MINISTRY OF EDUCATION
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PhD:

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-ABSTRACT-

DOCTORAL THESIS

Research on robotic welding of complex oversized parts

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CONTENT

INTRODUCTION

Within the production problems of INCDT Comoti that required a large number of the execution of the heat exchanger assembly, component of an industrial centrifugal air compressor (CCAE), it was found that with the existing soldering technology, no more than 12 pieces per year can be manufactured.

The analysis of the decision factors led to the need to change the technology of manufacturing the heat exchanger, identifying a new solution: GTAW welding.

The new technology for manufacturing the heat exchanger assembly which consists of replacing soldering with GTAW welding was determined by technical and economic considerations. Following the replacement of soldering with welding, the time to manufacture the final product is reduced by 25% and a decrease in execution costs is obtained by 15%.

The main difference between the two processes, soldering and GTAW welding, is the use of filler material in the case of soldering and the lack of filler material in the case of GTAW welding.

By changing the heat exchanger manufacturing technology, the institute production production capacity and ability to fulfill orders increased to 15 pieces per year.

The modification of the manufacturing technology of the heat exchanger assembly, after the technical and economic analysis, did not ensure the total coverage of the orders received by the institute. This consequence generated the need for a new approach to the problem. The only solution that could solve the created situation was the implementation of a robotic GTAW welding process.

Through the new technological approach, the institute production capacity and ability to fulfill orders increased to 45 pieces per year.

Among the main objectives of this doctoral thesis are:

- Analysis of a case study to establish the directions of the PhD thesis by identifying a part that can be robotically welded.
- Designing a positioning, fixing and support device to allow robotic welding of the heat exchanger.
- Implementation of software programs for performing the robotic welding process.
- Carrying out verification and confirmation tests of the robotic welding process with the designed fixture and the implemented software program.
- Performing SEM, EDAX metallographic analyzes developed on samples from the test piece.
- Application of the new technological process for series production only after confirming the dimensional control and pressure test for the first part according to the requirements of the execution drawing.
- Analyzing the production cost of the part made by robotic welding compared to manual welding.

CHAPTER I

1. THE CURRENT STATE REGARDING ROBOT WELDING

1.1. INTRODUCTION

Dynamic market changes and existing competition determine compatibility with small and medium series production. In this context, the robotic welding industry stands out as having a good profitability from the point of view of the unit cost of a part compared to performing manual welding or performing automated welding. [1]

The profitability is highlighted in fig.1, where a production volume analysis of the costs of a part is carried out for the three types of welding: manual, automatic and robotic.

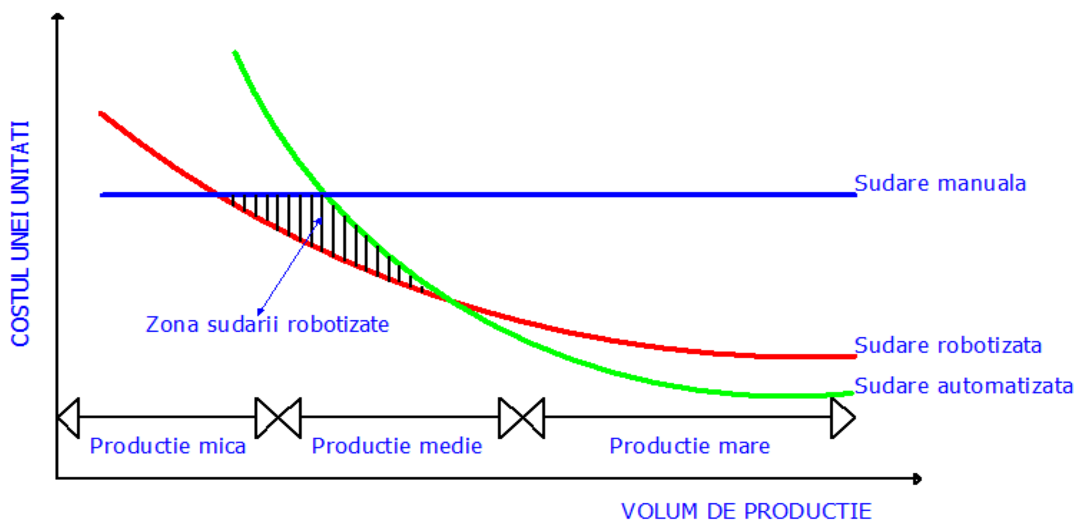


Figure 1 - Application area of robotic welding

1.1.1. General information about welding processes

The most used electric arc welding processes are:

- GTAW - arc welding in protective gas atmosphere with non-fusible electrode;
- GMAW - electric arc welding with fusible electrode in an inert/active protective gas environment .

Shielded Gas Arc Welding (GTAW) is the process in which an electric arc is created between a non-fusible electrode and the base metal. This welding process is also known as tungsten inert gas (TIG) or wolfram inert gas (WIG), since the non-fusible electrode is made of tungsten/wolfram with 100% purity or tungsten/wolfram alloyed with thorium, cerium, lanthanum or zirconium from the consideration of having a melting temperature as high as possible (over 3400 C). The high temperature of the electrode reduces the possibility of accidental contamination of the molten metal pool.

In order to avoid contamination of the molten metal pool during welding by elements from the ambient environment (oxygen, carbon, hydrogen, nitrogen), a shielding gas is used. The most commonly used shielding gas is argon and argon-based gas mixtures (eg argon+hydrogen). It should be stated that in countries where there are massive Helium reserves, this gas is used (eg the USA) for economic reasons.

1.1.2. Adaptation of robots for the robotic welding process

The need for a high-quality product and the requirement to reduce costs as much as possible requires the use of a robot in the production process. The appearance of manipulator robots in the industry determined their introduction in the welding process, thus aiming at its improvement. The characteristics of the handling robots are described in table 1.[2]

Table 1 – Specifications of a manipulator robot

Speed	Up to 5 m/s
Acceleration	Up to 25 m/s^2
Loading	From 2-3 kg to 750 kg
Weight	30-40 kg
Axis	6 axis
Communication protocol	Profibus, Devicenet, Ethernet, Can
Inputs/Outputs	Analog and digital inputs just like a programmable logic controller

1.2. SHIELDING GAS ARC WELDING WITH NON-FUSIBLE ELECTRODE (GTAW)

The GTAW welding process is widely used on most metallic materials: low alloy steels, stainless steels, superalloys (alloys based on nickel, chromium or cobalt), alloys based on titanium, aluminum or magnesium and is especially used in aerospace industry for materials with small thicknesses (0.8 ÷ 3 mm).

The GTAW welding process generates radiation, noise and gases. For this reason, the personnel related to the welding process must be provided with specific means of work protection: anti-radiation equipment, protective masks with a light sensor, earplugs, air absorption and ventilation systems. [17]

The use of the GTAW process is explained by the fact that the resulting welded joint is more resistant and of better quality, the molten metal pool being well protected from the argon flow. [19]

The main components required during the GTAW process are shown in fig.2.

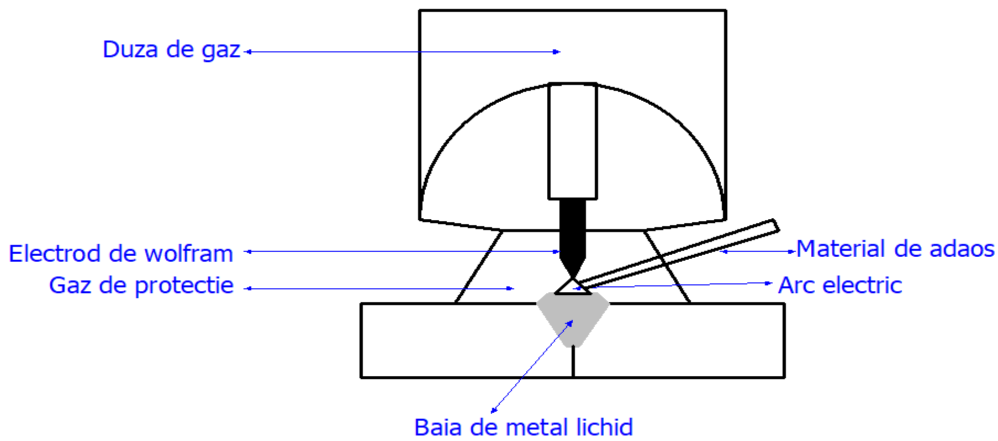


Figure 2 - Simplified diagram of the welding zone in the GTAW process

1.3. ELECTRIC ARC WELDING IN PROTECTIVE ENVIRONMENT WITH FUSIBLE ELECTRODE (GMAW)

In the GMAW process, the electric arc is established between the consumable electrode (filler wire), which continuously feeds the molten metal pool, and the workpiece. Initially, the pool of molten metal is protected by an inert gas hence the popular name of the welding process "metal inert gas" (MIG). Active shielding gases such as carbon dioxide (CO2) or mixtures of inert and active gases are used in the metal active gas (MAG) welding process. The generic name of the GMAW welding process includes both MIG and MAG sub-processes.

The GMAW welding process has several advantages over other welding processes in that it can weld any kind of material with thicknesses from 1 mm to 30 mm, in all welding positions, with a very high filler metal deposition rate. high, with a very high welding speed and with the elimination of the interruptions required for refilling with filler material. In addition, minimal cleaning of the weld seam is required after the process is completed due to the fact that no slag is formed after the molten metal pool has solidified.

The welding equipment used for the GMAW process consists of: the power source, the advance unit of the filler wire (electrode), the welding torch and the protective gas supply regulator represented in fig.3.

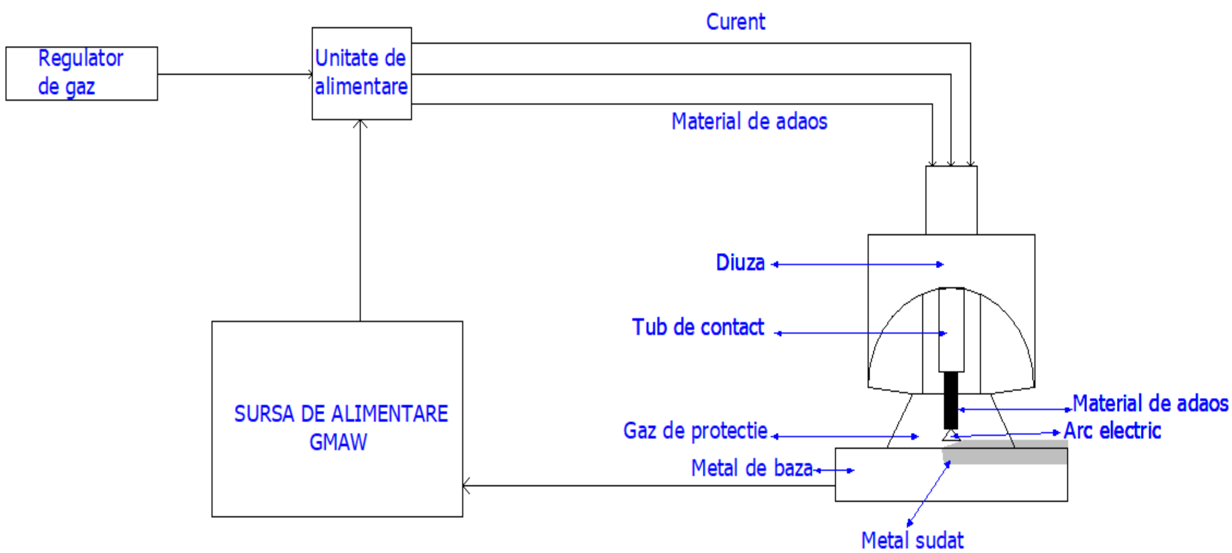


Figure 3 – Schematic representation of the GMAW welding process

CHAPTER II

2. CASE STUDY ON ROBOTIC WELDING OF A FLANGE - PIPE SYSTEM

2.1. INTRODUCTION

The main scientific research objectives in this chapter are:

- Presenting a case study by identifying a part that can be robotically welded.
- The design of a fixing device that allows robotic welding of the respective piece.
- Analyzing the production cost of the part made by robotic welding compared to manual welding.

2.2. CONSTRUCTIVE AND TECHNOLOGICAL DESIGN

2.2.1. Part design

In the case study [36], to exemplify how to design a device necessary for robotic welding of a part, the part used is a pipe that has a flange welded to both ends (fig.4). This part is a component in the gas or pressurized water system of a building. In general, the vast majority of flanges and pipes used in construction are large, but this part is used in smaller systems. The reason for choosing these dimensions for the case study is the low cost price relative to the components obtained, the dimensions chosen meeting the above conditions, namely not being too large in relation to the working space, but not too small in relation to the robot capability.

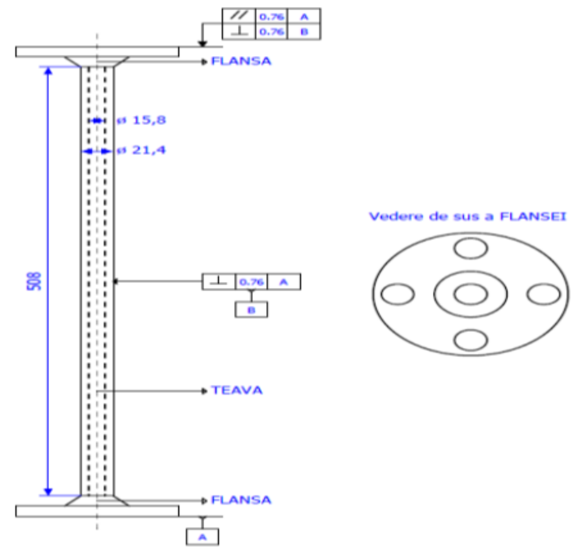


Figure 4 - Schematic drawing of the part used in the case study

2.2.2. Device design

The design of the device was made after the execution of the demo piece. The design of the device for robotic welding of the part in this case study was performed according to [45].

2.2.2.1. Definition of requirements

The fixing device must hold the pipe and the two flanges in place during the welding operation. Also, the tightening of the three components must ensure the maximum reduction of deformations during the welding process. At the same time, the device must allow unrestricted access of the robot to the welding area. The material chosen for the execution of the device must withstand the heating due to the welding process. The last condition that the device must meet is to be easy to place and fix on the robot table and easy to remove after welding.

2.2.2.2. Obtaining and analyzing information

2.2.2.2.1. Robot specifications

The robot used is a Fanuc Arc Mate 50ic type and is capable of rotating in 6 axes. Axis 1 can rotate 360º, axis 2 can rotate 200º, axis 3 can rotate 388º, axis 4 can rotate 380º, axis 5 can rotate 240º, axis 6 can rotate 720º.

These features involve reaching almost any position of the robot inside the workspace, which has the dimensions of 1 m long, 2 m wide and 1.5 m high. Thus, there are restrictions on the positions that can be reached by the robot.[36]

2.2.2.2.2. Part specifications

The part used in this case study consists of two flanges and a half-inch pipe. Starting from the dimensions of the components, the requirements for the part were perpendicularity and parallelism because the assembly must be mounted with the counter part in the system. The tolerances imposed for this assembly will be controlled using a caliper that ensures the reading and precision imposed in [46]. The base material of the part is a pressure-resistant low-alloy carbon steel.

2.2.2.3. Technological analysis of constructive variants

2.2.2.3.1. Flange fixing component

The component used to fix the flange is shown in fig. 5. The flange is placed on the flat surface of the fixing component, making the height of the part and centering on the inside of the flange with the help of pins that are inserted into the holes of the flange. The hole in the center of the fixing component allows the flange collar to enter and center the components. Flange dimensions and tolerances have been taken into account when designing the fixing component. This variant is a simple method of locating and fixing because it does not require moving the device to assemble the components.

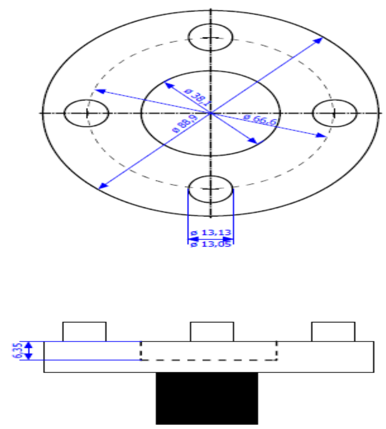


Figure 5 - Flange fixing component

2.2.2.3.2. Device C

Device C (fig. 6 [36]) is made of a steel rod placed on a plate. A single fixing component is welded directly to the plate, the pipe fitting into the V-cut in the end of the rod into which the other end of the centering piece is inserted. The pipe is locked in place using an elastic clamp which is easy for the operator to do and provides enough stability during welding. The main advantage of this solution is represented by the length of the pipe, which can vary significantly. Another advantage of this solution is that the device provides enough room for maneuver for the welding robot according to its capabilities. The disadvantage of this solution is the need to position the part twice to weld it at both ends.

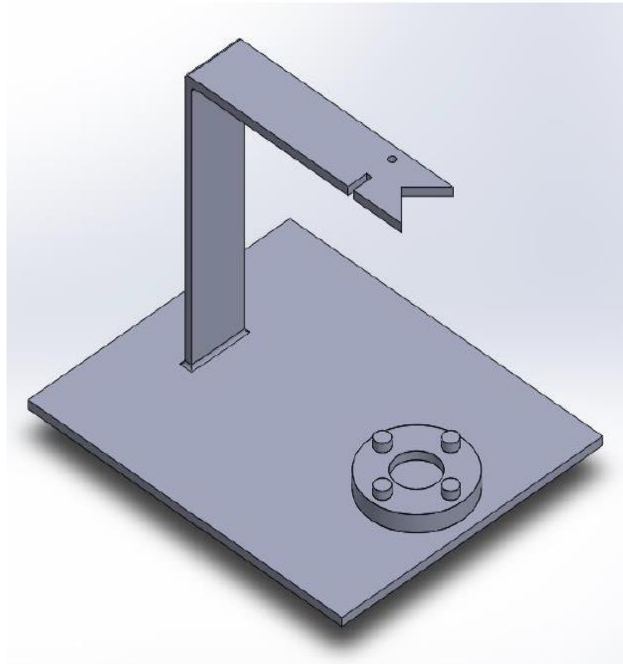


Figure 6 – Device C

2.3. FUNCTIONAL ANALYSIS OF THE TECHNOLOGICAL ASSEMBLY FOR WELDING

2.3.1. Device manufacturing

2.3.1.1. Fixing component

The fixing component is the closest to the area to be welded of the flange + pipe system. This means that it works at high temperatures and must withstand it. The base material from which the fixing component is made is a low-alloy carbon steel, in the form of a bar with the size of Ø 89 mm and it was processed in a milling center with numerical control. The milling operations were necessary to execute a clean straight face, a channel on the other side with the dimensions Ø 38.1x 6.35 mm and the execution of 4 holes arranged on the diameter of Ø 66.6 mm at 90° having the diameter Ø 13.09 ± 0.04 mm. The four pins to be assembled into the holes in the fixing component were machined on the lathe respecting the assembly dimension by pressing at the end.

2.3.1.2. The body of the device

The base material from which the other part of the device is made is also a low alloyed carbon steel as the device must be able to withstand wear. The base plate and the two traverses were cut to size using a guillotine. The V channel of the upper traverse was made by stamping and the grip cut was made using a vertical saw. The three components were welded on a welding device. The fixing component was welded to the plate, only after a vertical fixation of a standard piece was previously achieved, achieving the perpendicularity conditions (0.76 mm) required in the documentation.

2.3.2. Robot programming

To test the fixing device design, a software program for the robot must be implemented. This objective was achieved using a programming console that allows the operator to impose the movements of the robot necessary to perform the welded assembly by controlling the 6 axes. Several points were defined along the weld seam between the flange and the pipe forming an arc around the pipe. The software was written so that the same trajectory is implemented for the robot every time the program is executed. As long as the device is placed in the correct position, the program will run and execute a correct arc around the part. The program that was used for welding this part is presented in fig.7.[36]

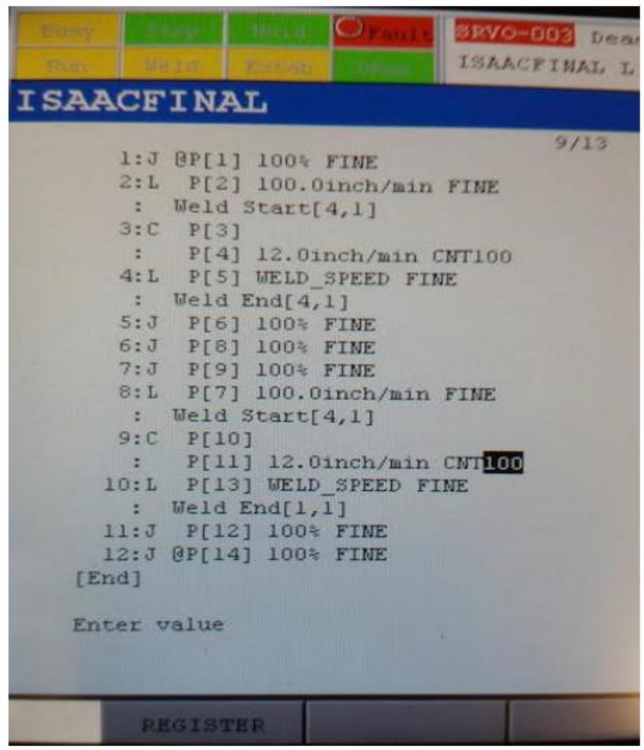


Figure 7 - The software program used for welding

CHAPTER III

3. RESEARCH ON THE ROBOTIZATION OF THE WELDING PROCESS FOR AN OVERSIZED HEAT EXCHANGER ASSEMBLY

3.1. INTRODUCTION

CCAE is an electrically driven centrifugal air compressor and is intended for supplying the necessary industrial compressed air.

Figure 8 - View of electrically driven centrifugal air compressor CCAE [47]

The five stages of the air compression compressor are individually formed by a centrifugal rotor with backward curved blades, mounted on its own pinion and a palletized stator.

After steps I, II, III and IV, an internal heat exchanger is placed, with the role of moving the temperature of the compressed air at the exit of the respective stage. After the fifth stage of the compressor, the heat exchanger will be mounted outside.

3.2. OVERVIEW AND STRUCTURE OF THE HEAT EXCHANGER ASSEMBLY

The air-water heat exchanger assembly of CCAE 15-300 has the following operating parameters:

- For the air circuit:
    - A nominal flow of 4,4 kg / s;
    - A maximum inlet temperature + 140°C;
    - A maximum outlet temperature + 40 ° C.
- For the water circuit:
    - A flow rate of 38,5 ÷ 48,3 m^3 / h;
    - An inlet pressure of 2,5 ÷ 3,5 barg;
    - A maximum inlet temperature of 30 ° C.
- The maximum dissipated thermal power is 445 kW.

The main components of the heat exchanger assembly are:

- Front tubular board, 1 pc, base material 1.4306 (X2CrNi19-11 according to EN 10088-1 or 304L according to AISI / SAE or S30403 according to UNS) which is a chrome-nickel austenitic stainless steel wih low carbon.

- Rear tubular board, 1 pc, base material 1.4306 (X2CrNi19-11 according to EN 10088-1 or 304L according to AISI / SAE or S30403 according to UNS) which is a chrome-nickel austenitic stainless steel with a low carbon content.
- Exchanger element subassembly 288 pcs, composed of:
    - 28x1 mm pipe, 1 pc, basic material Cu 99,9.
    - 13x1 mm pipe, 1 pc, basic material Cu 99,9.
    - Fins, 3 pcs, basic material Cu 99,9, sheet with a thickness of 0,15 mm..
- Central tube subassembly, 1 pc, base material 1.4306 (X2CrNi19-11 according to EN 10088-1 or 304L according to AISI / SAE or S30403 according to UNS) which is a chrome-nickel austenitic stainless steel with a low carbon content.

Figure 9 - Side and frontal view of the heat exchanger assembly

3.3. MATERIALS USED IN THE MANUFACTURING OF THE HEAT EXCHANGER ASSEMBLY

3.3.1. Stainless steel 1.4306

1.4306 stainless steel (X2CrNi19-11 according to EN 10088-1 or 304L according to AISI / SAE or S30403 according to UNS) is a chrome-nickel austenitic stainless steel with a low carbon content.

The chemical composition, mechanical properties and physical properties of this material are described in Table 2, Table 3 and Table 4, respectively.

Table 2 - Chemical composition of stainless steel 1.4306

% C	% Si	% Mn	% Cr	% Ni	% N	% P	% S
≤ 0,03	≤ 1,0	≤ 2,0	18,0 ÷ 20,0	10,0 ÷ 12,0	≤ 0,11	≤ 0,045	≤ 0,015

Table 3 - Mechanical properties of stainless steel 1.4306 at 20°C

Hardness HB30 HB	0,2 % Flow limit R_p N/mm^2	Traction resistance R_m N/mm^2	Elongation A_5 %	Elasticity kN / mm^2
≥ 215	≥ 180	460 ÷ 680	45 / 35	200

Table 4 - Physical properties of stainless steel 1.4306 at 20°C

Density g / cm^3	Specific heat capacity J/kg K	Thermal conductivity W / m K	Electrical resistance Ω mm^2 / m
7,9	500	15	0,73

The weldability of the parts from this basic material is very good, in most cases no special conditions are imposed for the achievement of the welded joints. A special problem is represented by the tendency of hot cracking due to the formation of ferrite in the weld seam.

3.3.2. Copper-based alloy having Cu 99,9

Copper-based alloy Cu 99,9 is characterized by a very good electrical and thermal conductivity. The alloy is malleable, having a good ductility and a high degree of cold plastic deformation. Sheet metal, parts and pipes can be easily formed into a variety of shapes and sizes.[19]

The chemical composition, mechanical properties and physical properties of the copper-based alloy Cu 99,9 are described in Table 5, Table 6 and Table 7, respectively.

Table 5 - Chemical composition of copper-based alloy Cu 99,9

% Cu	% Bi	% Pb	% O	% Other elements
99,9	max. 0,0005	max. 0,005	max. 0,040	0,03

Table 6 - Mechanical properties of copper-based alloy Cu 99,9

Traction resistance Rm MPa	Flow limit $Rp_{0,2}$ MPa	Elongation $A_{100\ mm}$ %	A %
250	min. 200	min. 8	min. 12

Table 7 - Physical properties of copper-based alloy Cu 99,9 at 20°C

Density g / cm^3	Solidification °C	Electric conductivity %IACS	Thermal conductivity W / m K	Thermal expansion µm / m K
9,0	1070	100	390	17

3.4. EXPERIMENTAL RESEARCH ON ROBOTIC GTAW WELDING OF A SMALL-SCALE “HEAT EXCHANGER” ASSEMBLY

In order to weld the component copper pipes of the heat exchanger, experiments were carried out on a test piece. The aim is to develop a software program for a robotic welding system in 8 axes, type CLOOS CST FLEX S with laser sensor and TIG AC/DC GLW 500 welding source. The software program of the robotic system must be implemented in its control console using the language of programming Carola.

In order to be able to manufacture the test piece, 20 copper pipes were used which were fixed by spot welding inside a structure that has the role of supporting them and imitating the heat exchanger assembly. The test piece which is the faithful copy of the heat exchanger assembly is presented in fig.10.

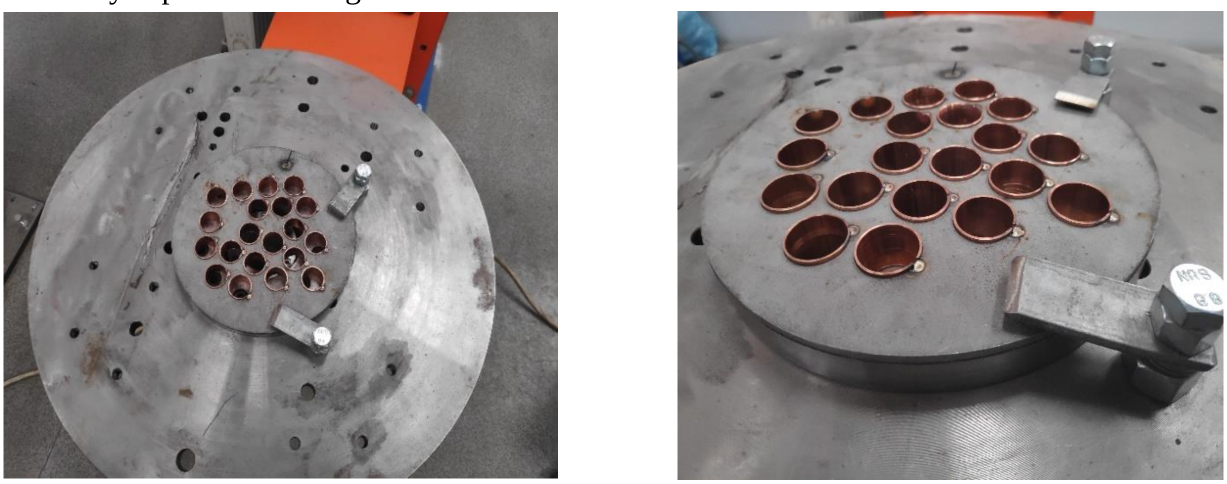


Figure 10 – The test piece used to perform robotic welding of copper pipes

3.4.1. Defining points within the robotic system

In order for the robotic system to weld the copper pipe with reference 9, seven points are defined, three of which are intermediate points. Each defined point is saved into the console memory of the robotic system and thus the position of the robot is recorded. The intermediate point 10 is shown in fig.11 by the final position of the robotic system before saving the point into the console.

Figure 11 – Saving the intermediate point 10

3.4.2. Experimental results on test specimen no. 9 welded with optimal parameters obtained from previous results

Test specimen number 9, copper pipe with reference 9 is shown in fig. 12, at the end of the welding process with the robotic system.

The values of the welding parameters are defined in the LN1 list within the robot software program:

- welding speed Vsud=15 cm/min;
- oscillation frequency Fpend=0.25 Hz;
- pulsation frequency Fpuls=0 Hz;
- base current Ibaza=125 A
- the pulsation current Ipuls=100 A;
- the speed of the filler wire Vsarma=0 cm/min.

Figure 12 – Image of robotic welded areas in the case of the copper pipe with reference 9 within the heat exchanger test piece

After the test specimen visual inspection with reference 9, it was concluded the copper pipe circumference complete welding. The width of the weld is acceptable and uniform on the entire pipe outline, being able to include the fastening tack weld.

The welding necessity without the additional material has been confirmed, melting being performed only of the reinforcement material related to the copper pipe.

CHAPTER IV

4. MICROSTRUCTURAL CHARACTERIZATION OF WELDED JOINTS

4.1. INTRODUCTION

The thesis presents results obtained to achieve a heterogeneous assembly consisting of a beam of “21 copper pipes with the diameter of 28 mm and the wall thickness of 1mm, welded at both ends to two 304L stainless steel plates, with the thickness of 20 mm. The welding was performed with a robotic system, by melting the reinforcement ends of the copper pipes with a height of 1,5 mm ±0,5 together with the edges of the machined holes in 304L steel plates, using the Gas Tungsten Arc Welding process.

For the assessment of weldability, microstructural analyzes of the welded areas are presented, highlighting the diffusion and mixing effects of the chemical elements at the welding level and in the transition areas of the HAZ. The novelty of the paper results from the analysis of the mixing areas that appear at the transition between the two materials, by performing measurements of the chemical composition in different areas of the joint, in the conditions of the robotic welding.

Following the analysis of the characteristic areas of the welded joint with the help of a SEM scan electronic microscope and the micro-chemical composition analysis performed with the EDAX method, it was found that on the interface between the weld and the 304L stainless steel there is a mixture area, with a mixed structure, composed from a metal matrix with a Fe-Cu alloy in which globular phases rich in Cu or Fe are separated.

4.2. METHODS

Heterogeneous welds were made with an 8-axis robotic system, equipped with a CLOOS CST FLEX S laser sensor. The workstation where the robotic system is located was large enough to perform all the movements necessary to make the welds, respectively 4 meters wide and 6 meters long, being located in an industrial hall and separated from other processing areas by means of rigid walls and of a opaque plastic curtain (fig. 13).

In this experimental and technological framework, the robotic arm can rotate in a semicircle with a radius of 2 meters around the axis of the basic support, without touching other equipment, and on the work area can make all movements in 4 directions, in order to position on the welding area and rotating around the axis of the pipes for welding. The workstation of the robotic system is also equipped with a safety system against accidental collisions that may occur inside the workspace, respectively an infrared barrier to limit personnel access to the active area during the welding process.

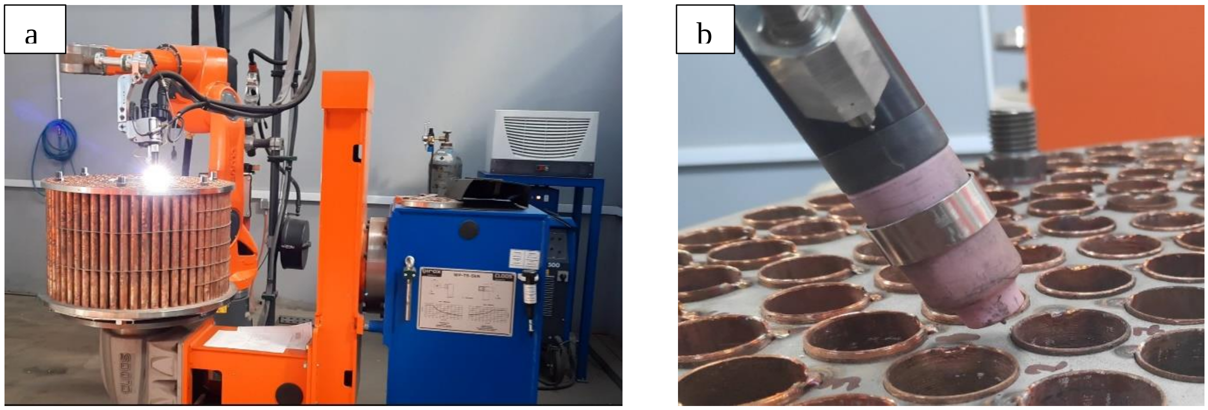


Figure 13 - Robotic welding workstation (a) and positioning of the welding gun for performing the operation of tack welding (b)

After welding, samples were taken from the welded areas. Sampling was performed using 1.25 mm thickness metallographic abrasive discs under coolant, with the Buehler IsoMet®4000 precision automatic cutting machine (BUEHLER USA, Lake Bluff, IL 60044, USA), from the LAMET laboratory, UPB.

The metallographic analysis was performed using an SEM Inspect S scanning electron microscope (FEI Europe B.V., Eindhoven, Netherlands) equipped with AMETEC EDAX Z2e chemical composition analyzer from LAMET laboratory, UPB. The hardness measurement in different areas of the welded joint was performed with the Shimadzu HMV 2T semi-automatic device (Tokyo, Japan, Shimadzu Duisburg, Germany), from the LAMET laboratory, UPB.

4.3. RESULTS

4.3.1. Carrying out welded tests

The welding of copper pipes in 304L stainless steel plates was performed without filler material, by melting the ends of copper pipes that are having an average height of 1,5 mm ±0,5, together with the edges of the holes from the 304L stainless steel plate. The two tubular plates used for the tests had an outer diameter of 714 mm, an inner diameter of 240 mm and a thickness of 20 mm.

In order to achieve a correct joint, the maximum height of the copper pipes above the surface level of the 304L steel plates was set to be a value between maximum 2 mm and minimum 0.5 mm. Tests have shown that a copper pipe height of more than 2 mm can lead to the formation of an excessive melted metal pool, characterized by a slower solidification and obtaining an irregular shape of the weld (leakage of molten metal outside the perfectly circular area, forming of solidification craters or insufficient melting of the 304L steel plate flank etc.). Copper pipes height below the limit of 0,5 mm will not ensure the required weld volume, leading to imperfections such as lack of joint filling, insufficient weld height and formation of an non-homogenous metal pool, which does not ensure the tightness of the welded joint.

The variation of the current during the robotic welding process of a Cu 99.9 pipe on the 304L stainless steel is represented in Fig. 3. The flow rate of argon to the welding gun has been set at 10 l/min and the pre-purging time with argon was at least of 1 sec for each welding operation. The argon purge time at the end of welding was at least of 2 sec, to ensure rapid cooling under inert gas protection.

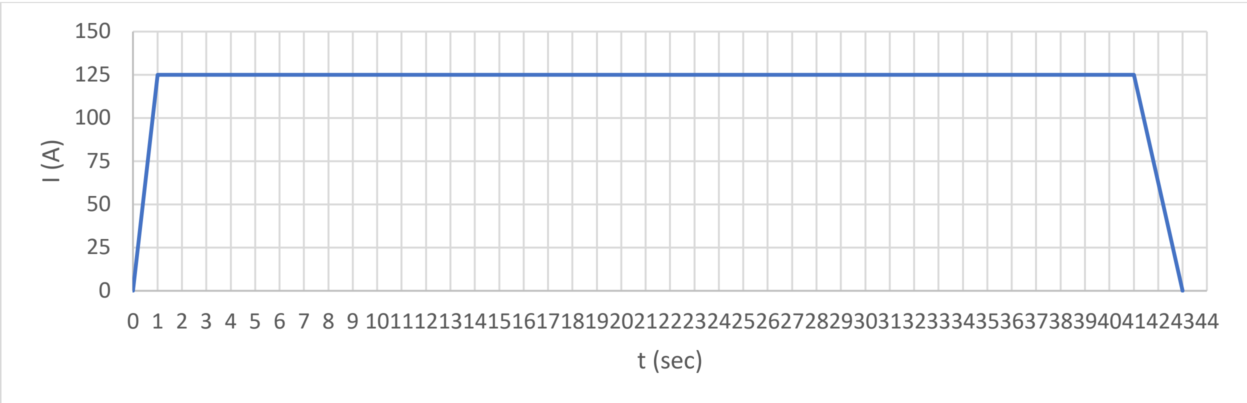


Figure 14 - Current time variation during the robotic welding process

During the GTAW welding process (welding through melting with an electric arc in an inert gas environment with a non-fusible electrode of wolfram), the length of the welding seam for each pipe was 93 mm, of which 88 mm is the perimeter of the copper pipe with the diameter of 28 mm, to which 5 mm were added over the starting point of the welding process in order to re-melt the beginning area and avoid the formation of cracks at the final welding crater.

4.3.2. Testing the quality of welds

The inspection weld quality made with the designed robotic welding technology was performed with nondestructive and destructive methods.

First, a 100% visual examination of the welds was performed using a magnifying glass with a magnification of 5x and a lamp with a lighting power of 100Lux. During the visual examination, the repeatability of the geometric shape of the welding cords on the entire circumference of the copper pipes was found. During the dimensional inspection, the width of the welding seam, between 3 ÷ 4 mm, is uniform over the entire contour of the copper pipe with a reinforcement between 0.5 ÷ 1 mm.

The second method of non-destructive examination of welds was the control with penetrating liquids (according to SR EN 571-1: 1999, SR EN 571-1 and technical prescription CR6-2003). This type of examination consists of spraying a thin, continuous film of penetrating liquid (type DP-55 Sherwin) over the entire controlled surface, leaving about 10-15 minutes for it to penetrate into small surface imperfections, or in the volumetric ones that communicate with the surface. After that, the excess penetrant was removed by washing with water, the surface was dried with warm air. A uniform and continuous layer of developer (type D-100 Sherwin) was applied by spraying on the dry surface, which, due to its absorption properties, highlights the open discontinuities on the surface. The examination with the penetrative liquids was performed in visible light where the noticed imperfections were written down in the examination report (final crater in the weld, insufficient heightening and uneven seam shape). After applying the measures to avoid the formation of imperfections found during the inspection with penetrating liquids, other welded pieces were performed, in which no external imperfections were registered.

Finally, the welded product was subjected to a global leak test performed with water under pressure at 12,5 barg for 15 minutes and no losses were found through the optimized welds.

Destructive testing consisted in taking samples in a transverse direction to the welds performed and examining them by scanning electron microscopy (SEM). For obtaining the necessary electronic analysis specimen it was first extracted a piece which was cut from the test piece with a 1 mm thickness flex disk in the direction of the adjacent reference 9 pipe holes. The two samples have been prepared for the metallographic analysis.

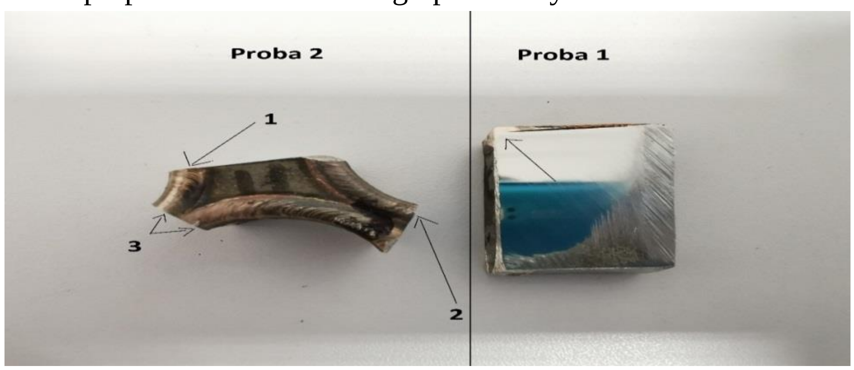
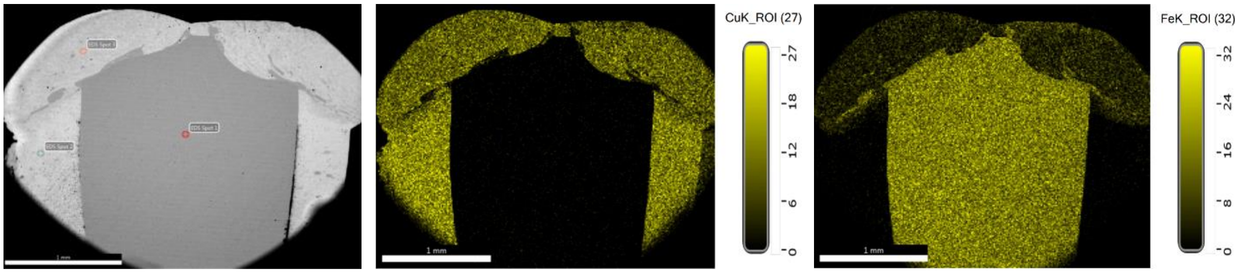


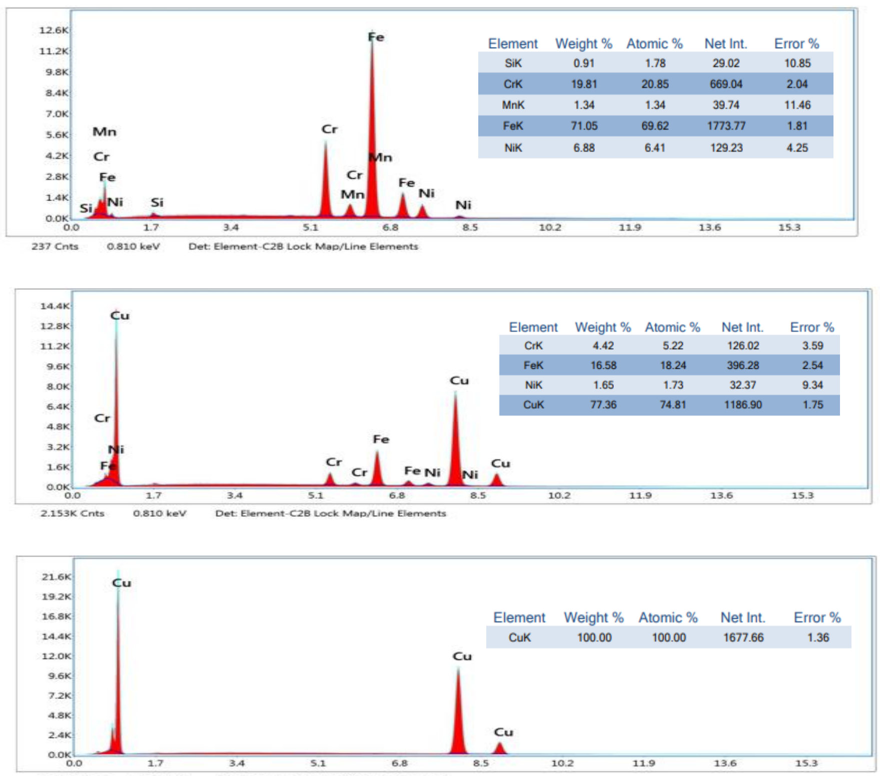
Figure 15 – Points on the two samples onto which the microscopic analysis will be performed

4.4. ANALYSIS OF THE MICROSTRUCTURE OF THE JOINT AREA

The analysis of the microstructure of the welded area consisted in examining at different magnification powers the interface between the two materials (Cu and 304 L stainless steel), diffusion zones and reciprocal mechanical mixing for the formation of welding and base materials. First, chemical microcomposition analyzes were performed on the base material of the tubular plate (Spot 1, 304 L), on the wall of the copper pipe (Spot 3) and on the weld (Spot 3) (fig. 6). From the data of the EDS analysis it results that the welding is a new alloy with Cu base (over 77wt.%), in which are found alloying elements that come from the stainless steel piece (over 4 wt.% Cr, about 16 wt.% Fe , about 1,6 wt.% Ni). There are also some differences in the chemical composition of 304 L steel compared to the standard composition, especially in terms of Ni concentration (about 7 wt%, compared to 8-10.5 wt% of the product standard). This difference may be due to the measuring area, which was quite close to the welded area (about 1 mm), where diffusion effects were possible, but also due to the location of the lot from which the piece was taken in the composition range closer to the minimum values.



a) b) c)



d)

Figure 16 - Location of chemical composition determination points on the cross-section of the heterogeneous weld Cu-304 L (a); b), c) the associated elemental distribution images for the Cu and Fe elements; d) the spectrum of the chemical elements and their concentration in the specified areas in fig. 16a

CHAPTER V

5. CONTRIBUTIONS TO THE DESIGN OF THE GTAW ROBOT WELDING PROCESS FOR AN OVERSIZED HEAT EXCHANGER

5.1. INTRODUCTION

The design and execution of a device for centering and fixing the assembly on the rotary table of the robotic system to achieve circularity and flatness will be analyzed.

The chapter will describe the first welding process performed on the heat exchanger assembly, called pilot welding.

The chapter will present the results of the first variant of robotic welding of the heat exchanger assembly. Improvements to the robotic heat exchanger assembly welding process will be established later.

5.2. DESIGN AND EXECUTION OF THE "AMIFIX" DEVICE FOR CENTERING AND FIXING THE ASSEMBLY ON THE ROTARY TABLE OF THE ROBOT SYSTEM TO ACHIEVE CIRCULARITY AND FLATNESS

5.2.1. Defining centering and flatness device requirements

The device for centering and fixing on the rotary table of the robotic system of the heat exchanger assembly must keep the assembly in a fixed position and ensure the maximum flatness of 0.5 mm and the maximum circularity of 0.5 mm of the welding flange during the welding process.[85]

Also, the device must not allow the part to rotate independently of the robotic system table rotation. At the same time, it must be taken into account that the maximum weight of the assembly and device does not exceed 500 kg, the maximum weight allowed by the rotary table of the robotic system. Given that the assembly weighs 300 kg, the weight of the device should not exceed 200 kg.

At the same time, the device must allow easy fixation on the rotary table of the robotic system, easy assembly of the part on the device, unrestricted access of the robotic arm to the welding areas and easy removal of the part after welding.

The material chosen for the execution of the centering and fixing device of the part must ensure resistance to the repeated heating and cooling characteristic of the welding process.

Also, to reduce deformations during the welding process, the material must have an expansion coefficient identical or as close as possible to that of the base material of the tubular plates. Consequently, considering that the base material of the tubular plates is 1.4306 (X2CrNi19-11 according to EN 10088-1 or 304L according to AISI/SAE or S30403 according to UNS), the material from which the centering and fixing device is made is 304L, under bar shape with a diameter of 260 mm.

5.2.2. Heat Exchanger Assembly Specifications

The main components of the heat exchanger assembly used in the robotic welding process are the front tubular plate, the rear tubular plate, the exchange element sub-assembly and the central tubular sub-assembly.

Figure 17 - The heat exchanger assembly before the welding process

The actual welding process is performed, on the one hand, between the front tubular plate and the 288 pipe ends of the exchange element subassembly. On the other hand, after turning the part, the rear tubular plate and the other ends of the pipes of the exchange element sub-assembly are welded.

5.2.3. Concepts for manufacturing the centering and fixing device for the heat exchanger assembly

In both phases of the heat exchanger assembly welding technology, the positioning and centering of the part on the rotary table of the robotic system is achieved by using a device. It must be centered on the one hand in the inner diameter of the rotary table of the robotic system, and on the other hand, it must be centered in the inner diameter of the exchange element subassembly.

Fixing the part to the device is achieved due to the 300 kg weight of the heat exchanger assembly.

A centering and fixing device, called "Amifix" was designed and executed for the heat exchanger assembly, having the same diameters at the ends, but provided with seating surfaces (shoulders) both on the rotary table and on the tubular plate, as shown in fig. 18.

Figure 18 - The final version of the "Amifix" centering and fixing device

At the end of the execution of the final version of the "Amifix" device, a significant shortage in the time for centering and fixing the part was found, obtaining a flatness of the tubular plate of maximum 0.5 mm and a circularity of maximum 0.5 mm. The heat exchanger assembly was placed on the rotary table of the robotic system using the final version of the "Amifix" centering and fixing device, as shown in fig. 19.

Figure 19 - Fixing and centering the part with the "Amifix" device on the robotic system table

5.3. PILOT ROBOT WELDING OF THE HEAT EXCHANGER ASSEMBLY

5.3.1. The implementation of the welding software program for a pipe in the robotic system console

Through successive tests on samples, the software for welding a copper pipe on the tubular plate was implemented. In order to achieve this objective, a series of stages were completed.

The first step was determining and saving the intermediate points found on the trajectory to the copper pipe in the memory of the robotic system, as was done for the robotic welding of the test piece.[88]

The distance of 1 mm was established between the wolfram electrode and the edge of the pipe.[89] The start list, the normal list and the end list got their welding parameters defined in the memory of the robotic system.

The welding process will take place with the welding gun at a 60^o angle in reference to the tubular plate, in the horizontal position 1G, with the rotary table of the robotic system in a horizontal position at a 0^o angle.

Also, the welding process will take place through one pass and without any filler material, melting only the material located in the reinforcement of the pipes in reference to the surface of the tubular plates.

The base welding current used is Is = 125 A. The decrease time of the current at the end is 2 sec. The argon flow for the welding gun is 6 l/min. The pre-purging time of the argon is at least 1 sec. The purging time of the argon after the welding is at least 2 sec.

A protective argon gas 5.0 type with the minimum purity of 99,999% has been used, the gas being stored in steel gas cylinders that have the cylinder neck marked with a dark green color, RAL 6001 type, with a filling capacity of 10,7 m3 at a 200 bar pressure.

A ceramic nozzle with the diameter of 12 mm, having the diameter of the wolfram WT20 electrode (wolfram + 2 ÷ 4% thorium) of 3,2 mm has been used.

By carrying out all these stages, the activity meant the development of a software in the console of the robotic system for the pilot welding of the part with the established welding parameters.[90]

5.3.2. The simulation of the pilot welding process

The developed software program for the front tubular plate was executed, without having the electrical arc active and the trajectory of the welding area was followed in order to make sure there is no collision with the components of the front tubular plate or the device.[92]

At the end of the welding simulation process, there has been concluded that the welding gun has not came in contact with any components or parts of the device. The robotic system has not accidentally stopped and there weren’t any unwanted collisions.[93]

5.3.3. Checking the software and the robotic welding process through pilot welding a circular row of pipes on the tubular plate

Having a positive result from the simulation of the welding process and the developed software technique, it was proceeded to the next testing step of the software program, activating the electrical arc during the execution of the robotic system console program.[10]

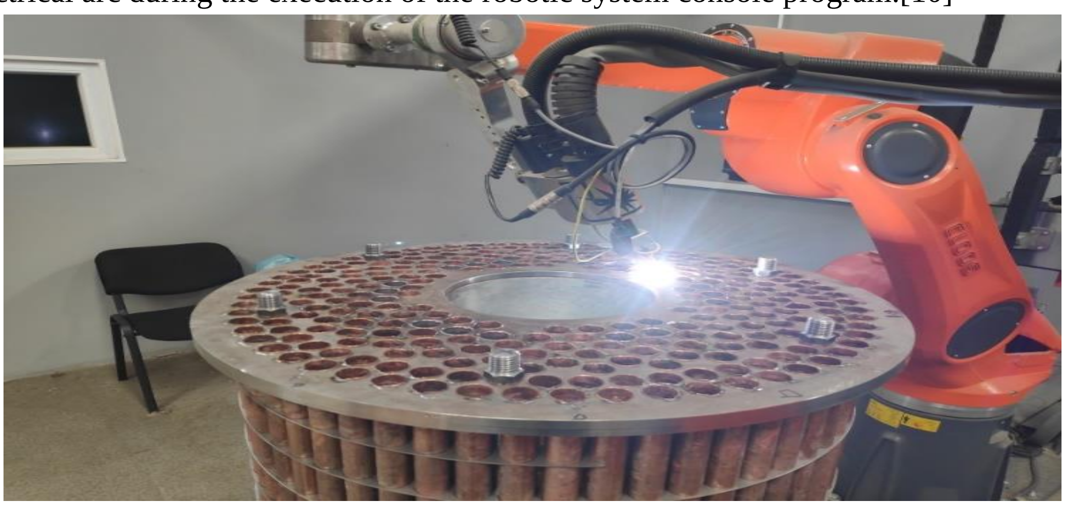


Figure 20 - The pilot welding of a circular row of pipes to the tubular plate

During the welding process, there weren’t noticed any deviations from the resulted trajectory of the simulation process and neither any distortion of the electric arc during the successive passing from a pipe to another with the robotic system.

The welding seams were performed uniformly and without any surface nonconformities.

5.4. FIRST ROBOTIC WELDING VERSION OF THE HEAT EXCHANGER ASSEMBLY

5.4.1. The principle algorithm, simulation of the welding process and welding of the part

In order to reduce deformations and avoid local overheating of the part, the pipe welding execution order was implemented by software.

Figure 21 – Grouping and welding of sections of 10 pipes on the tubular plate

Sectors of 10 pipes from the inside to the outside arranged at 60 degrees on the circumference were grouped on the part, starting with sector S11. After a complete rotation, the simulation of the welding process of the part continues to the adjacent sector S211. A new complete rotation is performed, after which it is passed to the adjacent sector S311. The welding process is repeated for sectors S411 and S511.

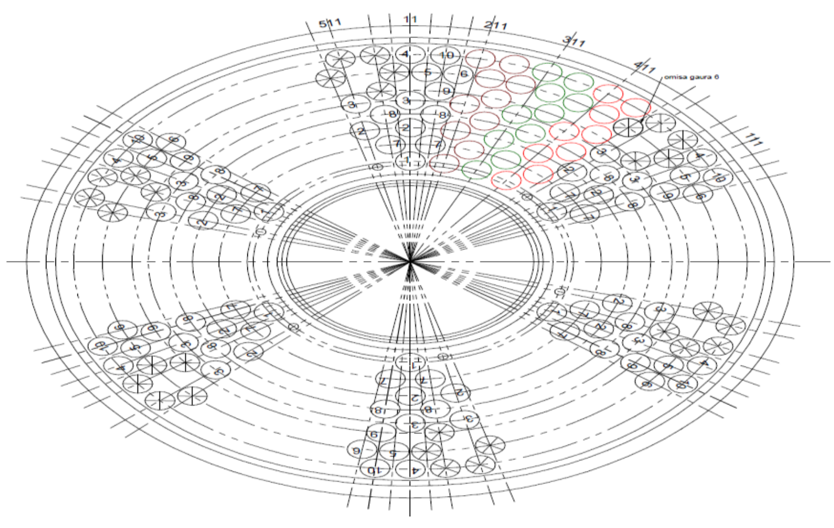


Figure 22 – Layout of 10 pipe sectors on the tubular plate

Taking into account the position of the six stiffening rods, in order not to produce a possible collision with the welding gun of the robotic system, after simulating the welding process, 5 adjacent pipes will not be welded. The 5 copper pipes adjacent to the six stiffener rods will be robotic GTAW welded at the end.

At the end of the welding process of the part, the appearance of all welded pipes was visually checked, identifying and marking, if necessary, the areas showing non-conformities.

5.4.2. Interpretation and validation of the robotic welding process in the first version

After going through the welding process simulation stages and the implicit welding of the part in the first robotic version, at the end of the visual inspection and the tightness test, it was found that the robotic welding process satisfies the conditions imposed in the documentation. At the same time, a series of observations related to the technological process were found.

Some of the copper pipes were not assembled correctly with the established reinforcement, resulting in imperfect weld seams.

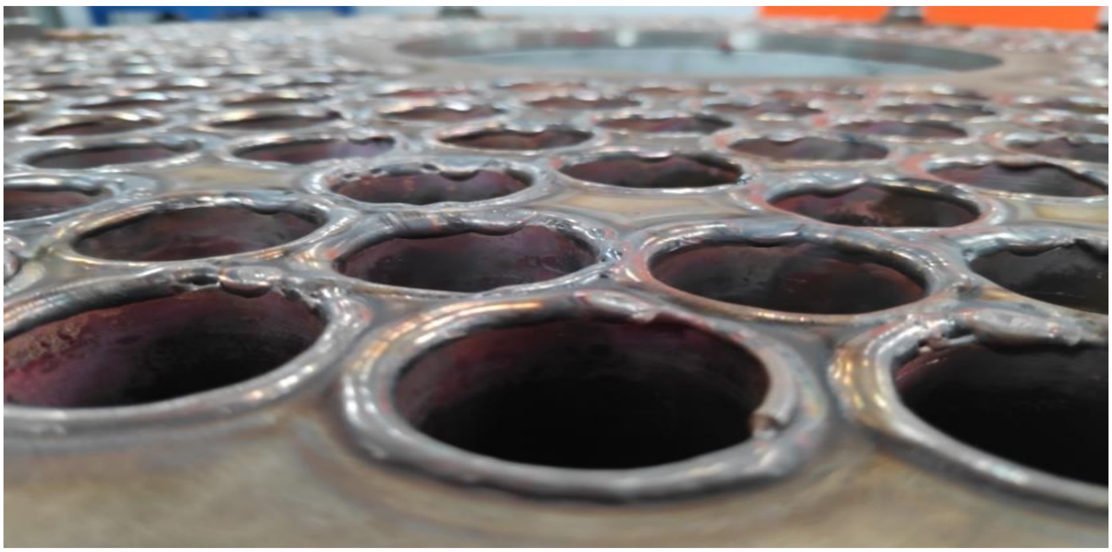


Figure 23 – Pipes with imperfect weld seams

It was also found that there were some weld seams that did not fully include the fastening and positioning tack welds of the pipe to the tubular plate. This was due to the larger size of some fastening tack welds.

Another observation resulting from the first robotic welding version was the finding of the appearance of craters in the welding seam at the end of the welding process of each pipe. The phenomenon was due to the sudden decrease of the welding current from the nominal value to 0 and the purging of argon in the molten metal pool.

The last observation resulting from the robotic welding in the first version was that during the welding process a tendency to overheat the part was found due to the consecutive beginning of welding the sectors of ten holes established initially.

All observations from this phase required a reanalysis of the entire execution cycle and the implementation of technological and software changes to improve the robotic welding process.

5.5. IMPROVEMENTS TO THE ROBOTIC WELDING PROCESS OF THE HEAT EXCHANGER ASSEMBLY

A flat aluminum template, named "Amisab", with a thickness of 5 mm, having the same diameter as the tubular plates, was designed and executed. In order to achieve a uniform reinforcement of the copper pipes of maximum 2 mm, the "Amisab" aluminum template is provided with 6 screws arranged at 60º on the outer diameter. The height of 2 mm is achieved by threading the screws. The aluminum template "Amisab" sits with the screws facing up over the centering and fixing device positioned on the rotary table of the robotic system. The part sits in the centering and fixing device resting on the "Amisab" aluminum template in the 6 screws. The role of the "Amisab" aluminum template is to ensure uniform reinforcement of all copper pipes.

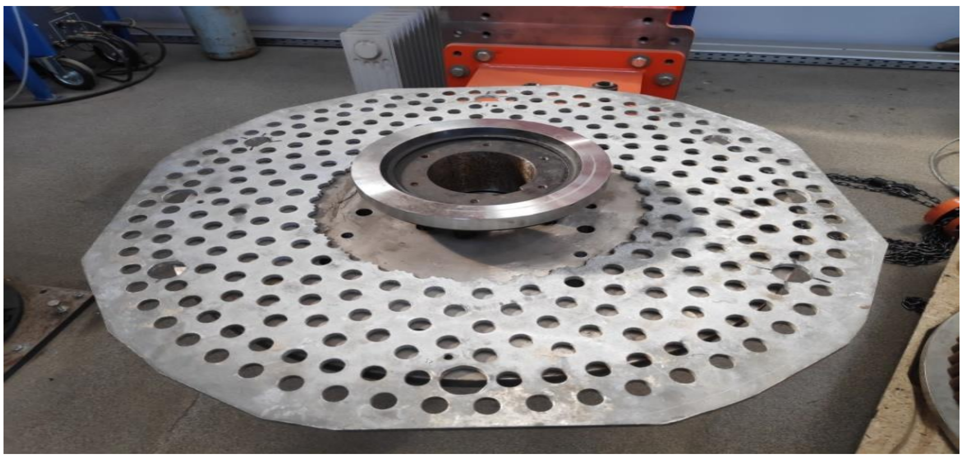


Figure 24 – Aluminum template "Amisab" designed to achieve uniform reinforcement of the part

Thus, the need to fix the copper pipes to the tubular plates by tack welding was eliminated by implementing the "Amisab" aluminum template in order to improve the assembly and welding process of the 288 copper pipes.

To avoid overlap of the start point with the end point of the circular weld seam, an additional point 5 mm away from the start point was defined in the software program. The point was added for each pipe in order to eliminate the appearance of non-conformities in the weld seam at the end of the welding process.

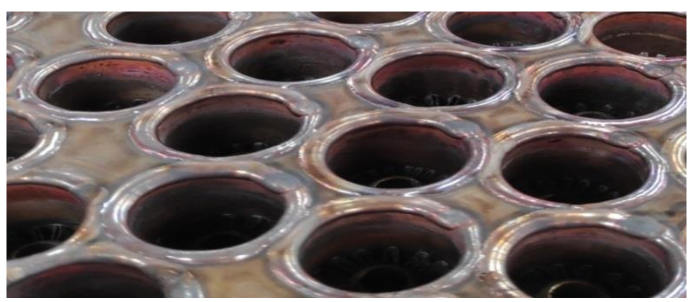


Figure 25 – Weld seams made by defining 5 points for each pipe in the robotic system

In order to avoid the appearance of craters in the welding seam, at the end of the welding process of each pipe, the current drop time was changed from 2 sec to 5 sec in the final list of the software program.

To reduce deformations and avoid local overheating of the part, software changes were made to the order of execution of the welding of the pipe sectors.

Sectors of ten pipes will be grouped on the tubular plate, from inside to outside, arranged at 60 degrees on the circumference, starting with sector S11.

After a complete rotation, the welding process continues at sector S311, then from 60º to 60º. A new complete rotation is made from 60º to 60º, after which it is switched to the S511 sector and robotically welded. A new complete rotation from 60º to 60º is performed, after which it is switched to the S211 sector and robotically welded. Another complete rotation from 60º to 60º is performed, after which it is switched to the S411 sector and robotically welded. The welding process is completed after the complete rotation from 60º to 60º of the S411 sector.

The robotic welding process requires the presence of an operator for all operations related to positioning, fixing, "cold welding", actual welding, handling and transport of the welded part who is assisted by a specialist programmer for adjusting and implementing the processing software. Robotic GTAW is performed by a single operator plus the need for a highly skilled programmer to implement the code for the software component of the robotic system.

An obvious change in the technological process of making the heat exchanger assembly is performed by the improvement of the working conditions of the operator, who is no longer obliged to work in conditions that can affect his health, such as inhaling fumes from melting metals, GTAW light radiation, molten metal spatter, accidentally touching the heated part.

5.6. CODE IMPLEMENTATION INTO THE SOFTWARE COMPONENT OF THE ROBOTIC SYSTEM

5.6.1. The first software program of the robotic system console

Using the first software program developed, a total of 258 pipes were welded from the total of 288 pipes in the heat exchanger assembly. The pipes in the vicinity of the six stiffening rods were welded separately. In conclusion, a dedicated software program was developed for the remaining 30 pipes.

Therefore, 4 intermediate points, 50 points for a single sector of ten pipes and 5 translation points of the robotic system table were defined. In order to carry out the robotic welding process, 59 points were saved in the console for 258 of the total of 288 pipes of a tubular plate.

Five sectors defined as S11, S211, S311, S411 and S511 are represented in Fig. 26 with the green, blue, yellow, orange and white colors. Being able to rotate the robotic system table, each of those five sectors will be translated six times from 60º to 60º in the follwing order: S11, S311, S511, S211, S411, preventing in this manner the overheating of the tubular plate.

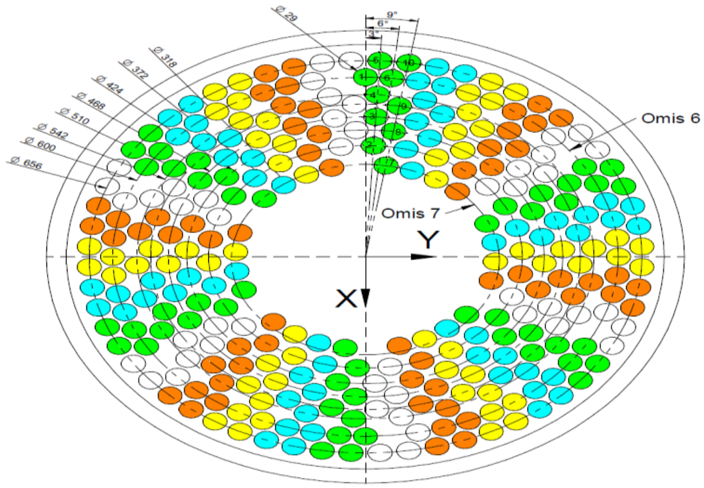


Figure 26 - Representation of the S11, S211, S311, S411 and S511 sectors of the tubular plate in different colors

5.6.2. The second software program of the robotic system console

The code was developed for the second software program in order to weld the remaining pipes from sectors S411 and S511, primary and translated. Finally, all 288 component pipes were welded to the front of the tubular plate.

As a result of the research carried out on the possibility of improving the technology of making the heat exchanger assembly by replacing soldering with robotic GTAW welding of copper pipes, a significant reduction in the execution time of the part was achieved.

Replacing soldering with robotic GTAW welding required a major financial investment in the acquisition of the 8-axis CLOSS CST FLEX S robotic system.

CHAPTER VI

6. MANAGEMENT OF THE WELDING PROCESSES

6.1. INTRODUCTION

The scientific research activity in chapter VI consists in the analysis of different welding methods in order to choose the most effective method from a technical-economic point of view. Thus, the calculations for each individual welding process are presented, as well as the ELECTRE method for establishing a single optimal method and for forming the necessary conclusions regarding the implementation of the chosen welding process.

In the first part of chapter VI, the management information about manufacturing the welded part is presented, in which the informational and technological flow is described.

The fundamental part of the chapter consists of technical-economic calculation for 3 different execution methods of the heat exchanger assembly, the component of a centrifugal industrial air compressor (CCAE), which also involves the SWOT analysis with reference to the optimal method that can be used for the process manufacturing of the heat exchanger assembly.

6.2. WELDED STRUCTURE MANUFACTURING MANAGEMENT

The management of the manufacture of the welded structure is an important process in order to obtain a superior quality product under specific conditions of time, market dynamics, external factors, imposed by the initial production objectives. The main objective of the management of the manufacturing of the welded structure is to ensure a technological process of maximum efficiency at the specific capacity of the factory, taking into account the specific requirements for the organization production and the qualification of the welding personnel. Welding is a special process and has a significant impact on the final quality of the product.

6.2.1. Description of the necessary flows to manufacture the welded product

For the maximum use of the production capacity of an enterprise, it is important to know all the processes that are necessary to develop a product. For the administration and management of these processes, the notion of technological flow is used, which contributes to the establishment and achievement of the basic objectives of the organization.

Informational flow refers to the circuit of product/technology-related technological information within an organization (between productive, design, supply, delivery, packaging, etc. departments) or between various entities or organizations. Information flow defines how certain information flows and is used between different departments within a company. A robust informational flow must have a way to record all the information that flows through the organization. The main steps in the implementation of an information flow consist of the execution phase, the decision phase, the response phase and the archiving phase, which are equally important.

The management of an organization (company, firm, educational unit, health unit, research institute, etc.) is defined by an organizational chart, in which all the departments that operate within it are found, with the indication of interaction relationships, the level of coordination, subordination and hierarchy at the top. Fig. 27 shows an example of an informational flow corresponding to the welding process, necessary for the production of the "Heat Exchanger" product.

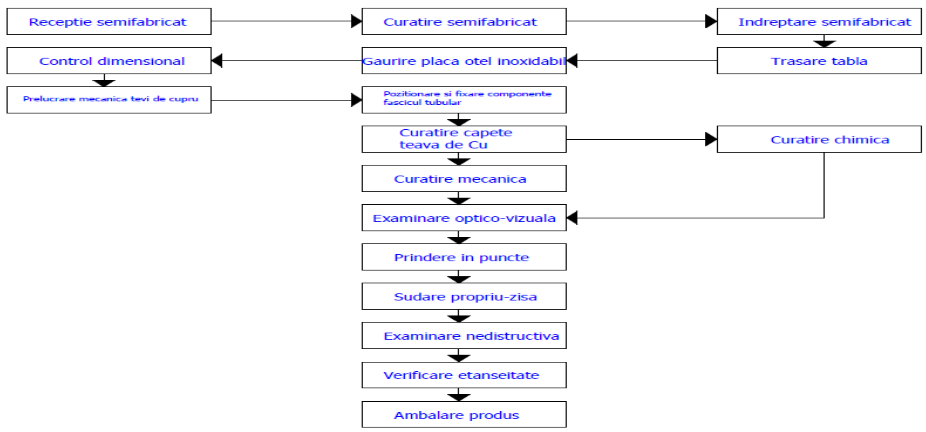


Figure 27 - The informational flow corresponding to the welding process, necessary to create the heat exchanger product

The tasks and responsibilities of the personnel involved in the processing, welding, execution planning, supervision and inspection activities must be clearly defined, according to the standard "SR EN ISO 14731:2007. Welding coordination. Tasks and Responsibilities", which includes the tasks and responsibilities related to quality, included in the coordination of activities related to welding. With regard to personnel dealing with welding or welding-related activities, it is specified that:

The welder or welding operator

- Prepares/checks the welding machines;
- Positions the parts for cutting or welding;
- Comply with the company internal regulations;
- Takes care of the integrity and proper functioning of the devices used;
- Ensures the cleaning of the workplace;
- Has the ability to make welded joints according to the qualification;
- Performs preheating when necessary;
- Removes non-conformities from the surface of the welding seam;
- Set the parameters for the welding process.

Welding engineer

- Prepares technological documentation (WPS, pWPAR);
- Ensures the correct selection of additive materials;
- Participates in the qualification of welders;
- Knows:
- • Legislation;
- • Provisions;
- • Technical prescriptions;
- • Standards.
- Supervises that the base materials are in accordance with the technical documentation.
- Determines the causes of the appearance of imperfections and takes appropriate measures.

Technical person in charge with welding

- Checks whether the execution technology is consistent with the approved welding procedure;
- Check the preliminary technical documentation for installation, assembly and/or repair;
- Follows the performance of the quality check of the joints and refers to the documents regarding the check of the welded joints;
- Keep up-to-date records of authorized welders, in the register of welders.
- Warns the other personnel structures about the existing dangers.

Quality control officer

- Performs quality inspection;
- Prepares test reports;
- Determines the qualification to be admitted / rejected for welded part.

6.3. ECONOMIC CALCULATIONS REGARDING THE EVALUATION OF WELDING PROCESSES FOR THE DEFINITION OF AN OPTIMAL METHOD

In fig.28, fig.29, fig.30 are presented graphs of the cost of materials, of the labor cost, of the total production cost related to the heat exchanger assembly for each of the 3 processes (robot welding, manual welding, soldering) obtained by calculation.

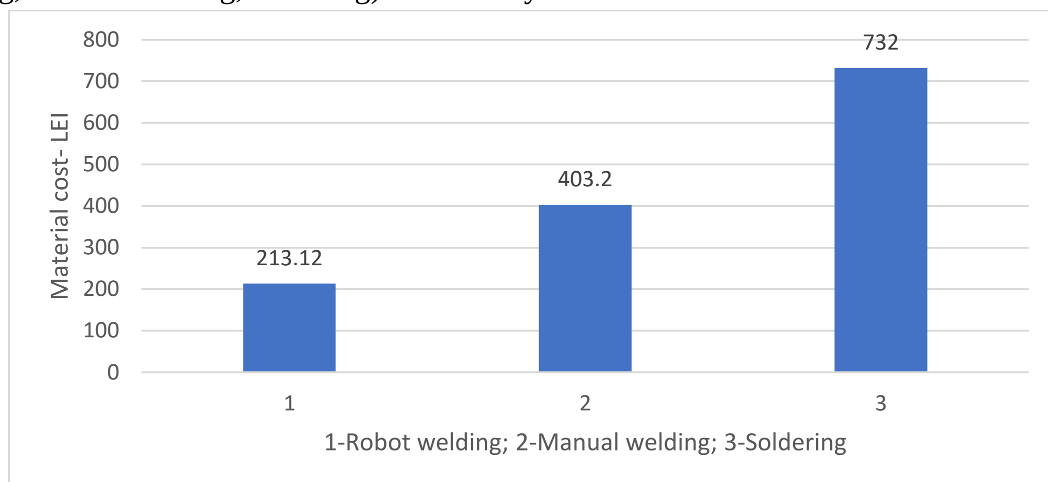


Figure 28 - The cost of materials for the execution of a heat exchanger assembly

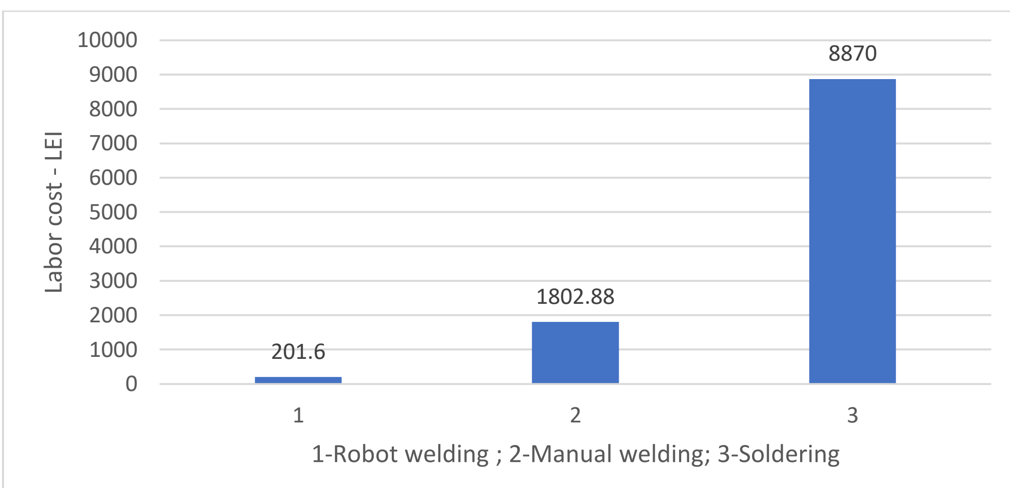


Figure 29 - Labor cost for the execution of a heat exchanger assembly

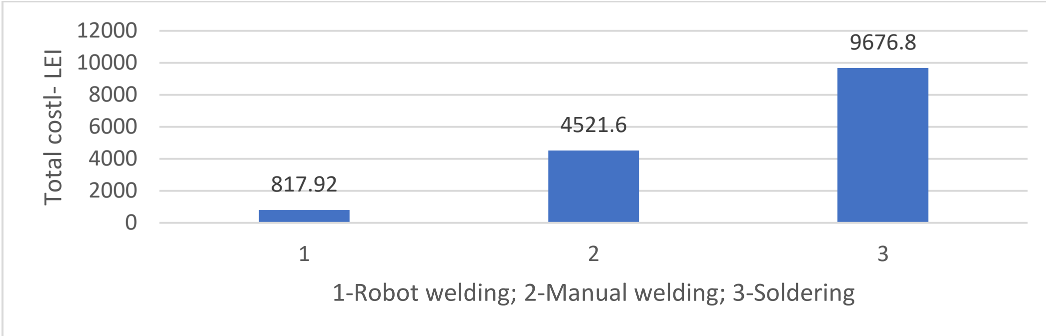


Figure 30 - The total cost for the manufacturing of a heat exchanger assembly

6.4. ELECTRE METHOD

The ELECTRE method is a mathematical tool that can be used to choose the optimal welding process from among several possible options, this serving to compare the options V_1, V_2, V_3, ... V_x, from the point of view of the criteria C_1, C_2, C_3, ... C_x. As I highlighted above, the application of the ELECTRE method is based on two groups of indicators, namely: concordance indicators (C_c) and discordance indicators (C_d). First, the list of the main possible processes that can be used to manufacture the welded product is performed, then the real data obtained following the analysis of the welding processes is added, namely for each of the criteria proposed for the analysis, according to the model in the following table.[98]

Table 8 - Matrix "Non-dismantle assembly procedures and analysis criteria"

Non-dismantle assembly procedure	Analysis criteria						
	Number of remedial actions out of 576 pipe ends (PIPE ENDS)	Manufacturing time (HOURS)	Productivity (PARTS/ MONTHS)	Profit (RON)	Investment into the device (RON)	Material cost (RON)	Energy cost (RON)
Soldering with LP60	120	160	2	10000	1500	7320	290
Manual GTAW	60	40	4	15000	2000	459	380,16
Robot GTAW	20	8	16	25000	2500	389	364,8
Importance coefficient,K_i	0,20	0,10	0,10	0,25	0,20	0,05	0,10
Minimum or maximum analysis criterion	minimum	minimum	maximum	maximum	minimum	minimum	minimum

The importance coefficients were established using the expert method, namely by a panel of experts in the field.

At the end of all calculations, for the final stage of analysis and the choice of the optimal procedure using the ELECTRE method, the concordance and discordance indices are combined by introducing a discordance threshold and a concordance threshold.

According to the concordance and discordance thresholds, the optimal method for the process of manufacture the oversized heat exchanger is established as robotic GTAW method.

6.5. SWOT ANALYSIS

6.5.1. Soldering method with LP60

Table 9 - SWOT analysis for the soldering method with LP60

Strong points: 1. Low cost of the system. 2. Existing qualified staff. 3.Lower pollution degree compared to GTAW welding method.	Weaknesses: 1. Additional costs regarding the use of additional material. 2.A much larger number of fixes compared to other welding methods. 3.Difficulty in producing parts in large quantity. 4. The major presence of the human factor, which can lead not only to repairs but also to work accidents. 5. The additional consumption of copper pipes.
Opportunities: 1.Manufacturing small parts that mostly only require manual welding.	Threats: 1. The human factor. 2. Entry of new competitors on the market that use more advanced technologies. 3. Increasing inflation means increasing staff salaries. 4. The risk of running out of quality labor.

6.5.2. Robotic GTAW method

Table 10 - SWOT analysis for the robotic GTAW welding method

Strong points: 1. The time to make the final product is reduced by 50%. 2. A decrease in execution costs is achieved. 3. Lack of use of additive material that reduces execution costs. 4. Reducing the consumption of the necessary copper pipe, by shortening the length of each pipe by 6 mm, and for the	Weaknesses: 1. High costs due to the expenses of specialized personnel in programming the robotic system. 2. Longer duration of schooling and staff attestation. 3. Implementation of a software and involvement of a trained programmer. 4. Additional cost required regarding the development of the fastening elements and

whole assembly 1728 mm. 5. High efficiency. 6. High quality. 7. Exclusion of the human factor. 8. Reduction of metal consumption. 9. Execution of structures of practically unlimited complexity. 10. High flexibility and mobility. 11. Reduced pollution and reduced energy consumption.	for the device for fixing the heat exchanger assembly on the table of the robotic system. 5. High costs of the whole system. 6. High costs with the evaluation, verification and qualification of the robotic welding process on samples and parts. 7. Occurrence of stresses and deformations after welding. 8. Local modification of the properties of the base metal, mechanical strength characteristics, corrosion resistance, etc.
Opportunities: 1. The fact that the production time is much faster compared to other welding methods, means that the company that owns this technology can increase the amount of parts made, which leads to an increase in profit. 2. The fact that the robot can be programmed in various scenarios can widen the customer base of the enterprise, which leads to its development over time. 3. Transition of the enterprise to the 24/7 format.	Threats: 1. Lack of investment in the robotic system that can lead to its damage, and to a lower quality of the welding process. 2. There are small parts where it is more convenient to use the classic manual welding method.

From techno-economic point of view, following the analysis of the heat exchanger assembly technologies, the robotic GTAW method showed more considerable advantages compared to the manual GTAW and soldering assembly methods.

In the case of changing the existing soldering method of the heat exchanger assembly to the automatic GTAW method using the CLOOS CST FLEX S robot and the TIG AC / DC GLW 500 welding source, production costs decrease, the execution time of the final product decreases, the production capacity increases, the company profit increases and product quality increases.

CHAPTER VII

7. GENERAL CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

7.1. General conclusions

The research problem in the PhD thesis involves efficient production control. The company must thus focus on automating the process by creating software capable of quickly managing production needs. It will be aimed at creating an automated production line, where the intervention of the human operator is minimal.

The welding robot industry is a success, but it is far from an easy technological process without challenges. The welding process is difficult to control. Process parameterization and software development are also complex activities.

The major advantage of an industrial robot solution is that the inherent error represented by the human factor is eliminated. Thus, the quality of the weld seam and the rate at which it is made increase significantly. What also increases is the complexity of the process for which the industrial robot will have to be programmed in order to fulfill its purpose. The programming of industrial robots is implemented by specialists and in this context, for some applications, industrial robots are difficult to integrate. On the other hand, taking into account that the human operator is replaced by an industrial robot, production costs will decrease significantly.

7.2. Original contributions

The solution of making the heat exchanger assembly for a centrifugal industrial air compressor (CCAE) by changing the soldering technology to the robotic welding technology means an in-depth research involving the redesign of the part, the design of a fixing device for the part and inserting the new technology.

Based on the results obtained on the test piece, it was possible to demonstrate that the GTAW robotic welding process is an optimal method for assembling the part components. Through the research activity, the small changes of some components (shortening the 288 Cu 99.9 pipes to the length of 436 mm, the design and execution of the positioning, fixing and support device) ensured the manufacturing of the heat exchanger assembly in a short time, at a high quality level.

Establishing the new technology for manufacturing the heat exchanger assembly was completed as a result of a continuous research activity involving the following contributions:

- Design and adaptation of the part for GTAW welding with the robotic system;
- Designing a positioning, fixing and support device that allows the part to be placed and fixed on the rotary table of the robotic system;
- Development and improvement of dedicated software programs through which the robotic system welds the components of the heat exchanger assembly;
- Analyzing production costs by applying robotic welding process management. Development of a comparison between the previous soldering process and the new robotic GTAW welding technology.

The modification of the heat exchanger assembly manufacturing technology was tested and verified on a series of samples. The test results led to the optimal welding parameters. A positioning, fixing and support device was designed and improvements were made during the assembly of the first part on the rotary table of the robotic system. The changes were designed for better centering and fixing of the part.

Throughout the research carried out both on the test piece and on the first heat exchanger assembly, a software program was developed, after which it was permanently optimized through code development and modification of the welding parameters.

By comparing GTAW welding and soldering, in the part production cost analysis, it was found that the cost difference did not meet the production requirements. In order to be able to cope with production requirements, it was necessary to research robotic GTAW welding technology.

7.3. Future research directions

A first future research direction is represented by finding the welding parameter values that, by launching the software program of the robotic system, will reduce the execution time of the heat exchanger assembly even more than what was achieved in the PhD thesis. In-depth research of welding parameter values through experimentation can result in reduction of Argon consumption, reduction of electricity consumption, reduction of electrode consumption.

Reducing the execution time of the heat exchanger assembly can also be achieved by finding a solution that involves the development of a single software program to robotically weld all 258 holes and the 30 neighboring holes to the tubular plate stiffening rods, in the same execution cycle of the software program. Therefore, this represents another future research direction considering that the thesis proposes two separate software programs for robotic welding of the heat exchanger assembly.

The solution proposed by the thesis may have as a future research direction the replacement of the soldering process with the robotic GTAW welding of all heat exchangers.

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