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”POLITEHNICA” UNIVERSITY OF BUCHAREST
FACULTY OF INDUSTRIAL ENGINEERING AND ROBOTICS

PhD THESIS SUMMARY

OPTIMIZATION OF REPAIR-BY-WELDING TECHNOLOGIES ON LOW-ACCESS JOINTS

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FOREWORD

During the period of carrying out the activities necessary for this doctoral thesis, I benefited by the guidance, trust, advice and moral support of the scientific coordinator, Prof. Dr. Ing. Gheorghe SOLOMON, of the help and collaboration of the teachers and technical staff of the Faculty of Industrial Engineering and Robotics within the Polytechnic University of Bucharest: Prof. Dr. Ing. Ionelia VOICULESCU, Prof. Dr. Ing. Alexandrina MIHAI, Prof. Dr. Ing. Irina SEVERIN, Conf. Dr. Ing. Gabriel GÂRLEANU, Conf. Dr. Ing. Dumitru Titi CICIC, Conf. Dr. Ing. Corneliu RONTESCU, Şef Lucr. Dr. Fiz. Gabriela MATEIAȘI, who helped me perform the experimental programs that required the use of specialized equipment and applications and gave me, on the occasion of presenting the research reports (doctoral papers), multiple and consistent suggestions on the content of the thesis and, not in the end, I benefited by the moral support and love of my family. I extend my warmest thanks to all of them and assure them of my full gratitude.

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Florina Ionescu

CONTENTS

INTRODUCTION

This thesis presents the methods for repair-by-welding technologies optimization of the spiral heat exchangers, which involves low-access joints, made of austenitic stainless steel (X2CrNiMo17-12-2), development of adapted devices to welding conditions in low-access areas (experimental welding equipment, welding torch improvement) and the usage of destructive and nondestructive testing in order to assess the quality obtained.

This doctoral thesis was developed to solve high technological problems of industrial beneficiaries, to perform repairs of spiral and pipe heat exchangers and thus developed the concept of laparoscopic welding, using the WIG procedure with an improved welding gun.

WIG - Laparoscopic welding, is necessary for the assembly / repair of various metal components, to which physical access is very limited or impossible and interstices are below 25 mm in conjunction with the large distance between the operator and the welded area (0.1 - 1 m).

From a scientific point of view, the development of such equipment and related technology is a worldwide novelty.

Such an equipment would be useful in various engineering fields such as aviation (structure / undercarriage - are areas periodically inspected with endoscopes but cannot intervene because there is no access), thermotechnics (heat exchangers, regardless of type construction, with pipes, plates or spirals where the constructive elements cannot be repaired locally and must be replaced), industrial installations (pipe routes), metal constructions of any type (halls, buildings, bridges, ships, etc.), automotive industry (construction or repair), thermal power plants.

The document is structured in 7 chapters that describe the research carried out in order to optimize the repair-by-welding technologies on low-access joints, the attention being focused especially on the spiral heat exchangers repair.

The first chapter of the thesis, entitled “Current stage of welding repairs on low-access areas”, presents theoretical aspects on the characteristics, functional role, classification and basic materials used in the heat exchangers construction. The second part of the chapter analyzes and describes the welding processes used for repairs on low-access areas: WIG (Wolfram Inert Gas) and MIG (Metal Inert Gas) welding processes.

In the second chapter, entitled "Research on welding technologies of heat exchangers and heat exchangers functioning analysis", the main problems of heat exchangers: corrosion, cavitation, and their effects are presented and analyzed. The current welding technology of spiral heat exchangers and the problems associated with it are described here. It also includes the analysis of the laparoscopic medical kit in order to realize the concept of laparoscopic welding and a study of destructive and non-destructive testing of welded joints.

The third chapter of the thesis, entitled “Research and development methodology”, consists of the research and development directions, as well as the objectives of this paper.

In the fourth chapter, entitled "Design of repair-by-welding equipment for low-access joints”, the design requirements and the execution of an experimental equipment for welding repair are being presented. The components of the equipment and the practical execution of an improved welding torch that responds to the problem difficulties are described.

The fifth chapter of the doctoral thesis is entitled "Research and contributions regarding welding reconditioning of heat exchangers made of austenitic stainless steel (X2CRNIMO17-12-2)” and is intended for the design and realization of samples, taking into account the input data, the basic material used, and the repair welding process.

In the sixth chapter, entitled "Quality assessment of the repairs made using the designed equiments", the testing methods used and the results of their application on the samples created are presented. The quality evaluation of the obtained welding joints/samples was performed using non-destructive testing methods (visual testing, penetrant testing, radiographic testing) and destructive testing methods (optical microscopy analysis, scanning electron microscopy analysis – SEM, chemical composition determination, material hardness determination).

The last chapter of the thesis, chapter 7, entitled "Final conclusions and personal contributions", contains a summary of general conclusions, based on research and experiments, the original scientific contributions of the author and the directions to follow for the next theoretical-experimental researches on repair-by-welding technologies on low-access joint.

CHAPTER I. CURRENT STAGE OF WELDING REPAIRS ON LOW-ACCESS AREAS

The heat exchangers are devices with a thermal transfer function, carrying out the heat transfer from one environment to another. They play an essential role in widely used systems including automobiles, heating, refrigeration, air conditioning, distillation (in the chemical and petrochemical industry), in thermal power plants, heating and as annexes to thermal machines [14, 15, 41].

One of the most known applications of heat exchangers is the car radiator where heat transfer takes place between the engine cooling water (hot fluid) and the ambient air. After conducting studies, it was found that more than two-thirds of the primary energy used in a country goes through at least two heat exchangers. An example of such a heat exchanger is shown in Figure 1.1 [15, 21, 41].

The following must be taken into account when choosing heat exchangers [14, 15, 21, 41, 43]:

- ✓ Construction material;
- ✓ Operating temperatures;
- ✓ Pressure and flow conditions;
- ✓ Thermal efficiency and pressure drops;
- ✓ Dirt trends;
- ✓ Fluid types and state of aggregation;
- ✓ Maintenance, inspection, cleaning and repair possibilities;
- ✓ Economic considerations;
- ✓ Manufacturing technique.

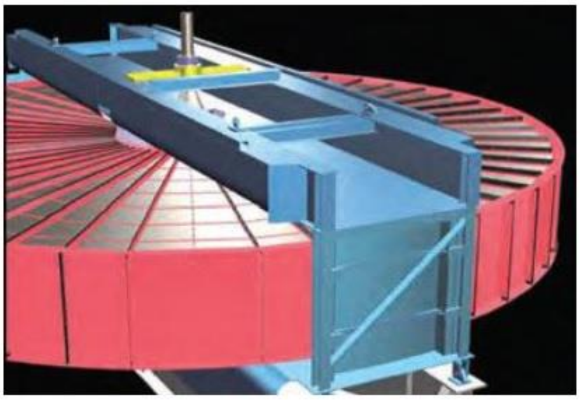


Figure 1.1. Heat exchanger example [21]

Usually, the heat exchangers are made of only one material, but sometimes two materials are also used (example: steel and aluminum). On a relatively small scale, anti-corrosion plastic coatings are also used. When choosing the manufacturing material, its properties must be taken into account, as well as the working parameters (example: temperature, pressure, aggressiveness of thermal agents) [14, 15].

Depending on the constructive-technological operation mode, the heat exchangers are classified according to table 1.1

Table 1.1. Heat exchangers classification according to constructive-technological operation mode [14, 15, 21, 41]

Exchanger type	***Passes number***	***Flow recovery mode***	***Main characteristics***
Tubular	One pass More passes	Rigid Semi elastic Elastic	The heat transfer surface consists of straight pipes. Thermal agents perform one or more passes. The expansions between the heat transfer surface and the outer body cannot be compensated for the rigid ones, they are partially compensated for the semi-elastic ones and totally for the elastic ones.
With cylindrical or flat coil	Several passes of the primary agent	Elastic	The heat transfer surface consists of coils of pipes inserted in containers (for boilers, heating tanks, etc.).
Special: ✓with plates; ✓with ribs; ✓with wings; ✓with needles; ✓with spirals.	One or more passes Mixed or cross flow	Rigid Elastic	The heat transfer surface has a special shape; corresponding to the particular heat transfer conditions

Because the activity of heat exchangers consists of the heat transfer between different media, the mainly used materials for their construction are stainless steels [14, 15, 21, 41].

Stainless steels are highly alloyed materials, based on iron, chromium and carbon, that contain other elements (example: Ni, Mo, Si, etc.), in which the main feature is very high corrosion resistance in various chemical or bio-chemical environments. To improve the welding behavior, the content of carbon in the composition is low (for austenitic stainless steels it is in the range of 0.1-0.01% C) and chromium is present in a proportion of over 12% Cr (mass percentages). The addition of chromium in the chemical composition of stainless steel ensures its stainlessness, manifested by a very low oxidation tendency in different environments and at different temperatures of use. Chromium forms a very thin, adherent and impenetrable oxide film on the steel surface, which protects the volume of material against chemical attack, capable of self-regeneration under conditions of mechanical or chemical alteration [14, 41, 43].

Spiral heat exchangers are those exchangers in which the heat exchange surface is represented by a spiral-shaped belt. Thus, two parallel channels are made, one for each fluid, offering a small contact surface with the external environment and due to this, special advantages in applications at extreme temperatures. Usually, the height of the channels is between 5 and 20 mm. They offer special advantages in applications at extreme temperatures, providing a small contact surface with the outside environment. The working principle of a spiral heat exchanger is presented in figure 1.2 [21, 41, 43].

Usually, the pressure is limited to 20 bar due to relatively flat surfaces, but there are also constructions that can be used at pressures of hundreds of bar and temperatures of hundreds of degrees Celsius. This type of exchanger is compact, with small pressure drops, and can be used for fluids that can clog the channels, the type of flow favoring self-cleaning [14, 21, 41].

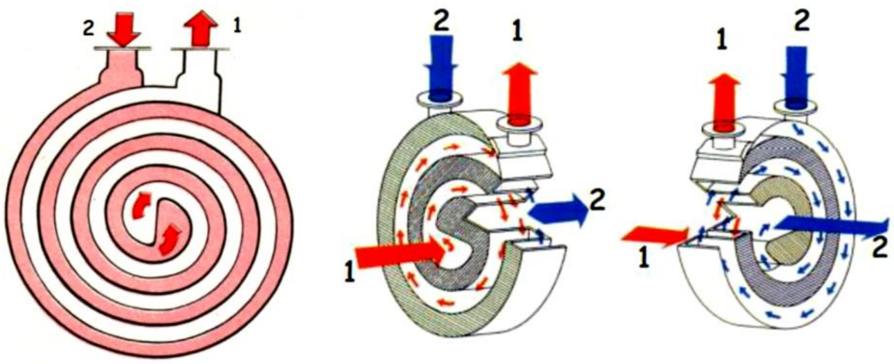


Figure 1.2. Working principle of a spiral heat exchanger [43]
1, 2 – thermic agent going out and in the heat exchanger (blue - cold fluid, red - hot fluid)

Some of the advantages of this type of heat exchangers are [14, 15, 21, 43]:
- ✓ High heat transfer coefficients;
- ✓ Compactness (high A / V);
- ✓ Small pressure differences;
- ✓ Dirt resistance;
- ✓ Relatively easy cleaning.

Disadvantages of spiral heat exchangers are [14, 15, 21, 43]:
- ✓ Complicated manufacturing;
- ✓ Reduced working pressure (max. 1.5 MPa);
- ✓ Relatively high cost;
- ✓ Sealing difficult to achieve.

CHAPTER II. RESEARCH ON HEAT EXCHANGERS WELDING TECHNOLOGIES AND HEAT EXCHANGERS FUNCTIONING ANALYSIS

During the use of the heat exchanger, various degradation phenomena occur due to the thermal regime, the corrosivity of the working environment, the flow rate of the fluids, the viscosity and the hardness of the microparticles in the fluid. In the paper, the phenomena that generate the deformation or perforation of the metal wall, such as corrosion and cavitation, were analyzed [25, 26, 27, 30, 39].

Erosive corrosion, a local form of corrosion, occurs due to the movement of fluid along the surface of the material. This can be found on the entire surface of the heat exchanger, less being exposed the outside because it does not come into direct contact with the moving fluid [25, 30, 39].

Erosive corrosion is generally accelerated when water entering the exchanger contains air or solid particles such as sand, but erosive corrosion can also occur when we use filtered or airless water. The most important in terms of resistance to erosive corrosion are the protective films of certain materials or alloys [27, 30, 39].

The parameters that influence the erosive corrosion are the “turbulences” and the parameters related to fluids such as speed, level of suspended particles, level of air bubbles present, local partial pressure, cavitation but also the geometry of the part [25, 26, 30].

Some images illustrating such defects that appeared due to the two phenomena are shown in the figure 2.1.

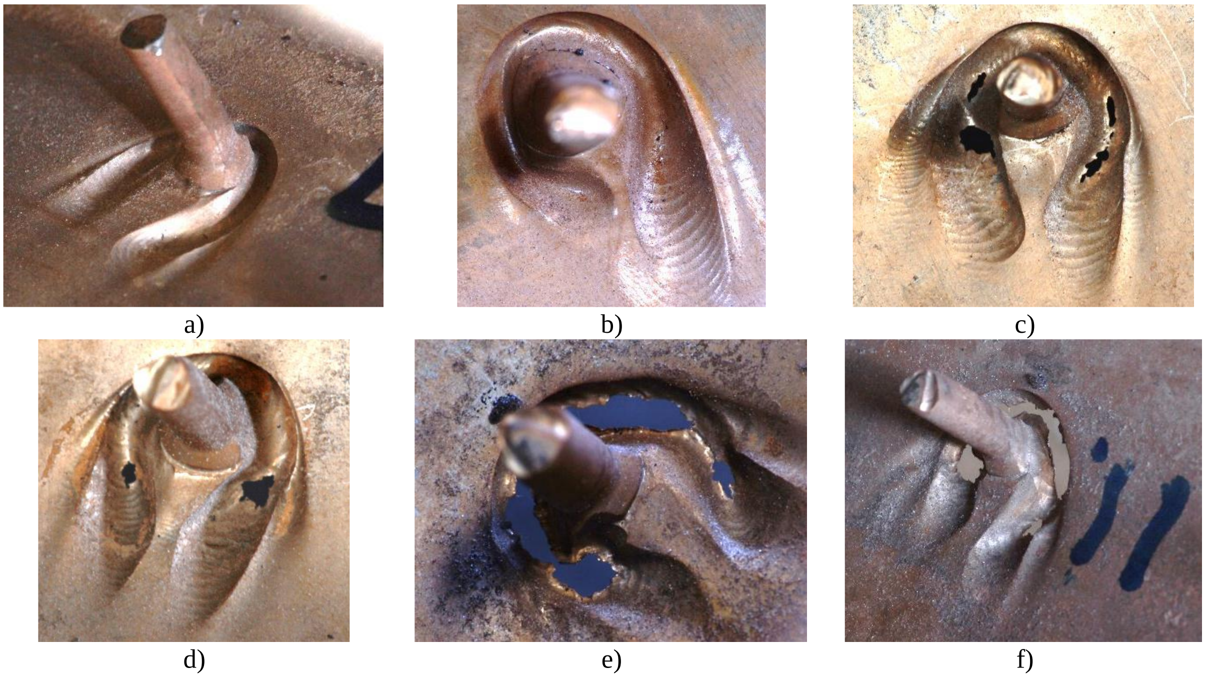
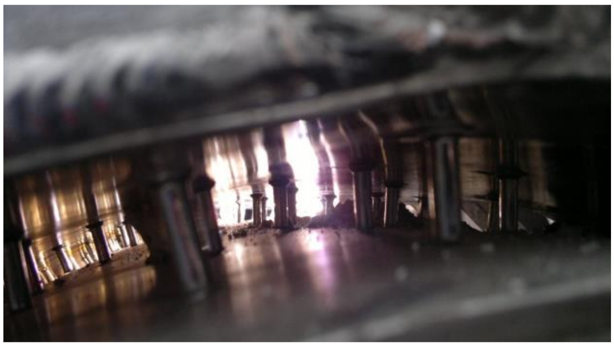


Figure 2.1. Defects that appeared due to the cavitation and corosion phenomena [30]
a), b) – thinning of the material in the form of waves / valleys appeared around the spacer;
c), d) – lack of material like holes around the spacer;
e), f) – „horseshoe”-shaped holes appeared around the spacer

Cavitation is the phenomenon of producing, in a stream of liquid, a partial vacuum where vapor or gas bubbles are formed which, when agglomerated, cause vibrations and mechanical corrosion, presenting a danger of destruction for the walls of the pipe through which the liquid passes (Dex online) [41].

Cavitation, sometimes also called corrosion cavitation or erosion cavitation, is the dynamic process of formation, development, and implosion of bubbles or cavities filled with vapors and gases from a liquid [27, 30, 39].

Among the factors favoring the appearance and development of cavitation bubbles we list first of all the decrease of the pressure but also the impurities, micro cracks, notches and solid bodies that can be seen in figure 2.2 a) and b). These factors determine the retention of microscopic volumes of undissolved gas in the liquid, thus creating start of cavitation [27, 30, 39].

a) b)

Figure 2.2. Main factors of cavitation phenomena increase [30]
a), b) Impurities, foreign bodies located between the coils of the heat exchanger

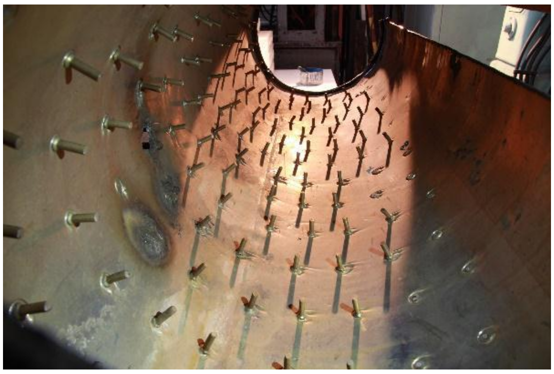
The stripping repair method is considered a problem in terms of cost, time and efficiency. The repair involves stripping, cutting from the outside to the inside of the exchanger sheets until the defective sheet is reached. The steps of performing the repair are: identifying the affected area; cutting the sheets from the outside to the inside to the affected area; repair by welding; the control of the repaired area; the welding of previously made cuts; the welding control of the cuts; and pressure testing [15, 21, 27, 30, 41].

Usually, most defects are located on the sheets (spirals) towards the center of the exchanger, where the peripheral speed increases greatly, due to the smaller diameter of the turn. The starting spire has a diameter of about 1 m and the final one is 0.3 m, which means a nearly 3-fold increase in the peripheral flow velocity with major implications on the cavitation phenomenon [15, 21, 30, 41].

The method is easy to apply, but it has several disadvantages [15, 21, 27, 30, 41]:

- the uncovering of the good sheets, which do not have a defect, and then by the subsequent closing welding we can introduce defects in the welded joint;
- in most cases, the defects are at the spire / spirals of small diameter, so those inside. This means that we will uncover more than half of the sheets to reach the defective sheet;
- if the defects are disposed in several areas along the entire diameter of a turn and it is positioned inside the exchanger, it means that the cutting is executed several times in different areas and the repair costs are very high and not justified.


a) b)




c) d)


e) f)

Figure 2.3. Spiral heat exchanger having defects along the entire width of the spirals, towards the center of the exchanger [30] a), b) overview of the spiral heat exchanger;
c) bare spiral; d), e) the waves / valleys created around the spacers - on the inside;
f) waves / valleys created around the spacers - on the outsid;

The doctoral thesis is using methods to improve the quality of repairs, which consist in creating a miniature device for performing welds in low-access areas, by similarity to the laparascopic medical kit; the use of stainless steels with higher mechanical or corrosion resistance characteristics; and the use of non-destructive examination techniques with specialized equipment.

Drawing a parallel between repair-by-welding of low-access joints and the laparoscopy procedure, we can attribute the characteristic of low-access area to the abdomen. As it is not easy to access the stomach, it is not easy to carry out repair-by-welding work on low-access areas.

Laparoscopy is a surgical procedure that uses a thin, lighted tube called laparoscope, which is inserted into the abdomen through a small incision in the abdominal wall and is used to examine the internal abdominal or genital organs. It is used to diagnose conditions such as cysts, adhesions, fibroids and infections [41].

In many cases, laparoscopy eliminates the need of extensive surgery (laparotomy) that would require a large incision of the abdomen. Laparoscopy involves lower risks, is less expensive and can be performed without the need of hospitalization [41]. By similarity, also laparoscopic welding used to repair spiral heat exchangers eliminates the need to uncover its sheets and thus involves lower risks.

The laparoscopic equipment consists of the insufflation system, the image processing circuit, the electrosurgical circuit, the washing-suction and instrumentation system [41, 42]. Thus, in order to achieve the concept of laparoscopic welding, we took as an example the elements of the laparoscopic kit and we adapted it to the welding equipment to be done in order to repair by welding in low-access areas.

The elements of the experimental stand will be: video endoscopic inspection camera; system for data acquisition, processing, storage, and viewing: camera, laptop, external hard disk, printer; working materials: metal sheet, pipe, protective gas, additives, wire guide tube, video signal adapters VGA - SVGA etc.; the stand made for fixing the samples and repairing by welding; tools and devices necessary for processing the samples before and after welding, to analyze the quality of the welded joint; and the welding equipment ESAB - Origo Tig 3000i AC /DCl.

CHAPTER III.
RESEARCH AND DEVELOPMENT METHODOLOGY

The main objective of the research and development activity within the doctoral thesis is to carry out research and developments on repair-by-welding technologies on low-access joints.

The specific objectives of this activity are, as follows:

- ✓ OS1 → synthetize the important aspects regarding actual stage of repair-by-welding technologies on low-access joints and of the spiral heat exchangers.
- ✓ OS2 → establishing the research and development methodology.
- ✓ OS3 → design and construction of an experimental stand for welding repairs on low-access areas.
- ✓ OS4 → actual realization and quality assessment of the repairs done on small diameter austenitic stainless steel pipes (X2CRNIMO17-12-2).
- ✓ OS5 → summarize the general conclusions, the original scientific contributions and further directions of researches**.**

Achievement of these objectives resulted in seven chapters of the doctoral thesis and 4 research papers that were developed and published in specialized journals (1) and at national and international conferences (3).
In relation to the main objective of the research and development activities, the following work structure is considered:

- ✓ Heat exchangers analysis;
- ✓ Analysis of the basic materials used in the construction of heat exchangers;
- ✓ Analysis of welding processes used for welding repair on low-access areas;
- ✓ Analysis of the loads to which the heat exchangers are exposed;
- ✓ Equipment design for welding repairs on low-access joints;
- ✓ Design and realization of samples made of austenitic stainless steel (X2CrNiMo17-12-2) pipes with small diameters, in which defects that mimic cavities of different shapes and sizes were made, subsequently reconditioned by welding;
- ✓ Examination of joints made using a minimal set of non-destructive tests: visual testing, penetrant testing, radiographic testing and destructive testing such as: optical microscopy analysis, scanning electron microscopy analysis – SEM, chemical composition determination, material hardness determination.

Figure 3.1 shows the structure of this doctoral thesis.

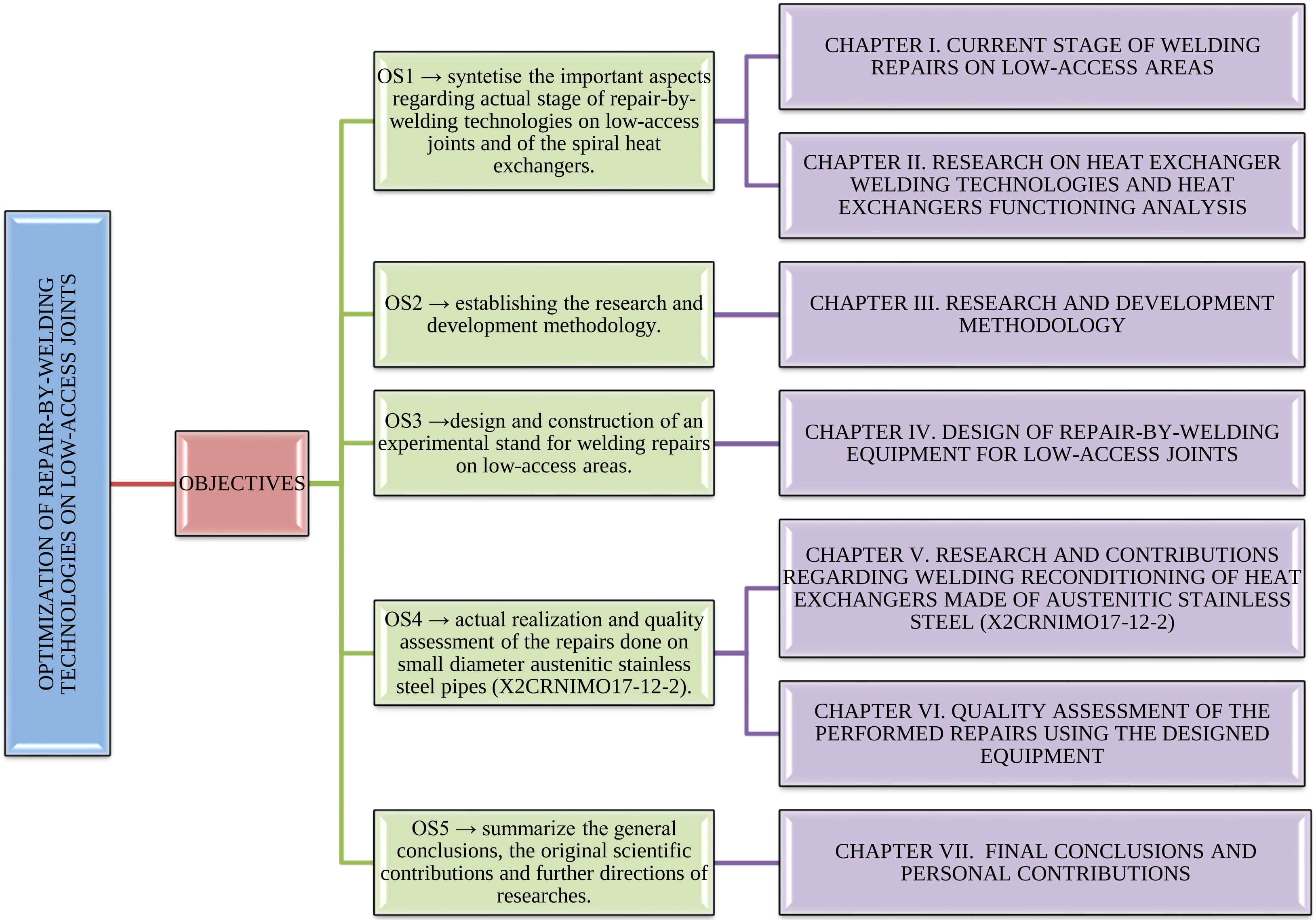


Figure 3.1. Doctoral thesis structure

CHAPTER IV.

DESIGN OF REPAIR-BY-WELDING EQUIPMENT FOR LOW-ACCESS JOINTS

Currently, there are WIG welding torches with or without wire, which can perform manual / mechanized / robotic welding, but their dimensions are relatively large, having at least two of the dimensions over 25 - 35 mm. For manual welding, the neck of the torch can be rigid or flexible, and its positioning and handling during welding is done directly by the operator, usually from a short distance, about 50 - 70 mm.

The experimental stand diagram made for the repaired-by-welding samples using the improved WIG welding torch is shown in Figure 4.1.

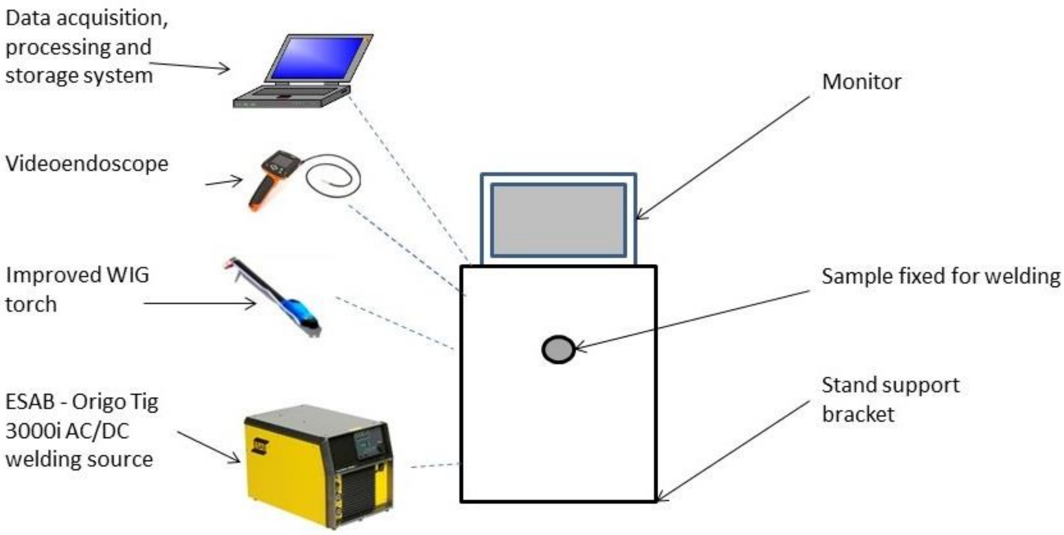


Figure 4.1. Experimental welding equipment diagram [32]

The following steps have been established in order to test the effectiveness of the experimental stand created [29]:

- ✓ Modification of a WIG torch chosen according to certain criteria;
- ✓ Purchase of an inspection video endoscope to be able to view and monitor the welding process. The images were processed and saved electronically;
- ✓ Carrying out welding tests on different type of semi-finished product and repairing mechanical processed defects in a pipe, defects that may occur in operation, pores, holes, cracks;
- ✓ Repair of defects in pipes by welding using the improved torch and the new laparoscopic welding technology.

Figure 4.2 shows the experimental equipment made.

Figure 4.2. Experimental welding equipment built [29]

The design and construction of such flexible welding equipment, having very small dimensions, less than 25 mm in any direction raised several technical issues that had to be taken into account [29]:

a) Design and construction of a miniature welding torch;

b) Exact positioning and handling of the welding torch;

c) On-line viewing: of the torch, of the parent metal, of the weld material (if applicable) and of the molten pool;

d) Bringing the shielding gas to the welding area;

e) Evacuation of gas / smoke / condensation from the welding area in order to be able to view in optimal conditions the molten pool;

f) Ensuring the transmission of welding current and voltage from the equipment to the torch by the exact dimensioning of it;

g) Working temperature - cooling during work of all components that are an integral part of the equipment designed. Laparoscopic kits are mainly used for investigations / operations where the working temperature does not exceed 40 - 50 ° C. In the welding situation, the working temperature is much higher than this value and therefore all mechanisms must be designed and adapted so that they can be used at higher temperatures.

Improving this welding torch and the related welding technology will open a new era in the welding world. The possibility of welding at a long distance of about 0.1 - 1 m and in low-access places, will open new research directions in all industrial fields. We can make an analogy with the medical field where the discovery of laparoscopic investigation led to new methods of operation, much less invasive, with low costs and very good results compared to the classic ones [29].

In order to identify the smallest torches that exist on the current market, the products of the largest companies producing welding equipment market were studied. The characteristics that were taken into account are:

- Type of torch cooling (with gas or liquid);
- Tungsten electrode diameter;
- Maximum direct and alternating welding current;
- Outer diameter of the torch neck;
- Nozzle characteristics (diameter, length, material).

Considering the torch characteristics mentioned above, the gun model chosen for improvement is the SR24WFX torch from TBi Industries. It is a liquid-cooled torch with a flexible neck suitable for current requirements where there are low-access areas. It can also be used in areas where it is impossible to weld with "everyday" WIG torches. When designing the miniature WIG-laparoscopic welding equipment, an analogy was made with the devices / mechanisms of operation / investigation in the medical field, especially with laparoscopic surgery but of course with the specific adapted fusion welding technology.

The designed torch must perform the following functions [29]:

- ✓ the size of the torch welding head in any direction should not exceed 20 mm;
- ✓ to be used remotely manually or by a mechanical system - as in the case of the arms used for laparoscopic kits or with the help of ultrasonic actuators through a wireless or wired control system using a joystick;
- ✓ the whole process to be viewed on a monitor and possibly recorded on an electronic medium using a micro camera used in laparoscopic surgery.

The welding torch design using Catia V5 program is presented in figure 4.3.

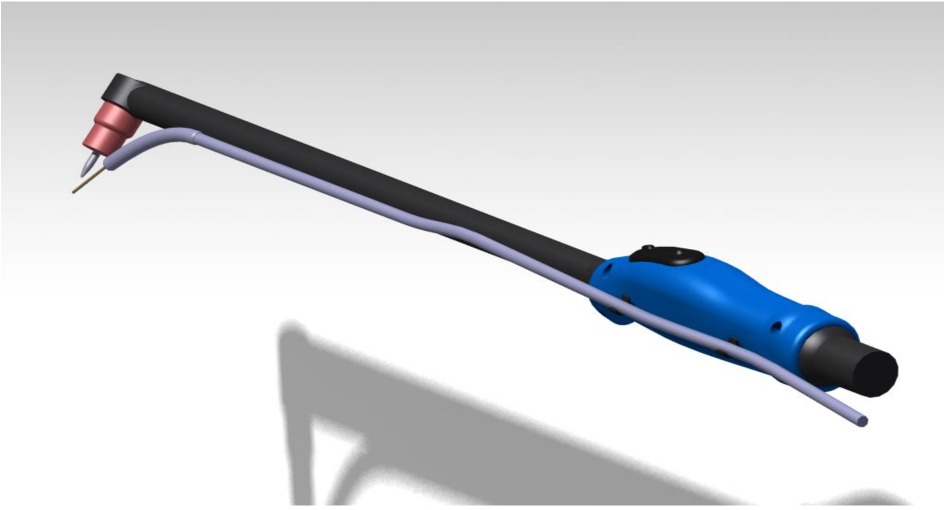


Figure 4.3. The welding torch design in Catia V5 program

The WIG welding torch used was modified in the sense that it was added to the part of the welding wire feed - roller. The welding wire comes next to the tungsten electrode through a metal guide tube. The guide tube was attached to the body of the welding torch and its neck to form a common body. The wire is driven out of the tube through a contact nozzle, see figure 4.4. [99, 101].

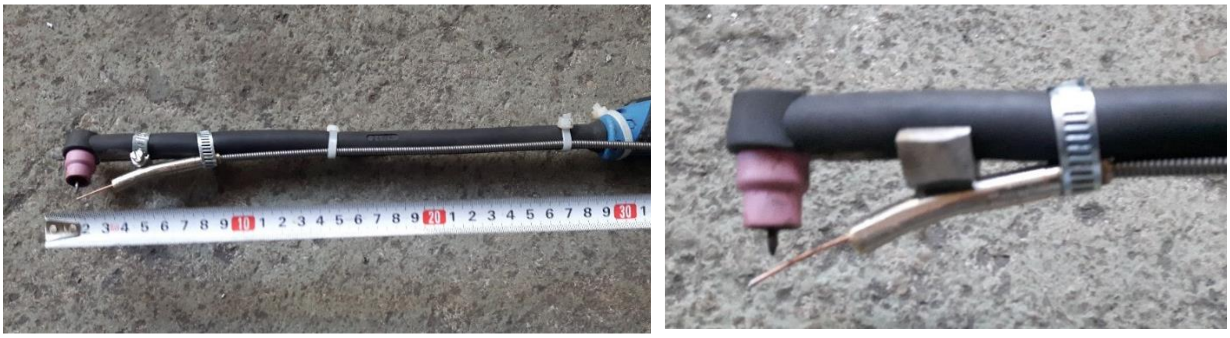


Figure 4. 4. WIG torch used.

1) The control of the two subassemblies, torch and welding wire feed-roller is done separately. The torch can initiate the electric arc and, if necessary, the pedal can start and stop welding wire feed-roller.
2) Considering the welding speed, a roller at which the wire feed rate should be at least 0.8 m/min -LN 27 with two rollers was chosen.
Welding tests were carried out using different type of semi-finished product and repaired mechanical processed defects in a pipe, defects that may occur in operation, pores, holes, cracks; repair of defects in pipes by welding was using the improved torch and the new laparoscopic welding technology- figure 4.5 and 4.6. These tests were performed in order to accustom the operator to the new type of torch. All welding tests were performed by inserting the torch into the pipe and monitoring the molten pool using video endoscope.

Figure 4. 5. Pipe-type products with artificially created defects

Figure 4. 6. Pipe type samples repaired by welding

CHAPTER V. RESEARCH AND CONTRIBUTIONS REGARDING WELDING RECONDITIONING OF HEAT EXCHANGERS MADE OF AUSTENITIC STAINLESS STEEL (X2CRNIMO17-12-2)

In order to carry out the experiments, a series of tests were performed, which were subsequently destructive and non-destructive tested.
The following steps were carried out:
- ✓ artificial cavities were made;
- ✓ the reconditioning technology used for the tests was established;
- ✓ the reconditioning was performed;
- ✓ mechanical and chemical cleaning (degreasing) of samples was done;
- ✓ visual testing;
- ✓ penetrant testing;
- ✓ radiographic testing;
- ✓ samples chemical cleaning;
- ✓ cutting in order to obtain samples for destructive testing;

- ✓ samples rectification;
- ✓ microstructure analysis;
- ✓ chemical composition analysis by spectrometry;
- ✓ Vickers hardness measurement.

In order to test the efficiency of the proposed repair-by-welding process of the heat exchangers, samples were created by cutting pipes with different dimensions: pipes made of X2CrNiMo17-12-2 austenitic stainless steel with the dimensions 250 x 42 x 3 mm and 50 x 42 x 3 mm. In the samples were created artificial flows to imitate the cavitation phenomena. The parent metal used in the experimental plan was the X2CrNiMo17-12-2 austenitic stainless steel [31].

The X2CrNiMo17-12-2 austenitic stainless steel is a version of X5CrNiMo17-12-2 and is distinguished by a lower carbon content, but also by a lower yield strength and tensile strength. In table 5.1 it is presented the chemical composition of X2CrNiMo17-12-2 austenitic stainless steel in accordance with the EN ISO 100088-3 standard, and in table 5.2 the steel equivalences are presented according to other standards. The mechanical properties of X2CrNiMo17-12-2 steel are presented in table 5.3. [31].

Table 5.1. Chemical composition of X2CrNiMo17-12-2 steel [31, 34]

Material	*Chemical composition*										
EN ISO 100088-3	*C [%]*	*Mn [%]*	*P [%]*	*S [%]*	*Si [%]*	*Cr [%]*	*Ni [%]*	*Mo [%]*	*N [%]*	*Cu [%]*	*Other elements [%]*
X2CrNiMo17-12-2	0,03	2	0,045	0,03	0,75	16 – 18	10 – 14	2 – 3	0,10	–	–

Table 5.2. X2CrNiMo17-12-2 steel equivalences. [31, 34]

ASME	DIN 17440	EN 10088 – 3	UNS	AFNOR
316L	1.4404	X2CrNiMo17-12-2 (1.4404)	S31603	Z3CND17-11-02

Table 5.3. Mechanical properties of X2CrNiMo17-12-2 steel [31, 34]

Material	**Mechanical properties**				
EN ISO 100088-3	Tensile Strength [MPa]	Yield Strength [MPa]	Elongation [min, %]	Hardness	
				Brinell [HB]	Rockwell [HRB]
X2CrNiMo17-12-2	485	170	40	217	95

The welding process chosen is TIG with filler material, and the protective gas is Ar 100%. The parameters of the welding regime used in the experiments were established according to the manufacturer's recommendations, the values are shown in the table 5.4. and were monitored throughout the welding process.

Table 5.4. Welding parameters [31, 33]

No.	Parameter	Value
1.	Welding amperage I_s [A]	137±10
2.	Welding arc voltage U_a [V]	14,2±2
3.	Feed rate of welding wire v_a [m/min]	1.8±0.1
4.	Gas flow, Ar 100%, D_g [l/min]	13±1
5.	Welding speed v_s [cm/min]	12-15

During the experiments the molten metal used was austenitic stainless steel wire, brand OK Tigrod 316L (L = low, symbolizing a low carbon content).

This steel is often recommended for welding, welding loading or repair operations because it offers very good corrosion resistance characteristics, have good weldability and mechanical strength. The 316L brand has superior features compared to the 304 brand (which is cheaper), because it is additionally alloyed with 2-3% Mo, which also increases the resistance to point corrosion (pitting) in case of hot loads. At the same time, 316L wire can be used for low-access areas, as it does not require cleaning of the welding root before the next layer is welded, which would require additional operation in the low-access welding area.

For the experiments, X2CrNiMo17-12-2 austenitic stainless steel pipes were prepaired with an outer diameter of 42 mm, thickness 3 mm and the following lengths [101]:

- 250 mm - samples 1 ÷ 3 - presented in figure 5.1, on which holes with diameters of 2, 3, respectively 4 mm were made;
- 50 mm - sample 4 - presented in figure 5.2, on which a linear defect positioned along the length of the pipe was made;
- 50 mm - sample 5 - shown in figure 5.3, on which a linear defect positioned on the circumference was made.

The cutting process of the samples was done with a manual cooling cutting machine in order to avoid structural changes of the austenitic stainless steel.

Figure 5.1. Austenitic stainless steel pipe X2CrNiMo17-12-2, 1÷3 samples [31, 33]

Figure 5.2. Austenitic stainless steel pipe X2CrNiMo17-12-2, sample 4 [31]

Figure 5.3. Austenitic stainless steel pipe X2CrNiMo17-12-2, sample 5 [31]

The samples were fixed in the experimental stand and repaired by welding. ESAB - Origo Tig 3000i AC / DC equipment was used to perform the tests. It allows the formation of the welding arc starting with 5 A - 300 A. The samples repair took place using WIG process with additive material, see figure 5.4.

Figure 5.4. Welding repair of samples [31, 33]

The samples obtained are presented in the figures 5.5÷ 5.9 [32].

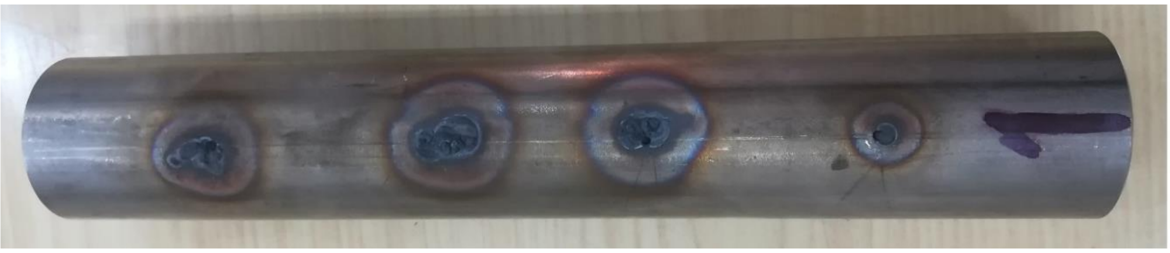


Figure 5.5. Sample 1 –2 mm diameter holes

Figure 5.6. Sample 2 –3 mm diameter holes

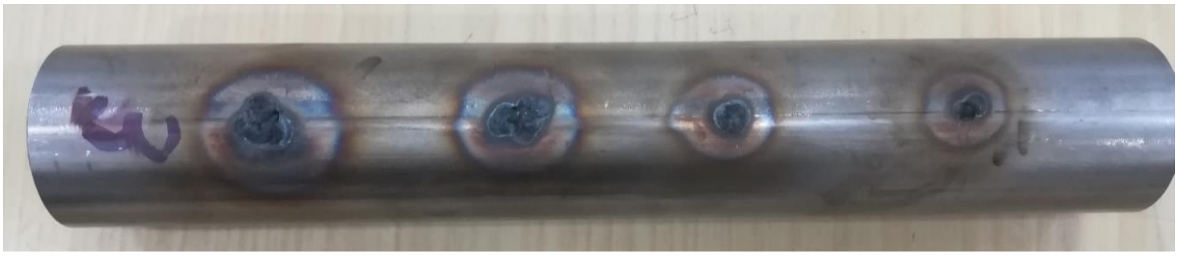


Figure 5.7. Sample 3 – 4 mm diameter holes

Figure 5.8. Sample 5 – linear defect on the circumference

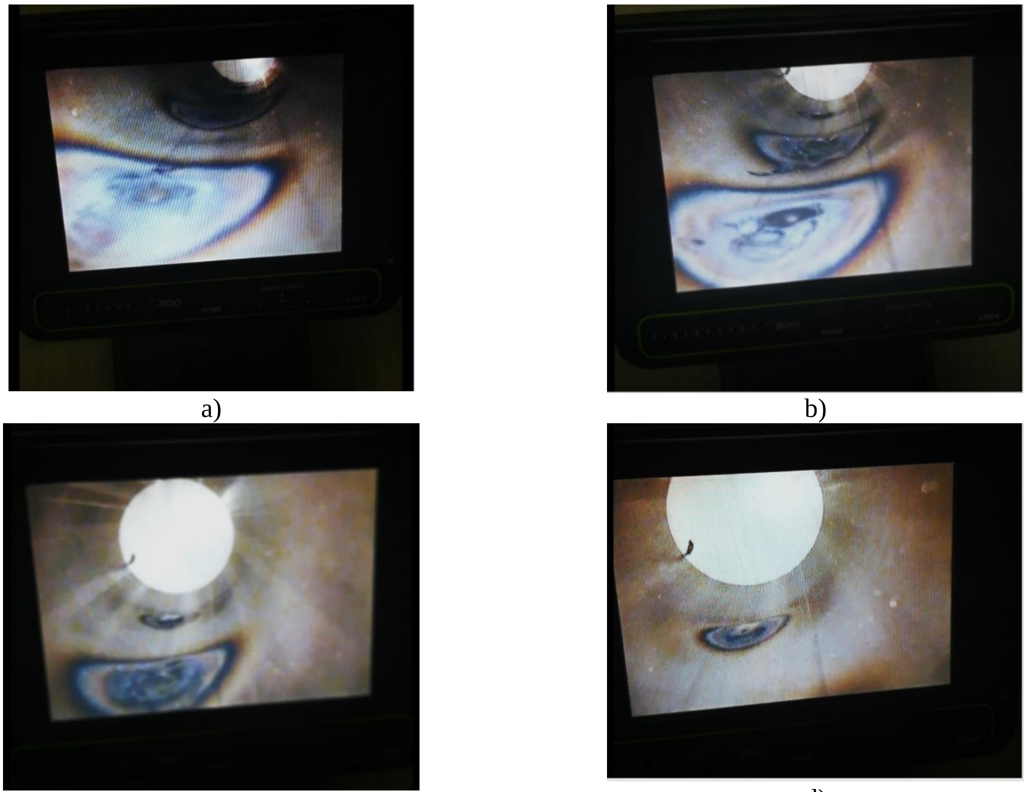
Figure 5.9. Sample 4 – linear defect along the length of the pipe

CHAPTER VI. QUALITY ASSESSMENT OF THE REPAIRS MADE USING THE DESIGNED EQUIPMENT

In order to assess the quality of the welding joints obtained using the chosen welding repair process, a series of non-destructive examination methods were used, after which, samples were prepared in order to perform destructive tests.

The visual examination applied on the samples was made by direct visual testing and remote visual testing. Following the direct visual testing, it was found that the larger the cavity, the smaller the penetration. The following imperfections were identified: lack of penetration, improper appearance, material leaks.

For the remote visual testing, the following equipment was used: a video scope VIDEOPROBE VP 300 and an UV AB/LUX Check for the light intensity measurement. The examination was performed 3 times by changing the light intensity from 230 lux to 330 lux and 430 lux [31]. Figure 6.1 shows the images taken with the VIDEOPROBE VP 300 video scope for sample 1 with light intensity of 230 lux.



a) b) c) d)

Figure 6.1. Images taken with the videoscope using light intensity of 230 lx - sample 1
a) welding repair point 1 located 50 mm away from the access point; b) welding repair point 2 located 100 mm away from the access point; c) welding repair point 3 located 150 mm away from the access point; d) welding repair point 4 located 200 mm away from the access point

Analyzing the images, it can be seen that the greater the distance from the access end, the poorer is the welding repair quality. Up to a distance of approximately 100 - 150 mm from the access point, the weld looks good, with no serious imperfections. At a distance of 200 mm there can be seen metal leaks, splashes but also burned surfaces. In terms of light intensity, the higher it is, the easier it is to visualize the defects, except those located on the opposite end of the pipe.

For the detection of small imperfections on the surface of the samples (which cannot be visually detected) or in the immediate proximity of the surface, the penetrant testing was used.

To carry out the examination with penetrating liquids, the ambient temperature of 20ºC and the set of penetrating liquids (penetrant PFINDER 860, developer PFINDER 870) were established.
The penetrant testing steps are:

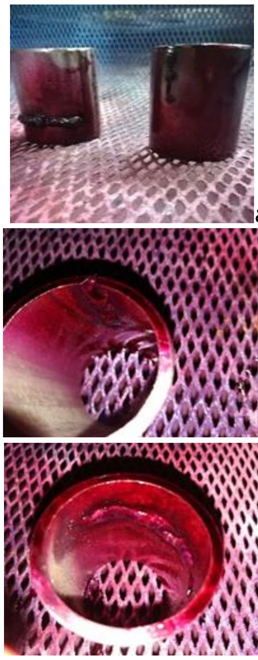
1. Sample cleaning - chemical cleaning was performed by degreasing - degreaser PFINDER890;

a) b)

Figure 6.2. Sample cleaning,
a) Sample 1÷3 – circular defects, b) Samples 4 and 5 - linear defects

2. The surface drying was forced using a hot air jet;
3. The application of the penetrant was made by spraying on the surface from a distance of about 10 cm, the penetration time used: 10 min; sample 4 and sample 5 were also examined inside (figure 6.3, respectively figure 6.4);

Figure 6.3. Penetrant application - samples 1÷3



a)
b)
c)

Figure 6.4. Penetrant application – sample 4 and 5, a) outer of the samples 4 and 5, b), c) inner of the samples 4 and 5

4. Excess penetrant removal - was done by washing;
5. Surface drying - was done using a hot air jet;
6. Developer application - see figure 6.5, respectively 6.6
   - ✓ the developer was applied in a uniform and thin layer, on the entire surface to be examined, being well agitated before use;
   - ✓ after being applied to the developer, the examined surface was allowed to dry at room temperature; the development duration started immediately after the surface dried, the time being 20 min.

Figure 6.5. Developer application samples 1÷3

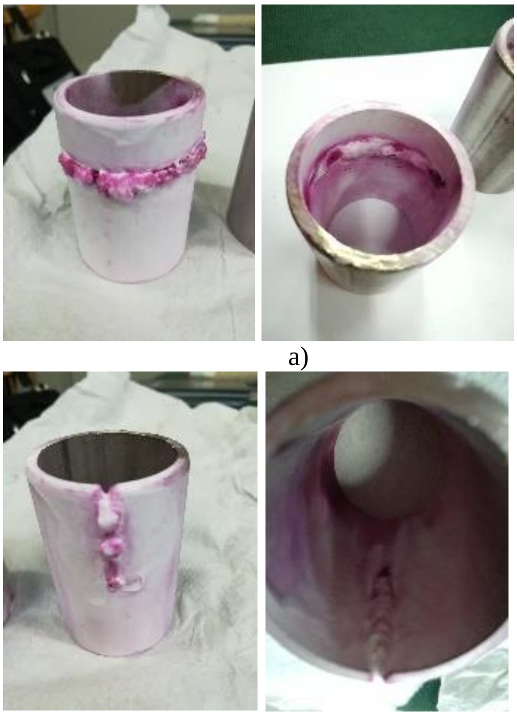


Figure 6.6. Developer application, a) inner and outer of sample 4, b) inner and outer of sample 5

During penetrant testing, it was observed that the outer surface of the weld has imperfections, the lack of penetration being the most common. The following imperfections were identified on the 5 verified samples: swelling (P5), lack of penetration (P1, P2, P3, P5), excess of penetration (P3, P4, P5), leakage of metal at the welding root (P1, P2, P3), overflow (P1, P2, P3) and excessive weld thickness (P4, P5).

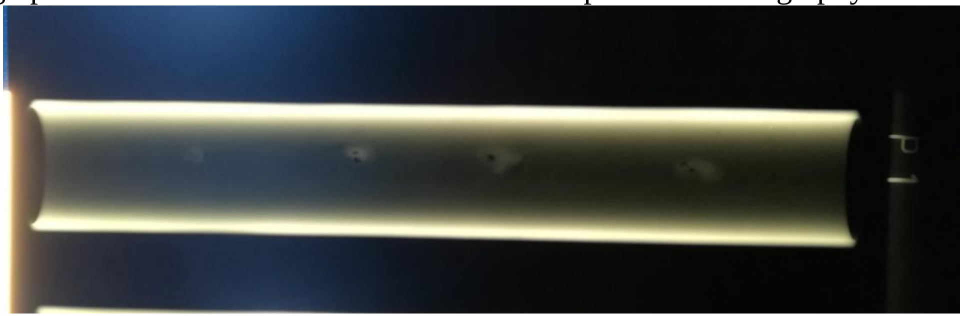
The examination of the samples with radiographic testing was performed using X-ray radiography installation and obtaining of the image on radiographic film. This was done in S.C. Weld Mildin CND S.R.L. laboratory in Pitesti and was made in proportion of 100%.

Technical data:

- Sample: pipe.
- Material: X2CrNiMo17-12-2.
- Dimensions: ϕ42.3 x 3
- Exposure geometry: normal geometry.
- X-ray technique: one wall.
- X-ray class: class B.
- Quality indicators used W 10 FE, sensitivity: W14 / 0.16.
- X-ray parameters:

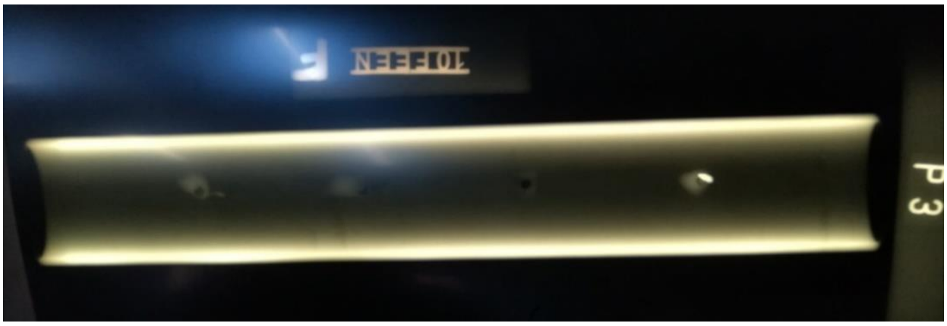
X-ray tube parameters: U = 190KV; I = 4.7 mA;
Focal spot size: 3 mm;
Source-film distance = 700 mm;
Exposure time = 16 s;
Film type: FUJI FILM IX 100 NIF;
Intensifier screen (Material: Pb, Thickness: 0.02 mm front, 0.02 mm rear).

The interpretation of radiographic films was performed in accordance with SR EN ISO 17363 - 1, Level B, SR EN ISO 5817, Level B and SR EN ISO 10675-1, Level 1. Figure 6.7 shows the radiographic films obtained after examination with penetrant radiography.



a)

b)



c)

d)

e)

Figure 6.7. Images obtained after penetrant radiography.

a) sample 1, b) sample 2, c) sample 3, d) sample 4, e) sample 5

Using penetrant radiography, it can be seen that all the samples showed solid inclusions, but the following defects were also identified: pore (P1), swelling (P2, P3), incomplete penetration at the welding root (P4) and lack of melting (P5).

In order to carry out the destructive tests, 8 samples were taken and processed by mechanical cutting under cooling fluid.
The preparation of the tests consisted of the following steps [33]:

- ✓ The incorporation of the samples was done in phenolic resin;
- ✓ Manual polishing of the samples using abrasive discs with a grain size of 360, 500 and 1000 and Topol 3 solution. The samples were chemically treated using royal water consisting of 3 parts HCl and one part HNO3. The samples are shown in Figures 6.8 and 6.9.

Figure 6.8. Sample 1 – positioning of welding points [33], 1.1. – point 1 - 50 mm; 1.2 – point 2 - 100m; 1.3. – point 3 - 150 mm; 1.4 - point 4 - 200 mm [33]

Figure 6.9. Sample 2 - positioning of welding points [33], 2.1. - point 1 - 50 mm; 2.2 - point 2 - 100m; 2.3. - point 3 - 150 mm; 2.4 - point 4 - 200 mm [33]

The metallographic analysis was performed by optical microscopy according to SR EN 1321: 2000, STAS 7626-79, CR 12361: 1996 + AC: 1997, with the Olympus GX51 microscope equipped with specialized image processing software - AnalySis. Measurement conditions: temperature + 26 ° C (reference temperature + 23 ° C ± 5 ° C), humidity 42% [33].

Some of the results obtained from the microscopic analysis are presented below: sample 1 - circular defects with hole diameter Φ 2 mm, parent metal structure in figure 6.10, welding joint 1 - 50 mm distance away from the access point - figures 6.11 - 6.13 and welding joint 2 - 100 mm distance away from the access point - figures 6.14 - 6.17 [33].

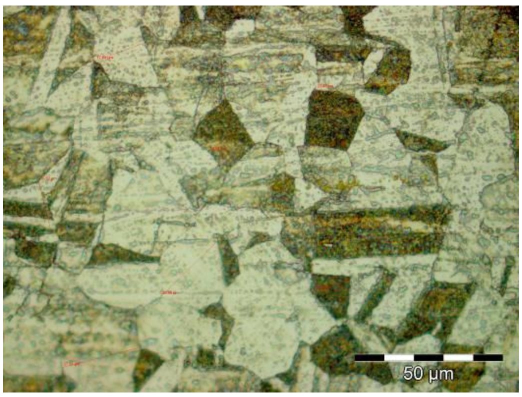


Figure. 6.10. Parent material microstructure Spotted polyhedral grains (plastically deformed by rotating atomic planes), specific appearance of materials with high plasticity.

Sample 1.1 (2 mm hole), area 1 (50 mm distance away from the access point)

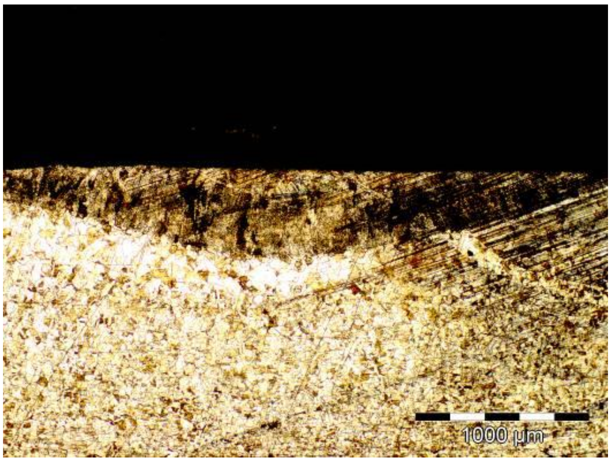


Figure. 6.11. Welding cross section (50x)

Welding was performed in two passes, with an overlap of about 500µm, to ensure the complete penetration and melting of the weld material, with the complete filling of the 2 mm hole. The weld has no overhang, the upper molten area being at the surface of the parent material.
In the root area is observed the area of thermo-mechanical influence (light in color) with a width of about 200 µm. On the analyzed area, the weld is well formed and without discontinuities.

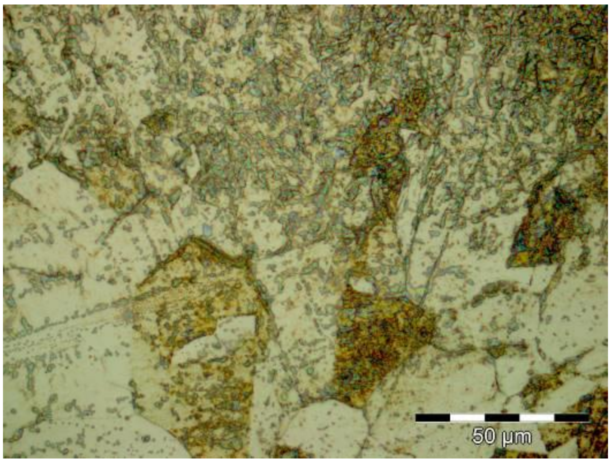


Figure 6.12. Parent material dilution area (500x)

The mixing area between the weld and the parent material is continuous and without defects. On the boundaries of the austenite grains of the parent material, slight segregations of some compounds are observed (dark color).

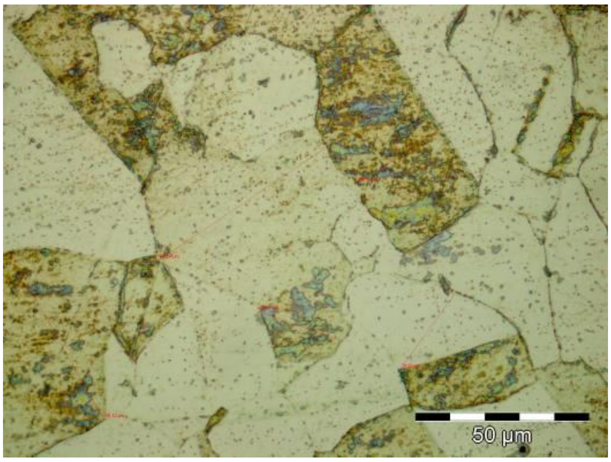


Figure 6.13. HAZ – overheating area with coarse polyhedral grains (500x)

Also, there is a tendency to increase the austenitic granulation, the average diameter of the grain being about 58 µm, compared to about 15 µm in the parent material.

Sample 1.2 (2 mm hole), area 2 (100 mm distance away from the access point)

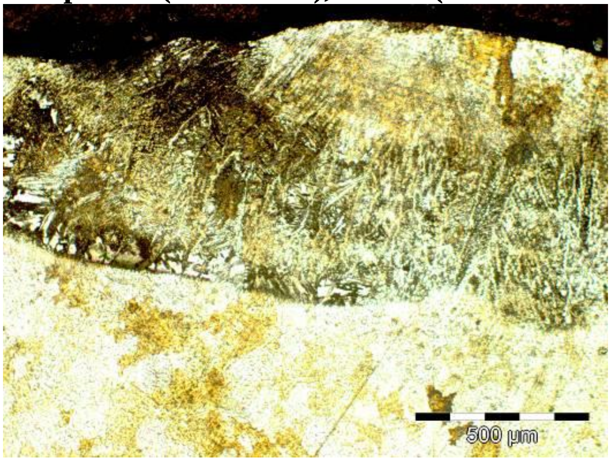


Figure 6.14. Welding final layer (100x)

In this case, the welding was done in two layers. A layer to fill the hole area and a surface layer to obtain the elevation. The first layer underwent a slow cooling, which generated a microstructure with coarse, dendritic granulation. The final layer of the welded seam has a height of 852 µm and a width of 3106 µm. The connection area with the main seam has an acicular microstructure.

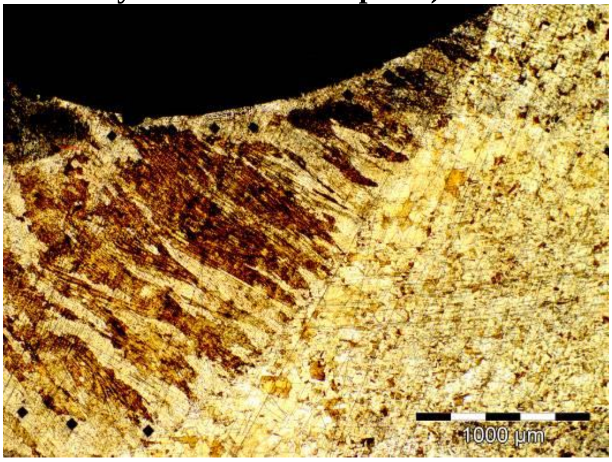


Figure 6.15. Main welding (50x)

The grains increased in length between 200 and 500 µm, being oriented in the direction of heat flow, towards the central area of the weld. The overheating was due to the too high value of the welding current (137A) compared to the wall of the 3 mm pipe. Another undesirable effect was the appearance of a shrinkage on solidification, which required another layer deposited to complete the welding at the inner wall of the pipe.

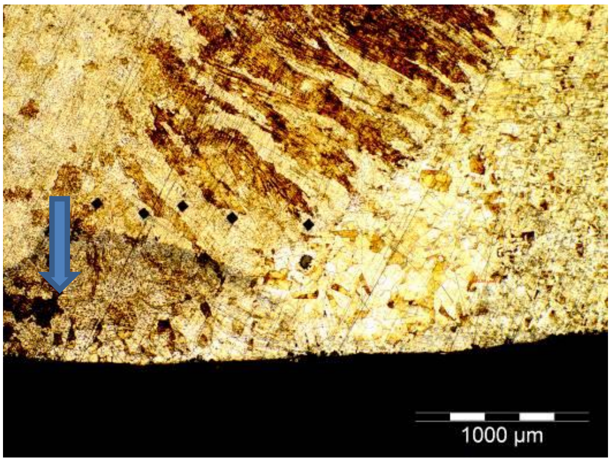


Figure 6.16. Welding root (50x)

The main seam has austenite dendrites and delta ferrite with inter-dendritic precipitation. The grains are elongated in the direction of heat flow. The thermo-mechanical influence area has large granulation. Excessive liquidity of the molten pool also led to the appearance of a perforation effect of the pipe wall, with the formation of a segregation defect at the base of the weld (indicated by the arrow).

The image also shows the microhardness marks on the root area of the weld.

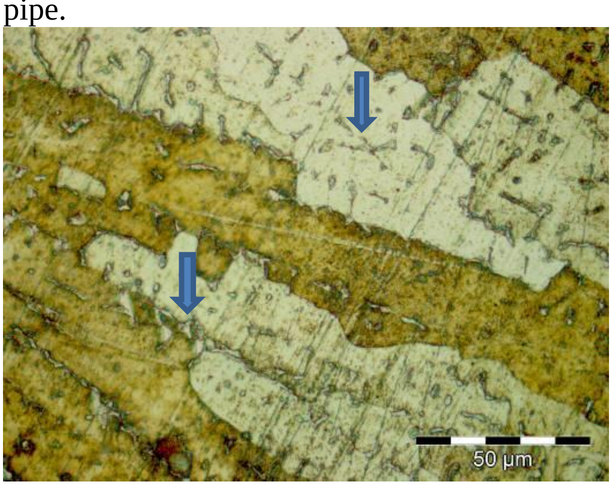


Figure 6.17. Welding root (1000x)

In this case, the inadequate thermal regime at welding caused the precipitation of delta ferrite particles (indicated by arrows), intra- and inter-granular in relation to coarse austenite grains, elongated and oriented in the direction of heat flow.

For sample 1 there were analyzed the areas with experimental welds performed with the WIG process, positioned at different depths in relation to the penetration end of the welding device. As the depth of placement of the weld increases, the difficulty of achieving a correct weld is amplified by the fact that the weld does not have a uniform geometry. By increasing the value of the welding current, there is a tendency for the molten metal to leak at the welding root and pores, segregation defects are formed. At the same time, the proportion of ferrite delta in the weld increases. This aspect is not desirable, because the percentage of ferrite that ensures the best conditions of crack resistance is in the range of 5-8%.

The examination by SEM electron microscopy was performed according to SR EN 1321: 2001, using the Quanta Inspect S electron microscope, FEI Netherlands, equipped with EDAX Z2e chemical microcomposition analyzer. Local micro-composition analyzes were performed to evaluate the distribution of chemical elements present in different areas, due to the effects of the thermal field on welding. At the same time, such analyzes can identify compounds or phases, and based on the actual values of their chemical composition, assessments can be made regarding the level of alloying (Cr, Ni, Mo or C content) or the tendency of segregation (formation of chromium carbides) [33].

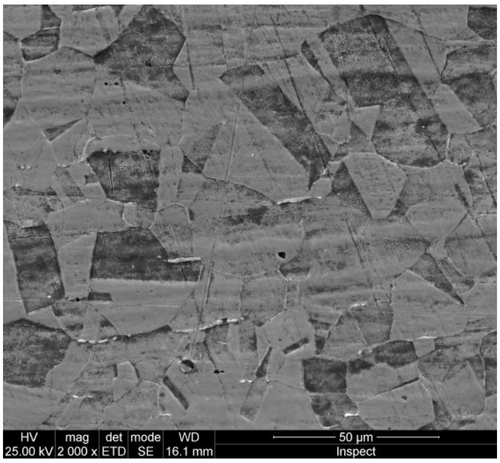


Figure 6.18. Parent material (2000x)
Parent material is an austenitic stainless steel, characterized by the polyhedral microstructure of austenite with sliding planes of specific atomic blocks (macles).
On the boundaries of austenite grains, the presence of delta ferrite is observed, with elongated islands form, lighter in color compared to crystalline austenite grains.

Using the EDAX detector and the related software program of the device, it is possible to acquire micrographic images of the areas of interest (figure 6.19 and 6.21), graphical representation of the atomic spectrum distribution of the identified elements (figure 6.20 and 6.22), of the chemical composition values (table 6.1 and 6.2), as well as the graphical representation of the spatial distribution of the chemical elements (elemental mapping) - figure 6.23.

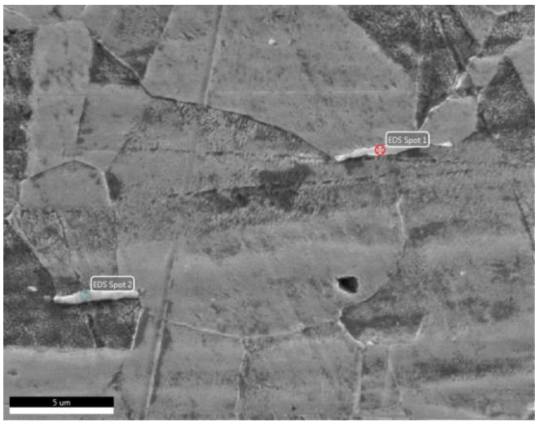


Figure 6.19. EDAX analysis on a microzone of the parent material (on delta ferrite islands)

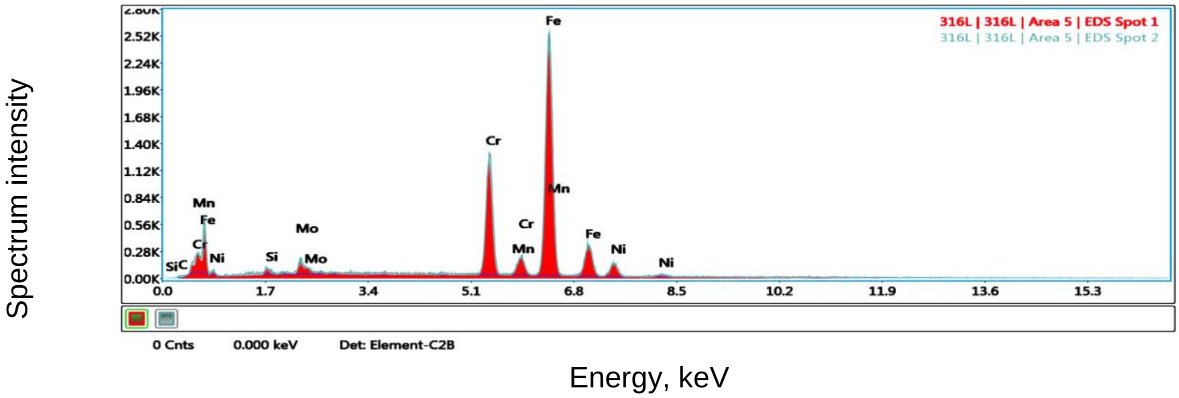


Figure 6.20. Parent material chemical elements distribution spectrum determined by EDAX analysis

Table 6.1. Individual chemical composition values for the analyzed areas (correlation with figure 6.19)

Element	Weight %	Atomic %	Error %
316L, Sample 1.2, area 1, Parent material			
C K	0,89	3,95	28,13
SiK	0,92	1,74	18,8
MoL	2,69	1,5	15,53
CrK	22,6	23,24	2,62
MnK	1,2	1,17	21,07
FeK	66,53	63,69	2,27
NiK	5,17	4,71	7,87

Welding (Sample 1.2)

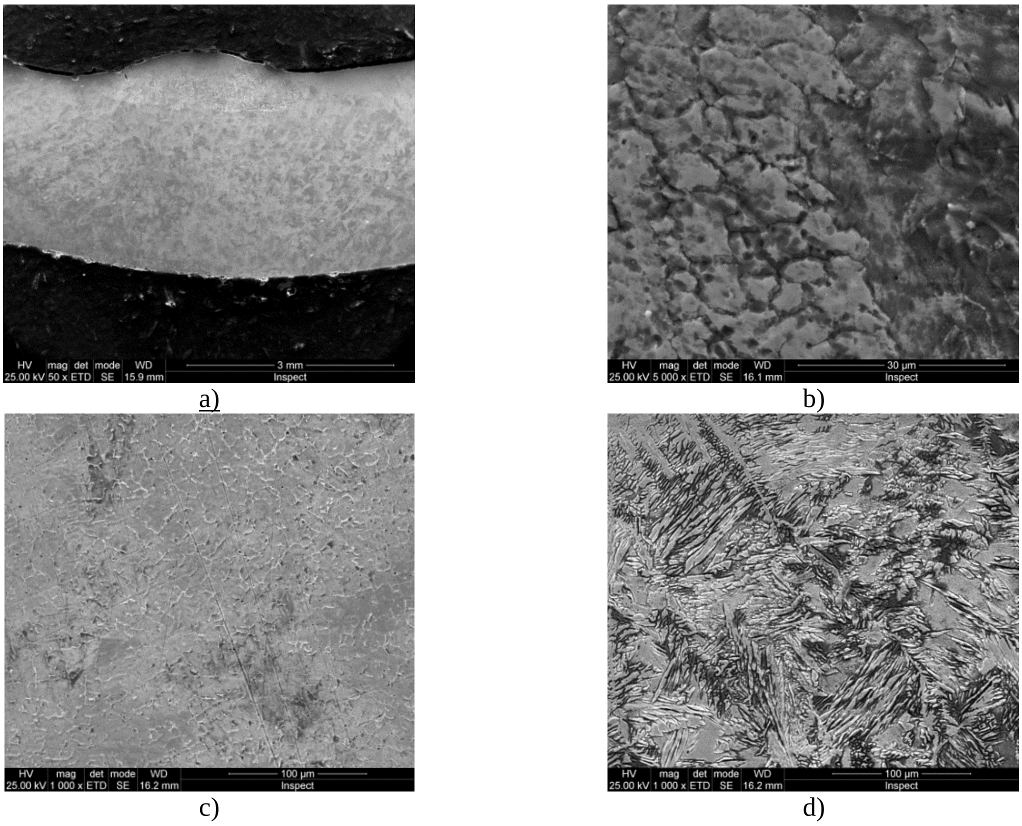


Figure 6.21. Micrographic images from different areas of the welded seam, a) Welding (50x), macroscopic appearance of the welded joint, b) Welding (5000x) Austenite - dendritic microstructure and fine films of inter-granular delta ferrite, c) Fine austenite microstructure with dendritic appearance, d) Welding (5000x) Austenite, ferrite and martensite.

2. EDAX analysis of the welding seam local chemical micro-composition

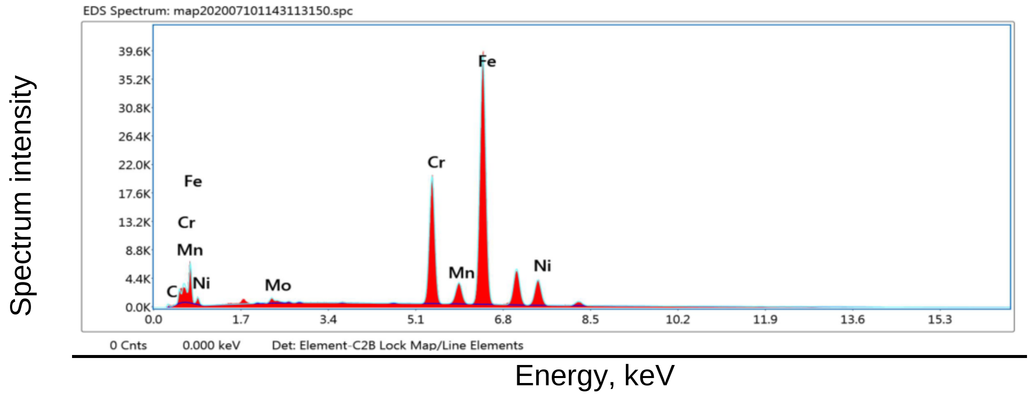


Figure 6.22. Parent material chemical elements distribution spectrum determined by EDAX analysis

Table 6.2. Individual chemical composition values for the analyzed areas (correlation with figure 6.21)

Element	Weight %	Atomic %	Error %
Sample 1.2, area 1, welding area			
C K	1,17	5,18	11,73
MoL	1,01	0,56	5,78
CrK	22,64	23,14	1,71
MnK	1,45	1,40	4,34
FeK	64,43	61,30	1,76
NiK	9,3	8,42	3,20

The determination of the material hardness was performed using the Shimadzu HMV 2T micro hardness tester, the pressing force of 4.903N, the test time of 10 seconds, and 5 successive measurements were performed, in line, on the characteristic areas with distances of about 500µm between fingerprints. The hardness values measured for the first two samples are centralized in table 6.3., and the representative graphs are presented in figures 6.24 ÷ 6.25 [32].

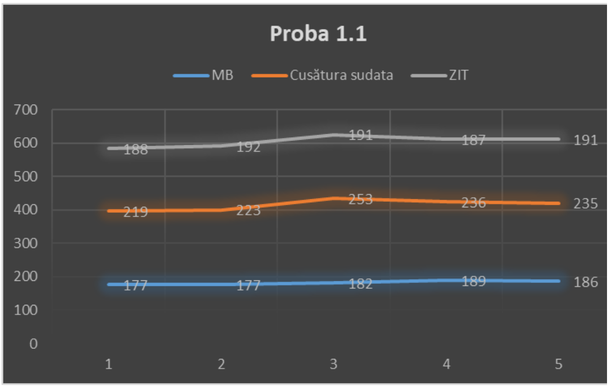


Figure 6.24. Hardness values graph for sample 1.1 [32]

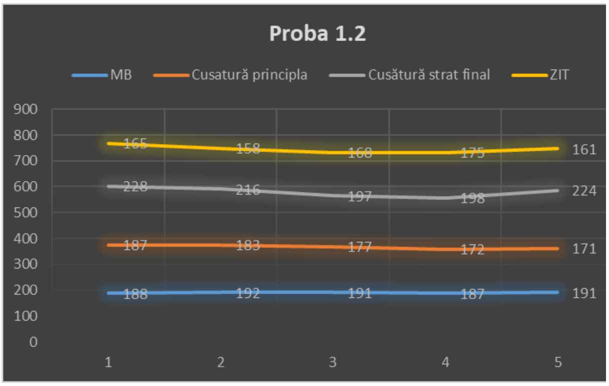
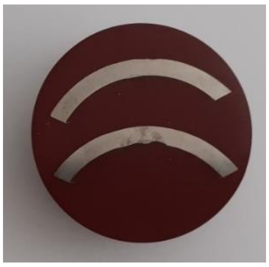


Figure 6.25. Hardness values graph for sample 1.2 [32]

Table 6.3. Hardness values [32]

Macroscopic image of the sample	**Hardness values, HV0,5**		**Average value, HV0,5**	**Standard deviation**	**Variation coefficient**
 *Sample 1.1 and 1.2*	**BM 1.1**	**177, 177, 182, 189, 186**	**182**	**5,36**	**2,94**
	Welded seam	219, 223, 253, 236, 235	233	13,31	5,71
	HAZ	220, 208, 213, 193, 195	206	11,61	5,64
	BM 1.2	**188, 192, 191, 187, 191**	**190**	**2,17**	**1,14**
	Welded seam, first layer	187, 183, 177, 172, 171	178	6,93	3,89
	Welded seam, last layer	228, 216, 197, 198, 224	213	14,45	6,80
	HAZ	165, 158, 168, 175, 161	165	6,58	3,98

CHAPTER VII.
FINAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS

➢ FINAL CONCLUSIONS

The following conclusions can be drawn:

- ✓ A research was carried out on the current state of repair-by-welding technologies on low-access joints.
- ✓ A study on the parent materials used in the construction of heat exchangers was performed.
- ✓ A study was made on the welding technologies used to repair in low-access areas.
- ✓ A study on non-destructive and destructive testing methods used in the welding field was performed.
- ✓ A study on the loads to which the heat exchangers are exposed was performed.
- ✓ An experimental equipment was made for welding repair of the low-access areas.
- ✓ Tests were performed on small diameter pipe samples, on which artificial defects were created, which were subsequently repaired by welding using the WIG process.
- ✓ The obtained samples were visually and penetrant tested to highlight any imperfections positioned on the surface of the welded joint or communicating with the outside.
- ✓ Following the welding repair procedure, it can be seen that the higher is the distance from the access end, the lower the quality of the weld obtained;
- ✓ The quality of the weld decreases with the increase of the cavity size;
- ✓ Following the direct visual testing, a series of imperfections were identified, but the most serious of these being the lack of penetration.
- ✓ During the inside visual examination, it could be observed that up to a distance of about 100 - 150 mm from the access end, the weld has a good appearance with no serious imperfections.
- ✓ At a distance of 200 mm, metal drops can be observed, but also burns.
- ✓ Following the examination with penetrating liquids, it was observed that the outer surface of the weld has imperfections, the lack of melting being the most common.

- ✓ Following the examination with penetrating radiation it can be seen that all the samples showed solid inclusions.
- ✓ In most of the analyzed samples the hardness values in the heat affected area are lower compared to those in the welded seam or the parent metal.
- ✓ There are small differences between the hardness values of the parent metals, although the samples are made of the same material (austenitic 316L stainless steel).
- ✓ The hardness values of the welds are considerably higher compared to those of the parent metal, which accredits the idea that it is possible that hard phases may form in the welds during welding or after cooling.

Thus, the objectives described in Chapter 3 of this thesis, a synthesis of important issues presented at the current stage of repair-by-welding technologies on low-access joints, a synthesis of important issues presented at the current stage of repair by welding of heat exchangers spirals, design and construction of an experimental equipment and an improved welding torch, realization and quality assessment of the welding repair of small diameter austenitic stainless steel pipes (X2CRNIMO17-12-2), have been met.

➢ PERSONAL CONTRIBUTIONS

Over the research and development period on the issue related to the topic, the main personal contributions presented below were made:

- ✓ Critical analysis, systematization and synthesis of existing information on the constructive-functional characterization of heat exchangers and welding processes used for repairs in low-access areas: a) WIG (Wolfram Inert Gas) welding process, b) MIG welding process (Metal Inert Gas).
- ✓ Defining the main stresses to which heat exchangers are exposed and their effects: a) corrosion, b) cavitation.
- ✓ Analysis of the laparoscopic medical kit in order to realize the concept of laparoscopic welding and study the methods of destructive and non-destructive examination of welded joints.
- ✓ Design and construction of an experimental stand for repair by welding of low-access areas and an improved welding torch after analyzing the current welding torches.
- ✓ Design and realization of stainless steel X2CrNiMo17-12-2 pipe type tests with artificial defects.
- ✓ Welding repair of the samples made, using the stand created.
- ✓ Quality assessment of the welding points obtained, using methods of non-destructive testing of samples (visual testing, penetrant testing, radiographic testing) and destructive testing methods (optical microscopy analysis, scanning electron microscopy analysis – SEM, chemical composition determination, material hardness determination).

This doctoral thesis, through its problems, approach and results, covers a series of elements on repair by welding of spiral heat exchangers, non-destructive and destructive testing, as well as the development of an experimental equipment to facilitate the repair-by-welding process on low-access areas in order to develop new methods.

The scientific importance of this thesis is supported by its contributions to: proposing a technology for performing repair by welding of spiral heat exchangers and creating an experimental stand for testing welding joints.

The practical importance of this thesis is that the case studies made on the analysis of welding joints performed by the proposed technology on X2CrNiMo17-12-2 stainless steel pipe samples and their results are useful for students, specialists and other users for a better characterization of the deffects that take place during the welding process and to estimate the effects of this process, but also the quality of the welded seam in relation to the distance between the operator and the place that needs repair.

➢ FUTURE DEVELOPMENT

The issue of repair-by-welding technologies on low-access joints requires an extensive, continuous and analytical research and development activity. The complexity and large volume of the issue addressed in this thesis did not allow to analyze and solve all issues involved in the topic of this paper.

The further minimization of the welding torch and the development of a guideway to increase the positioning accuracy on the defect are two of the main directions to follow. Although the research and tests performed fulfilled their original purpose, it was not possible to physically perform a welding repair of the available spiral heat exchanger. However, there are also spiral heat exchangers to which the methods and equipment proposed in this thesis can be applied, but they were not available for experimentation, being outside the possibilities of the educational unit or to the developer of this thesis.

Also, research can be continued in order to perform repairs by welding on low-access areas to greater depths compared to those conducted in detailed experiments in the thesis but also in the direction of assessing the applicability and development of methods and equipment proposed to repair other types of heat exchangers and other low-access equipment.

In the engineering field, laparoscopic welding, being a completely new concept, will develop in an accelerated rhythm in several directions. One of the development perspectives will be the design and construction of new welding equipment, positioning, handling and real-time viewing.

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