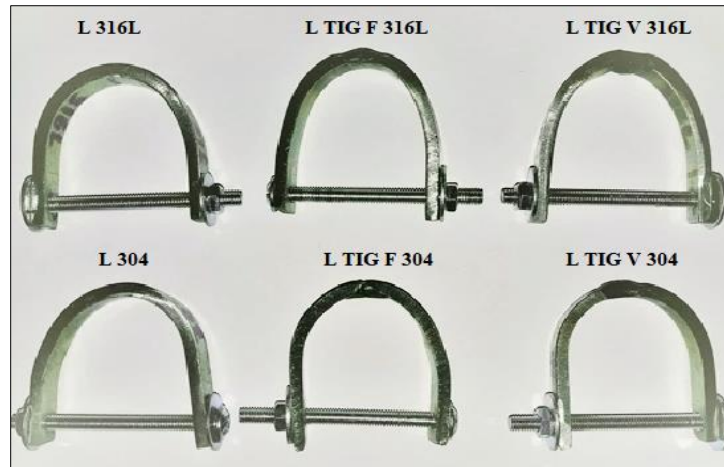


Fig. 6.5 Standard U-bend specimens used in SCC testing of AISI 304 and AISI 316L austenitic stainless steels

6.2. CORROSION TEST

6.2.1. Assessment of corrosion behavior of 304 and 316L austenitic stainless steel joined by TIG welding

Corrosion behavior was determined by the linear polarization technique. This technique consists of drawing the linear polarization curves involving the following steps:

- Measuring the potential of open circuit (E_{oc}), over a period of 3 hours.
- Drawing potentiodynamic polarization curves from $-1V$ (vs OCP) to $+1V$ (vs E_{ref}) with a scan rate of $de 1 mV/s$.

Tests for Assessment of corrosion behavior were performed using a Potentiostat/ Galvanostat (model PARSTAT 4000, producer Princeton Applied Research, USA), but potentiodynamic curves were acquired with the help of the software VersaStudio v.2.44.4.



Fig. 6.6 PARSTAT 4000 model Potentiostat/ Galvanostat device which is using for corrosion test

A corrosion cell consisting of a calomel saturated electrode (SCE) was used to perform the tests.

- the reference electrode, a platinum electrode.
- the recording electrode and the working electrode consisted of specimens which are to be investigated.

Tests were performed in saline solution NaCl 5%, at 25 °C. Before conducting the tests, the specimens were immersed in the electrolyte until stabilization the potential of open circuit (OCP).

Figure 6.7 refers to U-bending specimens of 316L and 304 austenitic stainless steel used in corrosion tests.



Fig. 6.7 Macroscopic images of the specimens tested after conducting the conductor wire

To better elucidate the evolution of open circuit potential and the potentiodynamic curves, these were superimposed by obtaining separate graphs **figure 6.8** and **figure 6.9**.

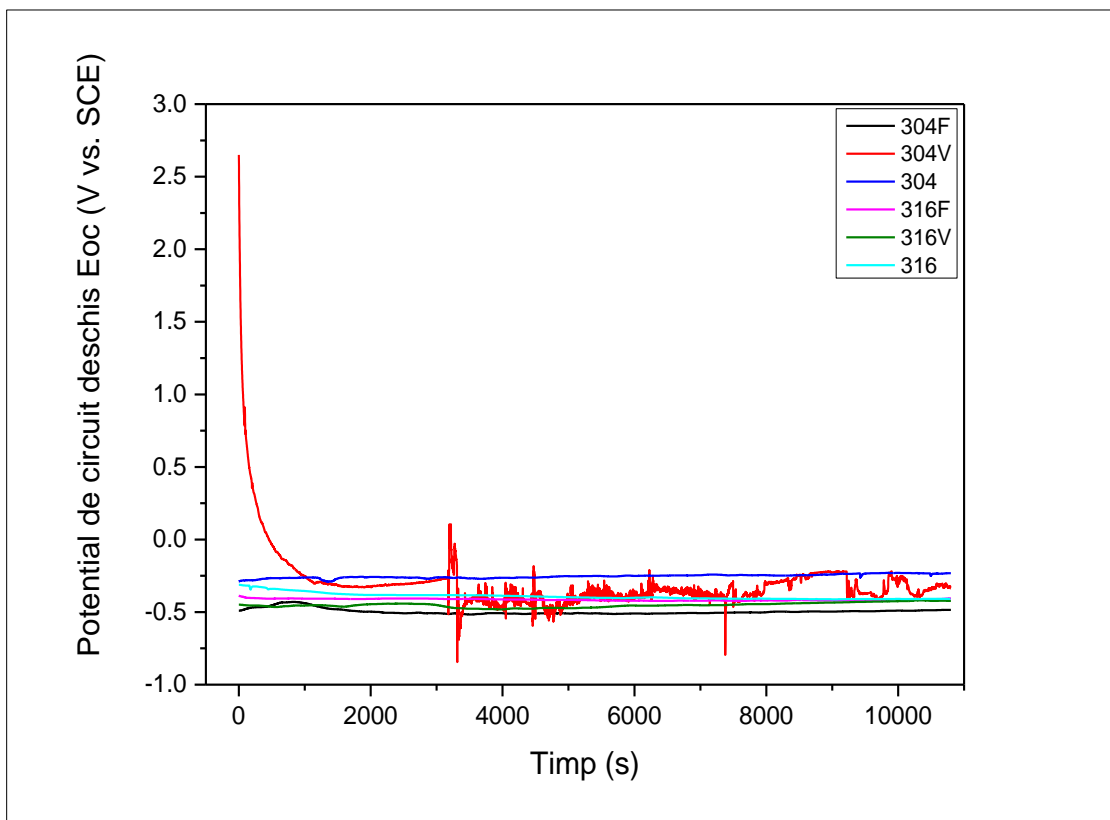


Fig. 6.8 Evolution of open circuit potential (E_{oc}) for all investigated specimens

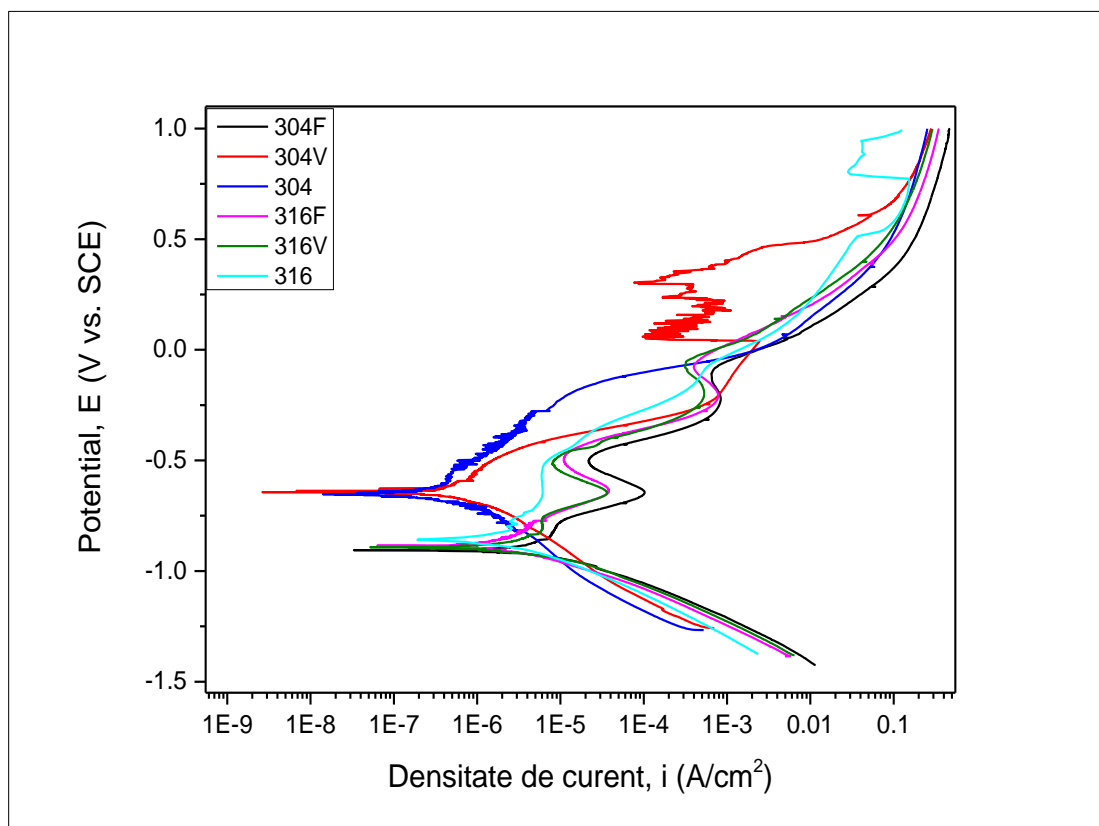


Fig. 6.9 Potentiodynamic curves for all investigated specimens

6.2.2. Discussion result of corrosion test

From the evolution for the potential of open circuit and the potentiodynamic curves that were determined by Tafel extrapolation, the following parameters characterizing the corrosion resistance of the investigated specimens:

- Potential of open circuit (E_{oc}).
- Potential of corrosion (E_{cor}).
- The density of corrosion current (i_{cor}).

The corrosion resistance of the experimental samples was examined based on several evaluation criteria.

The increase of electro-positive values shows a better corrosion behavior, if we consider the potential of open circuit value (E_{oc}). Electrochemical measurements showed that for the 304 alloys, the LTIGV304 specimen shows the most electro-positive value (-268 mV) followed by L304 specimen (-275 mV) and then LTIGF304 (-437 mV). For the 316L alloy, the most electro-positive value is obtained for the LTIGV316L sample but the values of all three specimens are approximately equal (differences are only a few mV).

The increase of electro-positive values shows a better corrosion behavior if we consider the potential of corrosion (E_{cor}). According to this criterion, for the 304 alloys, it is observed the most electro-positive value is obtained for the LTIGV304 (-641 mV), consequently a better corrosion behavior, followed by L304 specimen (-651 mV) and then LTIGF304 (-906 mV). for the 316L alloy, the L316L shows the most electro-positive value by comparing the potential of corrosion for 316L alloy, but in this case, the values are quite close.

A low current density of corrosion indicates a good corrosion resistance. Thus, taking into account this criterion, for the 304 alloys, the lowest value of the corrosion current density is obtained for the L304 specimen ($0.399 \mu\text{A}/\text{cm}^2$) and for the 316L alloy, the LTIGF316L specimen with a value of ($2.797 \mu\text{A} / \text{cm}^2$), as shown in [figure 6.10](#).

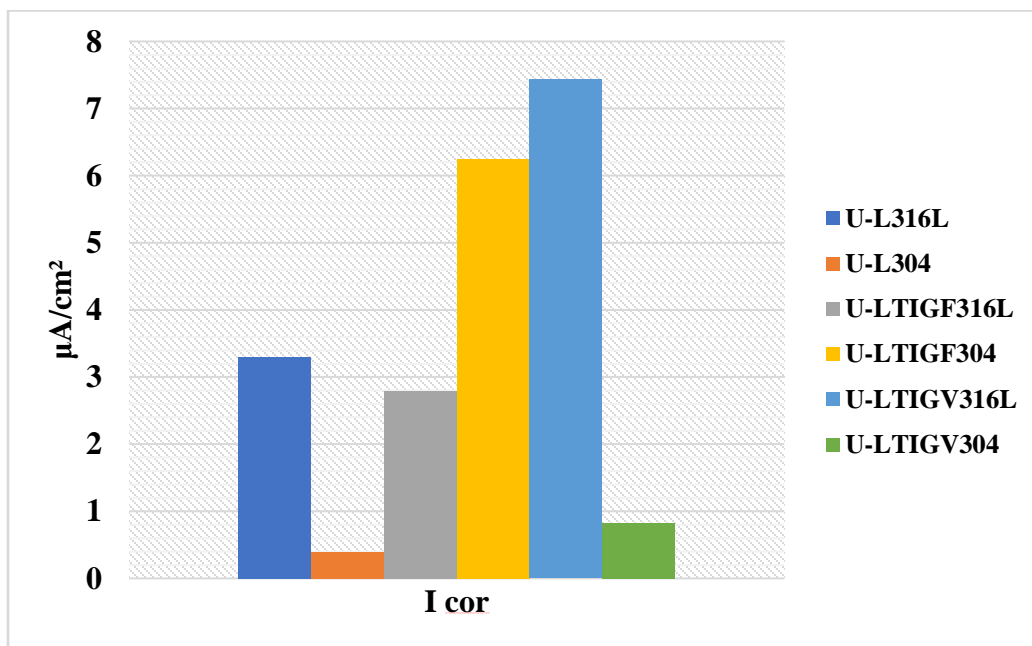


Fig. 6.10 Chart of current density for all investigated specimens

6.3. SEM RESULT

6.3.1. U-L316L & U-L304 Specimens

Figure 6.11 shows SEM micrographs in the face bend of U-L304 alloy which used in this study. From the results of the surface show, there are cracks on the outside surface. These cracks were mostly intergranular. This result is in accordance with previous scintifical researches.

We notice that the depth of the pit arrives at 75 μ m. And also, it is noticed that the shape of the Pit is often vertical.

Figure 6.11 shows SEM micrographs of U-L316L alloy used in this study. The results of the surface show, there are defects in the outside and inside surface (pitting corrosion).

Therefore, it was noticed that there was a destruction of the passive film of the 316L specimen that was exposed to stress in the experimental environment (such as seawater) because the seawater contains chloride ions which attack the passive film. This result is in accordance with previous scintifical researches.

We notice that the depth of the pit arrives at 50 μ m. And also, it is noticed that the shape of the pit is often vertical.

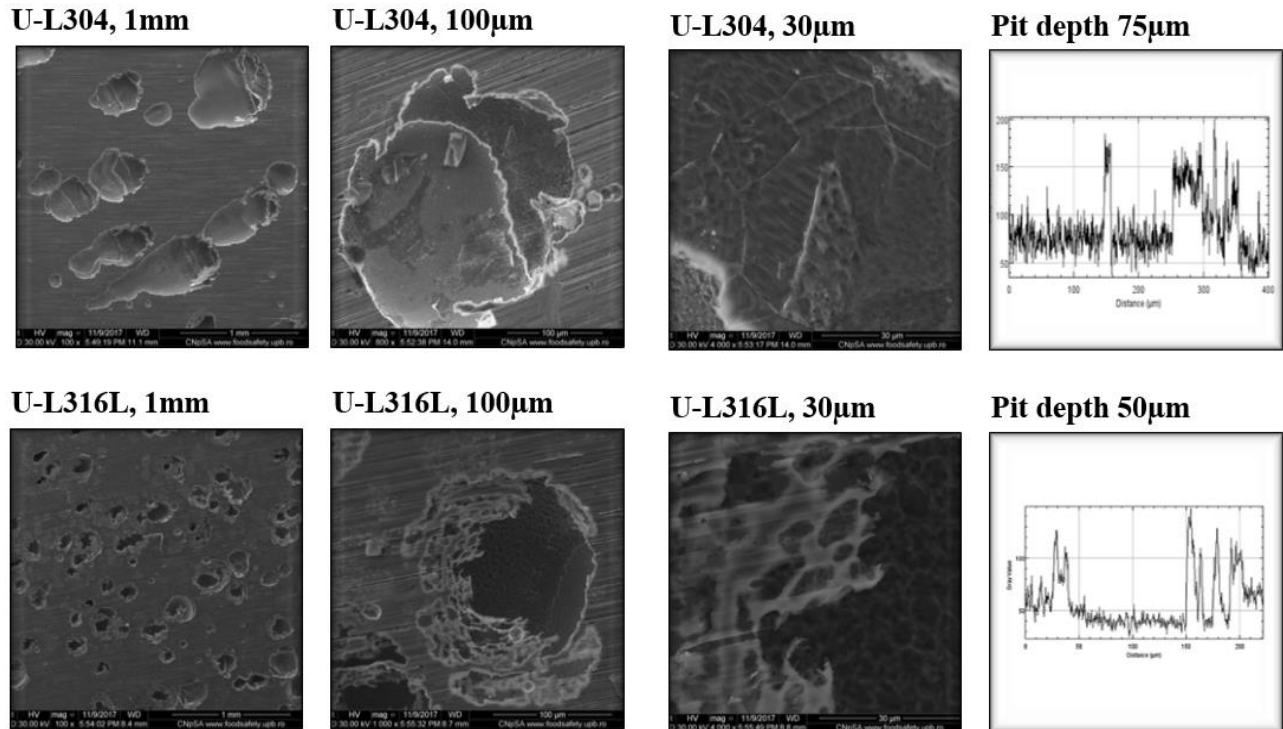


Fig. 6.11 SEM image, 3D image and curve of topography for U-L316L & U-L304 Specimens

6.3.2. U-LIGF316L & U-LIGF304 Specimens

Figure 6.12 shows SEM micrographs in the face bend of U-LTIGF304 alloy used in this study. From the results of the surface show, there is a defect in the outside surface.

we studied three zones: base material, heat affected zone (HAZ) and weld metal as follows:

BM zone: from the SEM images of the U-LTIGF304L specimen, it is observed appearance fatigue beach marks which one of the types of fatigue fracture;

WM zone: it is found a rectangular defect in the outside surface; these defects are as a pitting with fatigue. We observed that there appears transgranular fracture at interior pits, this due to several factors such as thermal stresses by welding process and stresses by bending test;

HAZ zone: we noticed appearance fatigue line in the fatigue fracture surface. This result is in accordance with previous scientific researches.

We notice that the depth of the pit arrives at approximate 75 μm . It is noticed that the shape of the Pitting by ASTM is vertical. This result is in accordance with previous scientific researches.

Figure 6.12. shows SEM micrographs in the face and root of U-LTIGF316L alloy used in this study. Results of the surface show that there is a defect or micro-cracks in the outside and inside surface.

We studied three zones: base material, heat affected zone (HAZ) and weld metal, as follows:

BM zone: from the SEM result of the U-LTIGF316L specimen, fatigue beach marks appear which is one of the types of fatigue fracture;

HAZ zone: we noticed the appearance of fatigue line in the fatigue fracture surface;

WM zone: by SEM result, we found that there is a rectangular defect in the outside surface, these defects are as a pitting.

We notice that the depth of the pit arrives at 100 μm . And also, it is noticed that the shape of the pit is often vertical. This result is in accordance with previous scientific researches. [4][101]

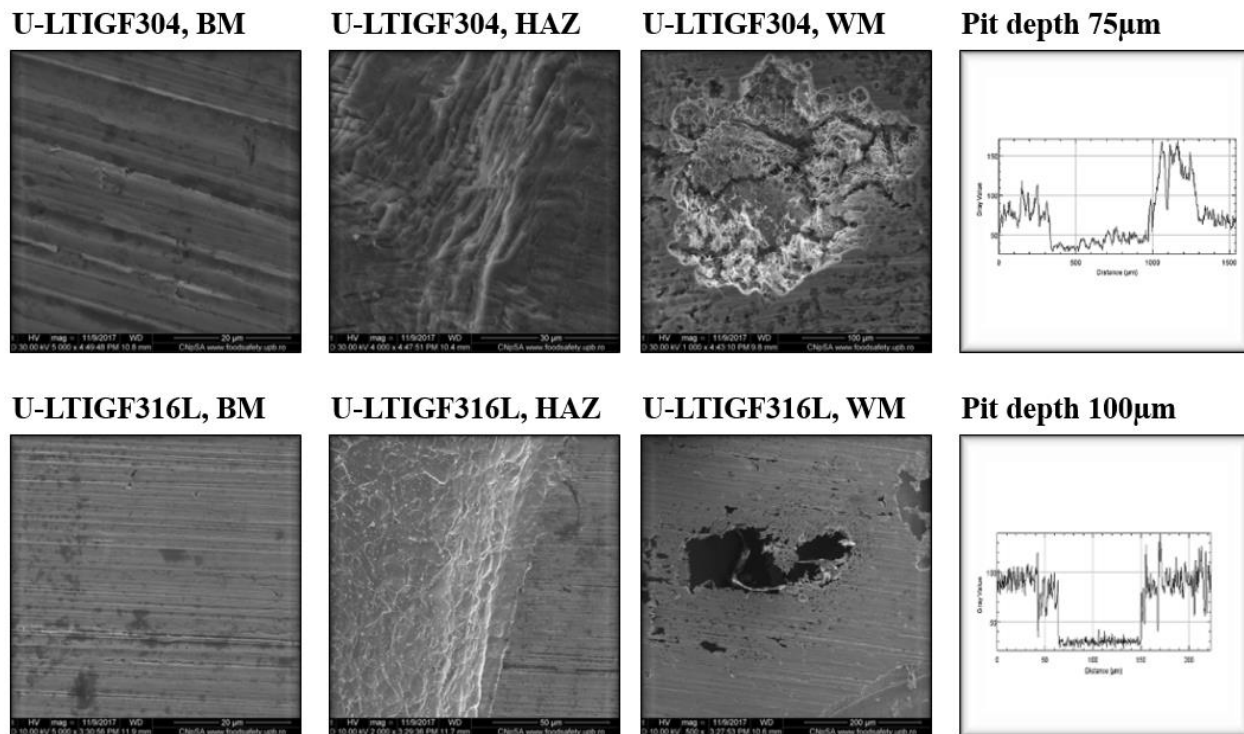


Fig. 6.12 SEM image, 3D image and curve of topography for U-LIGF316L & U-LIGF304 Specimens

6.3.3. U-LIGV316L & U-LIGV304 Specimens

Figure 6.13 shows SEM micrographs in the face bend of U-LTIGV304 alloy used in this study. From the results of the surface show, there is a defect and micro-cracks on the inside surface.

We studied three zones: base material (BM), heat affected zone (HAZ) and weld metal (WM) as follows:

BM zone: from the SEM images of the U-LTIGV304 specimen and by comparison with the other previous scientific researches, it is observed appearance fatigue stair line which one of the types of fatigue fracture. This type of fatigue fracture created through propagation different cracks at different duration and directions;

WM zone: by SEM images, we found that there is a defect in the surface, these defects are pitting corrosion;

HAZ zone: we noticed that there appears a fatigue line in the fatigue fracture surface.

Figure 6.13 shows SEM micrographs in the face bend for the U-LTIGV316L specimen which used in this study. From the results of the surface show, there is a defect or micro-cracks on the outside surface.

We studied three zones: base material, heat affected zone (HAZ) and weld metal as follows:

BM zone: from the SEM images of the U-LTIGV316L specimen, it is observed fatigue beach marks in the surface layer which one of the types of the fatigue fracture;

WM zone: it is found that there is a rectangular defect in the outside surface, these defects are as pitting corrosion;

HAZ zone: it is noticed that appearance fatigue line in the fatigue fracture surface.

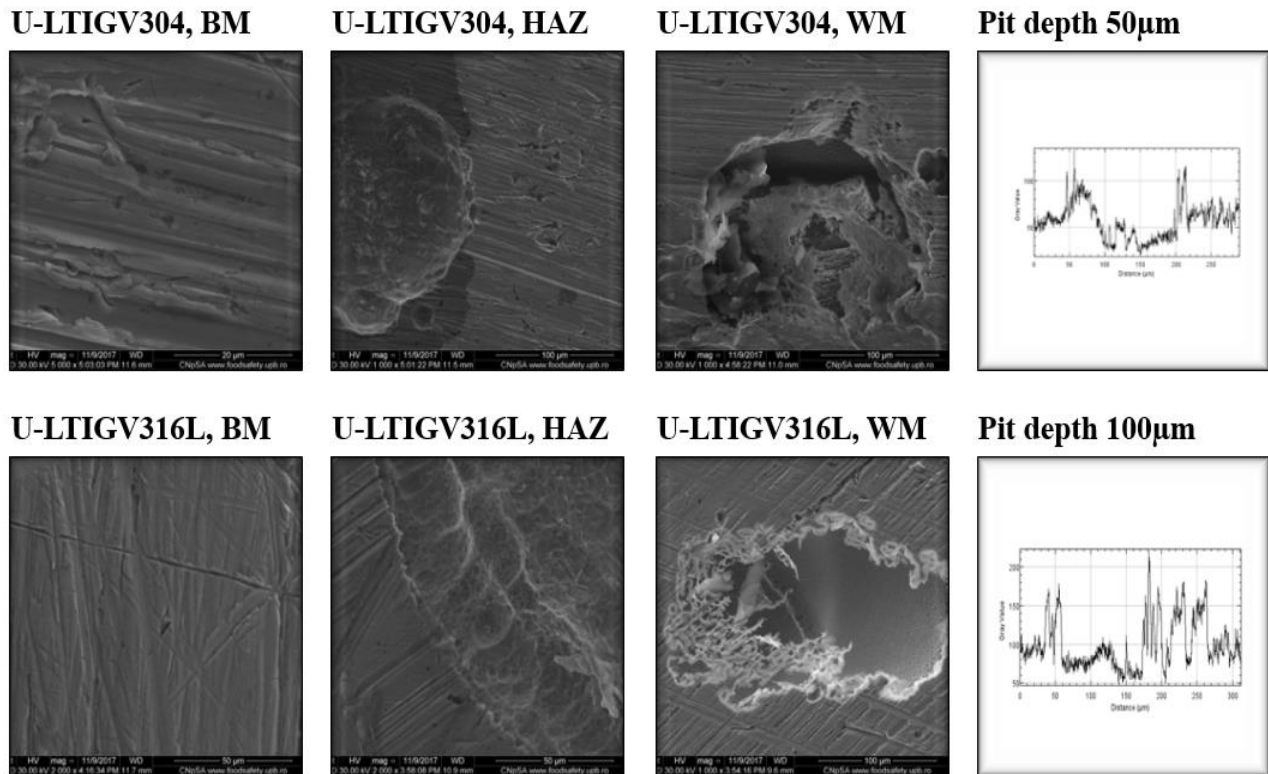


Fig. 6.13 SEM image, 3D image and curve of topography for U-LIGV316L & U-LIGV304 Specimens

6.4. EDX RESULT

6.4.1. U-LTIGF316L specimen

It can be seen in **figure 6.14**, two regions by using EDX spectra is analyzed: pit region from WM zone and pit region from BM zone, as follows:

In the zones WM and BM that are taken from the pit of U-LTIGF316L specimen the peaks for carbon, chromium, nickel, oxygen, silicon, molybdenum and iron elements are present.

Increased oxygen content and decreased carbon content in the WM zone, by comparison with the BM zone, has also been observed.

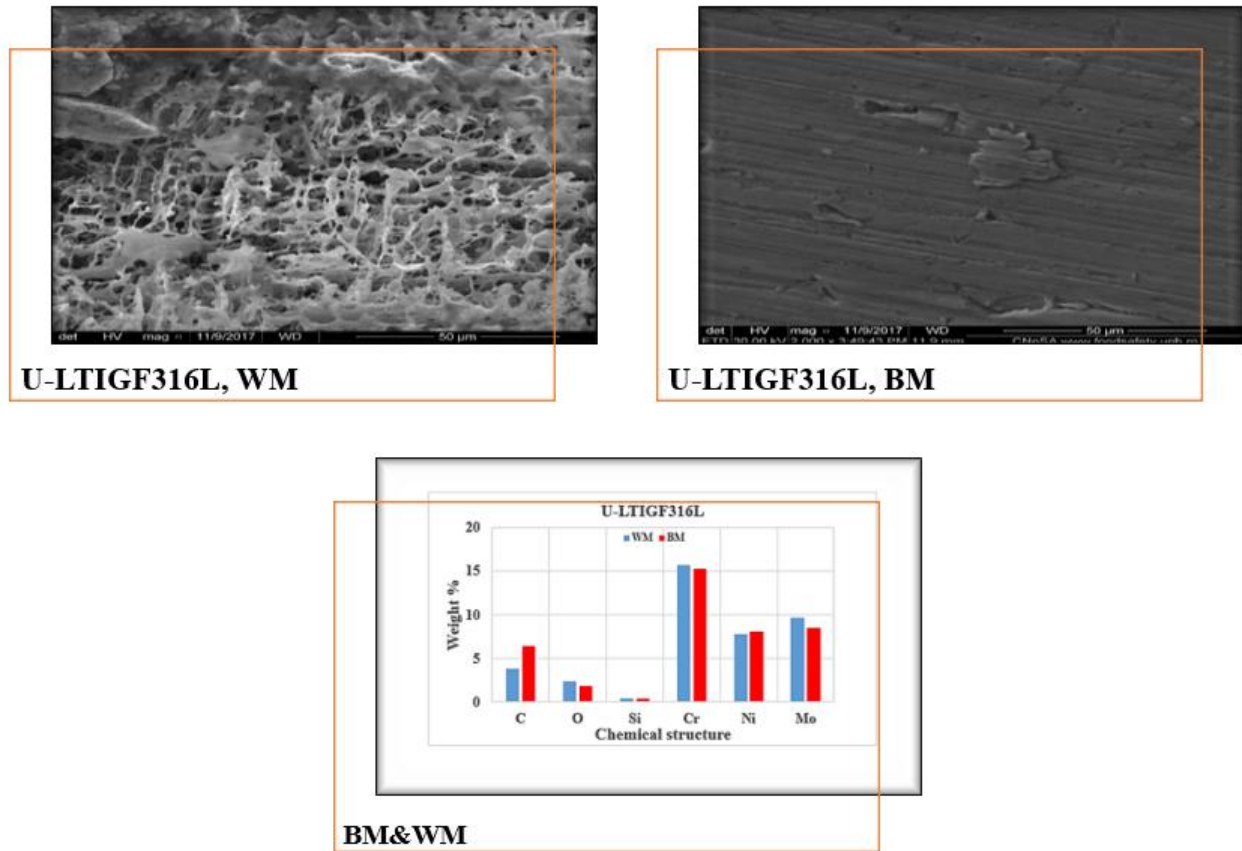


Fig. 6.14 SEM image and EDX results of the face bend for LTIGF316L specimen (WM&BM zones)

6.4.2. U-LTIGF304 specimen

By using EDX over two regions which are pit region (WM and BM), the following has been observed:

In the zones WM and BM that are taken from the pit of U-LTIGF304 specimen, the peaks for carbon, chromium, nickel, oxygen, silicon, and iron elements are present.

An increased chromium content and decreased carbon content and oxygen content in the WM zone, by comparison with the BM zone, has also been observed. **Figure 6.15.**

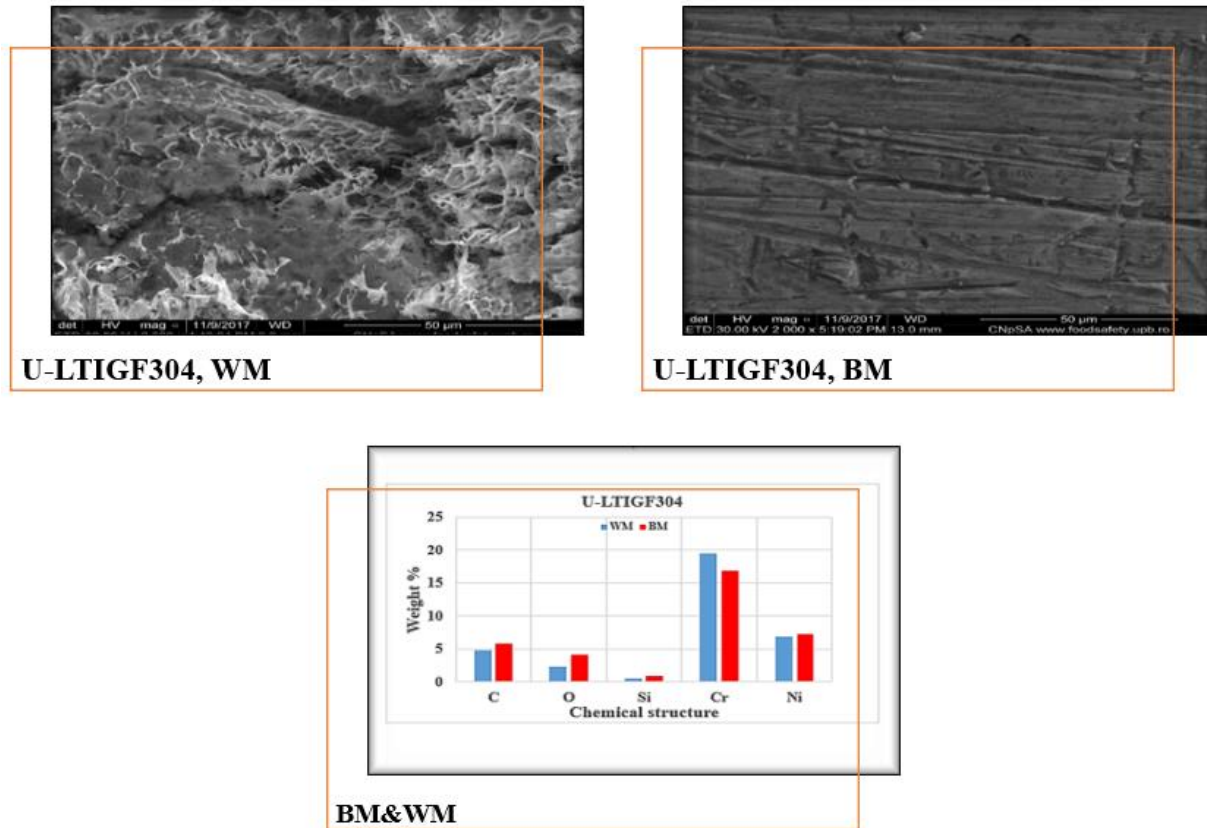


Fig. 6.15 SEM image and EDX results of the face bend for LTIGF304 specimen (WM&BM zones)

6.5. CONCLUSIONS

Electrochemical test using PARSTAT 4000 device is shown the following conclusions, according to current density:

- For 304 samples, it was observed that the best samples by order are: U-L304, U-LTIGV304 then U-LTIGF304.

- The test for the non-welded sample (U-L304) has proven that it was the best, by comparison with the welded samples using the TIG technique.

- For 316L samples, it was observed that the best samples by order are: U-LTIGF316L, U-L316L then U-LTIGV316L.

- The test for the welded sample (U-LTIGF316L) has proven that it was the best, by comparison with the welded sample using TIG technique and non-welded sample.

- By comparison between 316L and 304, it was noticed that the 304 alloy is better, because, it has a good corrosion resistance according to the experimental results.

SEM images are shown in the following conclusions:

- The U-316L sample was exposed to pitting corrosion that seems like small holes scattering on the outside surface. According to the ImageJ program, it was found that the depth of the pits arrived up to 50 μm .

- The U-LTIGF316L and U-LTIGV316L sample {[all zones (BM, HAZ, and WM)] and [all sides (face bend and root bend)]} were exposed to pitting corrosion and fatigue fracture. According to the ImageJ program, it was found that the depth of the pits arrived up to 80 μm for U-LTIGF316L and up to 40 μm for U-LTIGV316L.

- The U-304L sample was exposed to pitting and intergranular corrosion. According to the ImageJ program, it was found that the depth of the pits arrived up to 75 μm .

- The U-LTIGF304L and U-LTIGV304L sample {[all zones (BM, HAZ, and WM)] and [all sides (face bend and root bend)]} were exposed to pitting corrosion, transgranular corrosion, and fatigue fracture. According to the ImageJ program, it was found that the depth of the pits arrived up to 75 μm for U-LTIGF304L and up to 60 μm for U-LTIGV304.

CHAPTER 7

7 GENERAL CONCLUSIONS AND FUTURE RESEARCH DIRECTION

7.1. GENERAL CONCLUSIONS

Carrying out a program of comparative experiments on the mechanical behavior of austenitic stainless steels 304 and 316L, which allowed to emphasize the influence of the welding process, the existence of defects and the influence of the direction of orientation, on eight comparative groups of tests (either longitudinally-transversely, either on stainless steel type);

All the results exist in the following:

For samples of Group A (T304, L304, HT304, and HL304):

According to tensile properties, it was observed that the best samples by order are: L304, T304, HL304 then HT304.

According to hardness properties: it was noticed an increase in characters of hardness for the samples with defects (HT304, HL304), and that is by making a comparison with the regular samples (T304, L304).

According to the effect of defects, it was registered that the existence of defects increased the hardness properties and decreased the tensile properties.

According to samples orientations, it was observed the increase of tensile properties for L304, by comparing it with T304, but no differences in the hardness properties had been registered.

For samples of Group B (T316L, L316L, HT316L, and HL316L):

According to tensile properties, it was observed that the best samples by order are: T316L, L316L, HL316L then HT316L.

According to the hardness properties, it was noticed an increase in characters of hardness for the regular samples (T316L, L316L), by comparing them with the samples with defects (HL316L, HT316L).

According to the effect of defects, it was registered that the existence of defects decreased the tensile properties and hardness properties.

According to sample orientations, it was observed the increase of tensile properties for T316L, in comparison with L316L, but no differences in the hardness properties had been registered.

For samples of Group C (ELT304, ELL304, TIGHT304, and TIGHL304):

According to the tensile properties, it was observed that the best samples by order are: ELT304, ELL304, TIGHT304 then TIGHL304.

According to the hardness properties, it was noticed an increase in characters of hardness for the samples with defects that were welded by TIG (TIGHT304, TIGHL304), in comparison with the regular samples that were welded by MMAW (ELT304, ELL304).

According to the welding process, the TIG welding increased the hardness properties and decreased the tensile properties. On the contrary, MMAW welding increased tensile properties and decreased hardness properties.

For samples of Group D (ELT316L, ELL316L, TIGHT316L, and TIGHL316L):

According to the tensile properties, it was observed that the best samples by order are: TIGHT316L, TIGHL316L, ELL316L then ELT316L.

According to the hardness properties, it was noticed an increase in characters of hardness for the regular samples that were welded by MMAW (ELT316L, ELL316L), in comparison with the samples with defects that were welded by TIG (TIGHL316L, TIGHT316L).

According to the welding process, MMAW welding increased hardness properties and decreased tensile properties. On the contrary, TIG welding increased tensile properties and decreased hardness properties.

For samples of Group E (T304, L304, T316L, and L316L):

According to the tensile properties, no differences in the tensile properties had registered.

According to the hardness properties, the samples (L316L, T316L) have hardness properties better than the samples (T304, L304).

For samples of Group F (HT304, HL304, HT316L, and HL316L):

According to the tensile properties, no differences in the tensile properties had been registered.

According to the hardness properties, the samples (HT304, HL304) have hardness properties better than the samples (HL316L, HT316L).

According to the effect of defects, it was registered that when defects have existed, 304 alloy behavior was better than alloy 316L.

For samples of Group G (ELT304, ELL304, ELT316L, and ELL316L):

According to the tensile properties, it was noticed an increase in characters of tensile for the samples that were welded by MMAW (ELT304, ELL304), by comparison with the samples which were welded by MMAW (ELL316L, ELT316L).

According to the hardness properties, it was registered that the samples (ELL316L, ELT316L) have hardness properties better than the samples (ELT304, ELL304).

According to the welding process using the MMWA technique, it was observed that the samples (ELT304, ELL304) have tensile properties better than the samples (ELL316L, ELT316L). On the contrary, if hardness properties were compared

For samples of Group H (TIGHT304, TIGHL304, TIGHT316L, and TIGHL316L):

According to the tensile properties, it was noticed an increase in characters of tensile for the samples that were welded by TIG (TIGHL316L, TIGHT316L), in comparison with the samples which were welded by TIG (TIGHT304, TIGHL304).

According to the hardness properties, the samples (TIGHT304, TIGHL304) have hardness properties better than the samples (TIGHL316L, TIGHT316L).

According to the welding process using TIG technique, it was observed that the samples (TIGHL316L, TIGHT316L) have tensile properties better than the samples (TIGHT304, TIGHL304). On the contrary, if hardness properties were compared.

Carrying out an extensive program of experiments regarding the behavior of electrochemical corrosion of austenitic stainless steels of type 304 and 316L, in chlorinated environments (6% solution of calcium chloride, manganese chloride and iron chloride) in different states (welded and non-welded) or different areas of the weld. The experiments were performed comparatively, in a welded and non-welded state, being presented in different modes of investigation - stereomicroscopy, optical microscopy, electron microscopy, topographic analysis, which allowed to draw relevant conclusions, helping to complete the database in the field of corrosion resistance of austenitic stainless steels.

Comparing the resistance state of austenitic stainless steel 304 with 316L (without welding, area BM, WM and HAZ), it was observed that stainless steel 304 exhibited superior behavior to 316L stainless steel in CaCl_2 solution, while in MgCl_2 solution, the results were diametrically opposed. Also, the highest corrosion rate in the thermally influenced area was observed in all samples.

A hierarchical comparison of the austenitic stainless steels 304 and 316L in the tested chlorinated solutions (respectively MgCl_2 , FeCl_3 and CaCl_2) was performed, as follows:

316L stainless steel showed better results than 304 stainless steel in FeCl_3 solution. Also, 316L stainless steel has the best corrosion resistance in MgCl_2 solution, followed by CaCl_2 and then in FeCl_3 solution. The increase in corrosion rate was observed in the HAZ area for all samples.

Stainless steel 304 showed the best results in the CaCl_2 solution, followed by the MgCl_2 solution and then the FeCl_3 solution. The increase in corrosion rate was observed in the HAZ area for all samples.

Carrying out an extensive investigation program under the electron microscope, which allowed to highlight the corrosion mechanisms, the morphology of the breaking surfaces, as well as the identification of the corrosion forms compared to the austenitic stainless steels 304 and 316L.

Carrying out an extensive program of experiments regarding the behavior of electrochemical corrosion of U-samples of type 304 and 316L, in 5% solution of sodium chloride in different states (welded and non-welded) and different directions (root bend and face bend). The experiments were performed comparatively, in a welded and non-welded state, being presented in different modes of investigation - stereomicroscopy, optical microscopy, electron microscopy, topographic analysis, which allowed to draw relevant conclusions, helping to complete the database in the field of corrosion resistance. of austenitic stainless steels.

Conclusions were obtained by using PARSTAT 4000 device to determine the corrosion resistance on the U-samples that are exposed to static stress in 5% sodium chloride solution, as following:

- For 304 samples, it was observed that the best samples by order are: U-L304, U-LTIGV304 then U-LTIGF304.

- The test for the non-welded sample (U-L304) has proven that it was the best, by comparison with the welded samples using the TIG technique.

- For 316L samples, it was observed that the best samples by order are: U-LTIGF316L, U-L316L then U-LTIGV316L.

- The test for the welded sample (U-LTIGF316L) has proven that it was the best, by comparison with the welded sample using TIG technique and non-welded sample.

- By comparison between 316L and 304, it was noticed that the 304 alloy is better, because, it has good corrosion resistance according to the experimental results.

Carrying out an extensive investigation program under the electron microscope, which allowed highlighting the corrosion mechanisms, the morphology of the breaking surfaces, as well as the identification of the corrosion forms compared to the austenitic stainless steels 304 and 316L.

7.2. FUTURE RESEARCH DIRECTION

In the current work, corrosion tests were carried out on welded and non-welded joints of austenitic stainless-steel types 304 and 316L at room temperature but the performance of the metal regarding mechanical properties was not recognized during the corrosion test in chlorine-containing salts. I therefore recommend the following:

- Both metals are to be studied in subsequent research at room temperature by applying a constant tensile stress on the welded and non-welded metal joints during the corrosion test of the metal, and repeat experiment at certain limits of tensile stress, for example, applying even stress to the yield strength of the metal, observing the action of the metal through tensile curves in the corrosive environment and repeat this with certain percentages on other samples. For example, 10%, 20%, 30%, 40%, etc. of yield strength, or taking into account the practical reality of the environment in which the metal is to be used especially in tensile conditions.

- Welded and non-welded joints can also be tested on bending by applying a fixed percentage of a given load and increasing this percentage with known values on other samples, all this during the completion of the corrosion test where we can also monitor the performance of the metal and apply the results in the practical reality.

- It is also possible to do the same for the hardness properties where the corrosion test can be carried out periodically and the changes in hardness can be monitored over time if possible.

- The previous steps can also be performed in similar conditions in terms of chlorine-containing mineral salts, but at high or medium temperatures.

- The researcher can benefit from the results of this research as well as the research group contained in the following references [105, 106, 107, 108, 109]. And annexes 2 will include forms of samples that can be used to perform tensile, bending and hardness tests of standard dimensions.

7.3. RESULTS DISSEMINATION

7.3.1. Published papers

1. **A. A. Harb** et al., “*Effect of TIG Welding and Manual Metal Arc Welding on Mechanical Properties of AISI 304 and 316L Austenitic Stainless Steel Sheets*”, Key Eng. Mater., ISSN: 1662-9795, vol. 750, pp. 26–33, 2017.
DOI:10.4028/www.scientific.net/KEM.750.26
2. **A. A. Harb**, et al. “*Investigation of Mechanical Properties and Corrosion Behavior For 1010 Carbon Steel Pipes Used for Steam Boilers*”, Annals of the University “Dunarea de Jos” of Galati: Fascicle IX, Metallurgy & Materials Science, 2017, 35.1, ISSN 1453-083X
3. **A. A. Harb**, I. Ciuca, and B. Rahali, “*Investigation the Corrosion of Heat Transferring Unit in Hydrogen Peroxide & Sodium Chloride Solution Using Weight Loss,*” scientific bulletin of Politehnica University of Bucharest (B). vol. 79, 2017, ISSN 1454-2331.
4. **HARB, A. A.**, Ciuca, I., Vasile, M., & Alqasim, M. “*The Effect Of TIG Welding On Corrosion Behavior For U- Bend Specimens Of 316l Austenitic Stainless-Steel Joints In Saline,*” scientific bulletin of Politehnica University of Bucharest (B). vol. 80, 2018, ISSN 1454-2331.
5. Bilel, R., and **A. A. Harb**. “*Impact of the information system on decision-making within the company,*” 2017 9th International Conference on Electronics, Computers and Artificial Intelligence (ECAI). IEEE, 2017.
DOI: 10.1109/ECAI.2017.8166390
6. RAHALI, B., & **HARB, A. A.** (2017). “*Object-Oriented Architecture for Product Information System Engineering*”, Annals of the University “Dunarea de Jos” of Galati: Fascicle IX, Metallurgy & Materials Science, 2017, 35.1, ISSN 1453-083X.
7. ALSABTI, M. A., CIUCA, I., VASILE, B. Ş., **ABOU HARB, A.**, & TRUSCA, R. “*the effect of different surfaces roughness of TI6AL4V alloy on silver doped hydroxyapatite coating*”, scientific bulletin of Politehnica University of Bucharest (B). Vol. 82, Iss. 1, 2020. ISSN 1454-2331.
8. ALSABTI, M. A., CIUCA, I., VASILE, B. Ş., TRUSCA, R., & **HARB, A. A.** “*effect of surface roughness TI6AL4V modified by hydroxyapatite coating*”, the annals of “dunarea de jos” university of Galati: fascicle ix, metallurgy and materials science No. 4 - 2018, ISSN 2668-4748; e-ISSN 2668-4756.
DOI: <https://doi.org/10.35219/mms.2018.4.06>.

7.3.2. International conferences participation

1. **A. A. Harb.**, I. Ciuca., R. Ciocoiu., M. Vasile., A. Bibis., B. Rahali., I. Hawamda., “Effect of TIG Welding and Manual Metal Arc Welding on Mechanical Properties of AISI 304 and 316L Austenitic Stainless Steel Sheets”, Poster P10, ROMAT 2016, 09th -12th November 2016, Bucharest, Romania, *6th International Conference on Materials Science and Technologies*.
2. **A. A. Harb.**, I. Ciuca., B. Rahali., R. Gheța., “Investigation of Mechanical Properties and Corrosion Behaviour for 1010 Carbon Steel Pipes Used for Steam Boilers”, Poster, TEME 2017, 25th -27th of October, Galați, Romania, *4th Edition Of The International Conference “New Trends In Environmental And Materials Engineering*.
3. B. Rahali., **A. A. Harb.**, “Object-Oriented Architecture for Product Information System Engineering”, Poster, TEME 2017, 25th -27th of October, Galați, Romania, *4th Edition of The International Conference “New Trends in Environmental and Materials Engineering*.
4. B. Rahali., **A. A. Harb.**, “Impact of The Information System on Decision-Making Within the Company”, ECAI 2017, 29 June - 01 July, Targoviște, Romania, *9th International Conference Edition Electronics, Computers, And Artificial Intelligence*.
5. F. Mohammed Alqasim., I. Ciuca., **A. A. Harb.**, B.S. Vasile., R. Trusca., “Effect of titanium surface roughness modified by hydroxyapatite coating”, Poster P20, BRAMAT 2019, 13th – 16th of March, Brașov, Romania, *11th International Conference on Materials Science and Engineering*.
6. **Alaa ABOU HARB**, Ion CIUCA, Mohammed ALQASIM FAYEQ, Mihai VASILE., “corrosion behavior for u- bend samples of 304 austenitic stainless-steel joints which welded by TIG in saline solution”, TEME 2019, 23th -25th of October, Galați, Romania, *4th Edition Of The International Conference “New Trends In Environmental And Materials Engineering*.
7. Mohammed ALQASIM FAYEQ, Ion CIUCA, Bogdan ȘTEFAN VASILE, **Alaa ABOU HARB**, Roxana TRUSCA., “The effect of different surfaces roughness of ti6al4v alloy on silver doped hydroxyapatite coating”, TEME 2019, 23th -25th of October, Galați, Romania, *4th Edition of The International Conference “New Trends in Environmental and Materials Engineering*.

References

- [1] *Outokumpu stainless steel*, Handbook of Stainless Steel. Finland: outokumpu oyj, 2013.
- [2] *G. Koch, J. Varney, N. Thompson, O. Moghissi, M. Gould, and J. Payer*, “International Measures of Prevention, Application, and Economics of Corrosion Technologies Study,” NACE Int., pp. 1–3, 2016.
- [3] how2stats, “Watch @ www.Youtube.Com,” What is Cronbach’s Alpha? Explained Simply. 2015.
- [4] *G. S. Frankel*, “Corrosion: Fundamentals, Testing, and Protection,” ASM Handb., vol. 13A, pp. 44073–2, 2003.
- [5] *E. K. Brooks, R. P. Brooks, and M. T. Ehrensberger*, “Effects of simulated inflammation on the corrosion of 316L stainless steel,” Mater. Sci. Eng. C, vol. 71, pp. 200–205, 2017.
- [6] Kopeliovich, “Doku @ Www.Substech.Com.” 2012.
- [7] Uhlig’s, “Uhlig’s Corrosion Handbook,” p. 1285, 2011.
- [8] *A. P. Serra*, “World’s largest Science, Technology & Medicine Open Access book publisher,” Biomass Now- Sustain. growth use, 2013.
- [9] *A. A. Harb, I. Ciuca, and B. Rahali*, “Investigation the Corrosion of Heat Transferring Unit in Hydrogen Peroxide & Sodium Chloride Solution Using Weight Loss,” vol. 79, 2017.
- [10] *J. Beavers and T. A. Bubenik*, Stress corrosion cracking. Elsevier Ltd, 2017.
- [11] *C. Garcia, M. P. de Tiedra, Y. Blanco, O. Martin, and F. Martin*, “Intergranular corrosion of welded joints of austenitic stainless steels studied by using an electrochemical minicell,” Corros. Sci., vol. 50, no. 8, pp. 2390–2397, 2008.
- [12] <http://faculty.kfupm.edu.sa/ME/hussaini/Corrosion%20Engineering/04.05.01.htm>
- [13] “*McNaughton, K. J.* ‘Materials Engineering Volume II: Controlling Corrosion in Process Equipment.’ McGrawHill Book Co., NewYork. McSweeney, EE (1965) Off. Di g 37 (1980): 626 .,” vol. II, no. 1965, p. 1980, 1980.
- [14] “*Bridges, C. E., and M. A. Clarke.* ‘The importance of corrosion monitoring in oilfield system.’ Middle East Corrosion Conference . 1979 .,” p. 1979, 1979.
- [15] “*Petersen, P. R.* ‘Improve corrosion control by computer simulation.’ Hydrocarbon Processing:(United States) 71, no. 1 (1992).,” vol. 1, no. 1, p. 1992, 1992.
- [16] *Dilon, C.P. (1990)* "Corrosion control in the chemical process industries", McGraw – Hill, Book company.
- [17] Chemical engineering, (1970) "Engineering material", Oct. 12, 1970.
- [18] *Burns, R.M. and Bradley, W .W. (1967)* "Protective coatings for Metals ", 3 rd Ed, Reihold, New York.
- [19] *Mc naughton j. Kenneth and The Staff of Chemical Engineering, (1980)* "controlling Corrosion in Process Equipment", Materials Engineering II, McGraw – hill Publication Company. 73
- [20] hilti, corrosion handbook, may 2015.
- [21] *Lee, H. and Neville, K. (1967)* "Handbook of epoxy resins", McGrow –Hill, New York.
- [22] *Fontana G. Mars, (1965)* "Corrosion Engineering", Third Edition, Mc Graw Hill Book Company.
- [23] *Henthorne, M. (1971)* "Control the process and control corrosion ",chem. . . eng., Oct. 18, 1971.
- [24] *Van Dijk, J. (1984)* "The use of surfactants as corrosion inhibitor in oil production systrms". Servo delden bv
- [25] *Gentilveci, A. (1998)* "Technical reference notes", Chemic company, Rome, December 7th1998.
- [26] *Van Dijk, J. (1983)* "Contact and reaction time to form aprotective film with corrosion inhibitor ". Servo delden bv.
- [27] *Herbert h. Uhlig, (1948)* "Corrosion handbook", Juhn Wiley and Sons, Inc, USA.
- [28] www.dm-consultancy.com/TR/dosya/1-59/h/aisi-340-info.pdf.
- [29] www.sandmeyersteel.com/images/316-316L-317L-Spec-Sheet.pdf
- [30] Welding processes handbook. 2003.
- [31] http://www.substech.com/dokuwiki/doku.php?id=shielded_metal_arc_welding_smaw.
- [32]http://www.substech.com/dokuwiki/doku.php?id=tungsten_inert_gas_arc_welding_tig_gtaw&s=gas%20tungsten%20arc%20welding.

- [33] http://www.substech.com/dokuwiki/doku.php?id=metal_inert_gas_welding_mig_gmaw&s=gas%20metal%20arc%20welding.
- [34] Welding Handbook, Seventh Edition, Volume 4, Metals and Their Weldability, 1997.
- [35] http://www.substech.com/dokuwiki/doku.php?id=submerged_arc_welding_saw&s=submerged%20arc%20welding.
- [36] http://www.substech.com/dokuwiki/doku.php?id=plasma_arc_welding_paw&s=plasma%20arc%20welding.
- [37] Welding of stainless steels and others joining methods, American iron and steel institute, 1989.
- [38] http://www.substech.com/dokuwiki/doku.php?id=electron_beam_welding_ebw&s=electro%20beam%20welding.
- [39] http://www.substech.com/dokuwiki/doku.php?id=laser_welding_lw&s=laser%20beam%20welding.
- [40] C. Garcia, F. Martin, P. de Tiedra, Y. Blanco, M. Lopez, Pitting corrosion of welded Joints of austenitic stainless steels studied by using an electrochemical minicell, Corrosion Science 50 (2008) 1184–1194.
- [41] B.T. Lu, Z.K. Chen, J.L. Luo, B.M. Patchett, Z.H. Xu, Pitting and stress corrosion Cracking behavior in welded austenitic stainless steel, Electrochimica Acta 50 (2005) 1391–1403
- [42] A.H. Tuthill, Corrosion Testing of austenitic stainless steel weldments, Weld. J.5 (2005) 36–40.
- [43] C. Garcia, M.P. de Tiedra, Y. Blanco, O. Martin, F. Martin, Intergranular corrosion of welded joints of austenitic stainless steels studied by using an electrochemical minicell, Corrosion Science 50 (2008) 2390–2397.
- [44] Y. Cui, Carl D. Lundin, Evaluation of initial corrosion location in E316L austenitic stainless steel weld metals, Mater. Lett. 59 (2005) 1542–1546.
- [45] Y. Cui, Carl D. Lundin, Austenite - Preferential corrosion attack in 316 austenitic stainless steel weld metals, Mater. Des. 28 (2007) 324–328.
- [46] M. Dadfar, M.H. Fathi, F. Karimzadeh, M.R. Dadfar, A. Saatchi, Effect of TIG Welding on corrosion behaviour of 316L stainless steel, Mater. Lett. 61 (2007) 2343–2346.
- [47] C.T. Kwok, S.L. Fong, F.T. Cheng, H.C. Man, Pitting and galvanic corrosion behavior of laser-welded stainless steels, Journal of Materials Processing Technology 176 (2006) 168–178.
- [48] Klimpel, A. & Lisiecki, A. (2007). Laser Welding of Butt Joints of Austenitic Stainless Steel AISI 321. Journal of Achievements in Materials and Manufacturing Engineering, 25, 1, 2007.
- [49] Curcio, F.; et al. (2006). Welding of Different Materials by Diode Laser. Journal of Materials Processing and Technology, 175, 83-89, 2006.
- [50] R. Kovacevic, Welding Processes, ISBN 978-953-51-0854-2, InTech November 21, 2012.
- [51] W. Chuaiphan, L. Srijaroenpramong, Effect of welding speed on microstructures, Mechanical properties and corrosion behavior of GTA-welded AISI 201 stainless steel Sheets, Journal of Materials Processing Technology 214 (2014) 402– 408.
- [52] M. Aliofkhaezrai, Stress Corrosion Cracking, February 20, 2014.
- [53] <http://faculty.kfupm.edu.sa/ME/hussaini/Corrosion%20Engineering/04.05.01.htm>.
- [54] V. Kain, Stress corrosion cracking (SCC) in stainless steels, Bhabha Atomic Research Centre, India, 2011.
- [55] Sedriks A J (1986), ‘Effect of alloy composition and microstructure on passivity of stainless steels’, Corrosion, 42(7), 376–389, 1986.
- [56] Sridhar N (2011), ‘Mechanisms of stress corrosion cracking’, in Stress Corrosion Cracking, Raja V S and Shoji T (eds) Woodhead Publishing, Cambridge, 2011.
- [57] Parkins R N (1992), ‘Environment sensitive fracture of metals’, Canadian Metallurgical Quarterly, 31(2), 79–94, 1992.
- [58] Jones R H (2003), ‘Stress corrosion cracking’, in ASM Handbook 13A, ASM International, 346–366, 2003.
- [59] <http://www.substech.com>.
- [60] Itzhak D and Elias O (1994), ‘Behaviour of type 304 and type 316 austenitic stainless steels in 55% lithium bromide heavy brine environment’, Corrosion, 50, 131–137, 1994.

- [61] *Speidel M O (1981)*, 'Stress corrosion cracking of stainless steels in NaCl solutions', *Metallurgical Transactions A*, 12, 779–789, 1981.
- [62] *Gnanamoorthy J B (1990)*, 'Stress corrosion cracking of un-sensitized stainless steels in ambient temperature coastal atmosphere', *Materials Performance*, 29(12), 63–65, 1990.
- [63] *Dillon C P (1990)*, 'Imponderables in chloride stress corrosion cracking of stainless steels', *Materials Performance*, 29(12), 66–67, 1990.
- [64] *Kain R M (1990)*, 'Marine atmospheric stress corrosion cracking of austenitic stainless steels', *Materials Performance*, 29(12), 60–62, 1990.
- [65] *Turnbull A and Psaila-Dombrowski M (1992)*, 'A review of electrochemistry of relevance to environment-assisted cracking in light water reactors', *Corrosion Science*, 33, 1925–1966, 1992.
- [66] *Kain V (2008)*, 'Water chemistry: cause and control of corrosion degradation in nuclear power plants', *Proceedings of the National Symposium on Operational and Environmental Issues concerning use of water as Coolant in Power Plants and Industries*, Kalpakkam, 15–16 December 2008, BRNS and INS, Kalpakkam, pp. 19–28, 2008.
- [67] *Scott P (1994)*, 'A review of irradiation assisted stress corrosion cracking', *Journal of Nuclear Materials*, 211, 101–122, 1994.
- [68] *Roychowdhury S, Kain V, Gupta M and Prasad R C (2011b)*, 'IGSCC 52 crack growth in simulated BWR environment – effect of nitrogen content in non-sensitized and warm rolled austenitic stainless steel', *Corrosion Science*, 53(3), 1120–1129, 2011.
- [69] *Shoji T, Lu Z and Murakami H (2010)*, 'Formulating stress corrosion cracking growth rates by combination of crack tip mechanics and crack tip oxidation kinetics', *Corrosion Science*, 52, 769–779, 2010.
- [70] *Arnoux P (2010)*, 'Atomistic simulations of stress corrosion cracking', *Corrosion Science*, 52, 1247–1257, 2010.
- [71] *Bruemmer S M and Thomas L E (2005)*, 'High resolution characterization of stress corrosion cracks in austenitic stainless steels from crack growth rate tests in BWR simulated environment', *Proceedings of the 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, eds Allen T R, King P J and Nelson L, The Minerals, Metals and Materials Society, 189–198, 2005.
- [72] *Roffey P and Davies E H (2014)*, 'The generation of corrosion under insulation and stress corrosion cracking due to sulphide stress cracking in an austenitic stainless steel hydrocarbon gas pipeline', *Engineering Failure Analysis*, 44, 148–157, 2014.
- [73] *Truman J E and Perry R (1965)*, 'The resistance of stress corrosion cracking of some Cr-Ni-Fe austenitic steels and alloys', *British Corrosion Journal*, 1(2), 60–66, 1965.
- [74] *Speidel M O (1977)*, *Stress corrosion cracking of austenitic stainless steels*, Ohio State University report to the Advanced Research Projects Agency, ARPA order no. 2616, Contract no. N00014-75-C-0703, 1977.
- [75] *Wheeler G C and Howells E (1960)*, 'A look at caustic stress corrosion', *Power*, 104(9), 86–87, 1960.
- [76] *Staehle R W and Agarwal A K (1976)*, *Corrosion, stress corrosion cracking and electrochemistry of the Fe and Ni based alloys in caustic environments*, Ohio State University Report to ERDA, Contract E(11-1)-2421, 1976.
- [77] *Ryabchenkov A V, Gerasimov V I and Sidorov V P, Prot. Met. (USSR)*, 2, p. 217, 1966.
- [78] *Rhodes C G and Thompson A W*, 'The composition dependence of stacking fault energy in stainless steels', *Metallurgical Transactions A*, 8, 1901–1906, 1977.
- [79] *Dai Q-X, Wang A-D, Cheng X-N and Luo X-M*, 'Stacking fault energy of cryogenic austenitic steels', *Chinese Physics*, 11, 596–600, 2002.
- [80] *Sedriks A J.* "Corrosion of stainless steels", 2nd edn, John Wiley and Sons, New York, 1996
- [81] *Andresen P and Morra M M (2005)*, 'Effects of silicon on SCC of irradiated and unirradiated stainless steels and nickel alloys', *Proceedings of the 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, eds Allen T R, King P J and Nelson L, The Minerals, Metals and Materials Society, 87–108, 2005.

- [82] *Hines J G and Jones E R W (1961)*, ‘Some effects of alloy composition on the stress corrosion behaviour of austenitic Cr-Ni steels’, *Corrosion Science*, 1, 88–107, 1961.
- [83] *Jones D A (1992)*, *Principles and Prevention of Corrosion*, 2nd edn, Prentice-Hall. *Jones R and Randle V (2010)*, ‘Sensitization behavior of austenitic stainless steel’, *Materials Science and Engineering A*, 527, 4275–4280, 2010.
- [84] *Kain V (1997)*, ‘Sensitization and susceptibility of austenitic stainless steels to intergranular corrosion and intergranular stress corrosion cracking’, PhD thesis, Indian Institute of Technology, Bombay, 1997.
- [85] *Kain V, Prasad R C and De P K (2002)*, ‘Testing sensitization and predicting susceptibility to intergranular corrosion and intergranular stress corrosion cracking’, *Corrosion*, 58, 15–38, 2002.
- [86] *Edeleanu C (1953)*, ‘Transgranular stress corrosion in Cr-Ni stainless steels’, *J. Iron Steel Inst.*, 173, 140–146, 1953.
- [87] *Schramm R E and Reed R P (1975)*, ‘Stacking fault energies of seven commercial stainless steels’, *Metallurgical Transactions A*, 6A, 1345–1351, 1975.
- [88] *G. De Queiroz et al.*, “Intergranular corrosion evaluation of friction stir welded AISI 410S ferritic stainless steel.” *Integr. Med. Res.*, no. x x, pp. 1–10, 2019.
- [89] *Jin W, Yang S, Kokawa H, Wang Z and Sato Y S (2007)*, ‘Improvement of intergranular stress corrosion crack susceptibility of austenite stainless steel through grain boundary engineering’, *Journal of Materials Science and Technology*, 23(6), 785–789, 2007.
- [90] <http://sassda.co.za/stainless-steel-and-corrosion>.
- [91] *EPRI GS 6913 (1990)*, *Feedwater heaters: replacement specification guidelines, Part 1.4, Tubing selection and preparation*, EPRI final report GS 6913, project 2504-5, August, 1990.
- [92] *Angeliu T M, Andresen P L, Hall E, Sutliff J A and Sitzman S (2000)*, ‘Strain and microstructural characterization of austenitic stainless steel weld HAZs’, *CORROSION 2000*, NACE paper no. 186, NACE, Houston, TX, 2000.
- [93] *Andresen P and Morra M M (2008)*, ‘IGSCC of non-sensitized stainless steels in high temperature water’, *Journal of Nuclear Materials*, 383, 97–111, 2008.
- [94] *Aaltonen P, Hanninen H, Nenonen P, Aho-Mantila I and Hakala J 54 (1988)*, ‘Aging related degradation of AISI 304 steel piping welds in BWR conditions’, *Proceedings of the 3rd Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, eds G.J. Theus, J.R. Weeks, The Materials Society, Warrendale, PA, 351–358, 1988.
- [95] *R. A. Cottis*. “Stress corrosion cracking”, *Corrosion and Protection Centre*, 1982.
- [96] <http://faculty.kfupm.edu.sa/ME/hussaini/Corrosion%20Engineering/04.07.03.htm>
- [97] <http://faculty.kfupm.edu.sa/ME/hussaini/Corrosion%20Engineering/04.07.03.htm>
- [98] <http://www.foodsafety.upb.ro>
- [99] “*Practice for Making and Using U-Bend Stress-Corrosion Test Specimens*”, G 30 Metal Corrosion, Erosion, and Wear, Vol 03.02, Annual Book of ASTM Standards, American Society for Testing and Materials.
- [100] ISO 7539-6: 2003. Corrosion of Metals and Alloys-Stress Corrosion Testing-Part 6: Preparation and Use of Pre-Cracked Specimens for Tests Under Constant Load or Constant Displacement. 2003.
- [101] *M. A. R. do Nascimento, L. de O. Rodrigues, E. E. B. G. Eraldo Cruz dos Santos, F. L. G. Dias, E. I. G. V. And, and R. A. M. Carrillo*, “World’s largest Science , Technology & Medicine Open Access book publisher .,” *Prog. Gas Turbine Perform.*, 2013.
- [102] *Ribeiro, R. B., Silva, J. W. J., Hein, L. R. O., Pereira, M. C., Codaro, E. N., & Matias, N. T. (2013)*. Morphology characterization of pitting corrosion on sensitized austenitic stainless steel by digital image analysis. *ISRN Corrosion*, 2013.
- [103] *T. Prosek, A. Iversen, C. Taxén, and D. Thierry*, “Low-Temperature Stress Corrosion Cracking of Stainless Steels in the ...,” vol. 65, no. 2, pp. 105–117, 2009.
- [104] *J. Klinglmayr and C. Bettstetter*, “Low temperature stress corrosion cracking of austenitic and duplex stainless steels under chloride deposits,” 2001.
- [105] *J. Bhandari et al.*, “Accelerated pitting corrosion test of 304 stainless steel using ASTM G48; Experimental investigation and concomitant challenges,” *J. Loss Prev. Process Ind.*, vol. 47, pp. 10–21,

2017.

[106] *J. F. Peng, C. Song, M. X. Shen, J. F. Zheng, Z. R. Zhou, and M. H. Zhu*, “An experimental study on bending fretting fatigue characteristics of 316L austenitic stainless steel,” *Tribol. Int.*, vol. 44, no. 11, pp. 1417–1426, 2011.

[107] *C. Garcia, M. P. de Tiedra, Y. Blanco, O. Martin, and F. Martin*, “Intergranular corrosion of welded joints of austenitic stainless steels studied by using an electrochemical minicell,” *Corros. Sci.*, vol. 50, no. 8, pp. 2390–2397, 2008.

[108] *B. T. Lu, Z. K. Chen, J. L. Luo, B. M. Patchett, and Z. H. Xu*, “Pitting and stress corrosion cracking behavior in welded austenitic stainless steel,” *Electrochim. Acta*, vol. 50, no. 6, pp. 1391–1403, 2005.

[109] *M. Vinoth Kumar, V. Balasubramanian, S. Rajakumar, and S. K. Albert*, “Stress corrosion cracking behavior of gas tungsten arc welded super austenitic stainless-steel joints,” *Def. Technol.*, vol. 11, no. 3, pp. 282–291, 2015.

[110] *A. A. Harb et al.*, “Effect of TIG Welding and Manual Metal Arc Welding on Mechanical Properties of AISI 304 and 316L Austenitic Stainless-Steel Sheets”, *Key Eng. Mater.*, ISSN: 1662-9795, vol. 750, pp. 26–33, 2017.

[111] *A. A. Harb*, et al. “Investigation of Mechanical Properties and Corrosion Behavior For 1010 Carbon Steel Pipes Used for Steam Boilers”, *Annals of the University “Dunarea de Jos” of Galati: Fascicle IX, Metallurgy & Materials Science*, 2017, 35.1, ISSN 1453-083X

[112] *HARB, A. A.*, Ciuca, I., Vasile, M., & Alqasim, M. “The Effect of TIG Welding on Corrosion Behavior For U- Bend Specimens Of 316L Austenitic Stainless-Steel Joints in Saline,” *scientific bulletin of Politehnica University of Bucharest (B)*. vol. 80, 2018, ISSN 1454-2331.