CONTRIBUTIONS TO CONSOLE PROGRAMMING OF A ROBOTIC SYSTEM FOR WELDING AN OVERSIZED HEAT EXCHANGER

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ABSTRACT: This paper first proposes to define the welding parameters of the GTAW (TIG/WIG) heat exchanger for a robotic system. The paper describes the first process of welding performed on the heat exchanger assembly, named pilot. An analysis will go through all the stages starting with the programming and simulating description of the welding process (cold tests), up to the analysis of the test results obtained after the pilot welding. The paper shows the programming technique used for the robotic welding process of the heat exchanger, more specifically, the article makes an explicit interpretation of the programmed code into the robotic system console. The documentation describes the existing sequences from the two programs developed in the console of the robotic system for the welding of the 288 pipes found as components of the heat exchanger assembly.
KEYWORDS: robotic system. heat exchanger assembly, welding parameters, pilot welding, console programming.

1. INTRODUCTION

For executing the welding process of the heat exchanger assembly, [1] a CLOOS CST FLEX S robotic system with 8 axis and a laser sensor has been used, with a GTAW AC/DC GLW 500 welding source placed into a work cell. [2]

Figure 1. The work cell for the 8 axis welding robotic system

The work cell in which the robotic system is placed has the dimensions of 4 m width and 6 m length. The work cell assures the free movement, without any obstacles, of the robotic arm, in a semicircle with the radius of 2 m around his first axis. Also, the robotic system work cell has been provided with a safety system for the accidental collisions inside the working space, but also with an infrared barrier against staff intruding during the welding process. [3]

The programming language used into the robotic system console is called Carola.

Initially, the heat exchanger assembly has been welded GTAW manually. A series of stages have been followed in order to establish the welding parameters for the manual welding. [4] The first stage consisted in fixing each pipe on the tubular plate by spot welding at a one small point in order to easily integrate it in the final welding seam.

In order to identify the parameters, the next stage was the manual welding of the 288 pipes onto the frontal tubular plate of the heat exchanger assembly.

The last stage was the GTAW manual welding of the 288 pipes to the rear tubular plate.

As a result of these stages, it has been selected a 110 A welding current.

It has been determined the required length of the assembly pipes in order to have a welding without filler material which is: L = 2 mm + 432 mm + 2 mm.

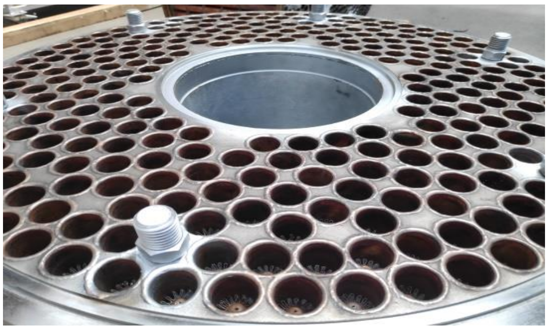

Figure 2. The 288 pipes on the tubular plate after the manual GTAW welding

In order to perform a correct assembly, it has been deduced that the pipes have to be reinforced with a maximum of 2 mm and a minimum 0.5 mm. The reinforcement over the admitted 2 mm of the copper pipes in reference to the surface of the tubular plate determines first of all an excessive quantity of melted metal, which leads through solidification to an irregular shape of the joint, and secondly it increases the chance of the appearance of surface faults. On the other side, implicitly on the opposite side of the rear tubular plate, the copper pipe will be at a lower level in reference to the tubular plate surface, the welding process not providing a homogenous pool of the melted material for performing of the welded assembly tightness.

2. ESTABLISHING THE ROBOTIC WELDING PARAMETERS

In order to determine the parameters, [5] specimens have been welded on a test piece by using the robotic system. [6]

Figure 3. Specimens obtained from the robotic welding process on the test piece [6]

According to the results obtained on the test piece and other experimentations, the parameter values for the normal list LN1 in the console software, as in fig. 4, of the robotic system are:

- Speed of the welding Vsud = 14 cm/min;
- Oscillation frequency Fpend = 0,25 Hz;
- Pulsation frequency Fpuls = 0 Hz;
- Base current Ibaza = 125 A;
- Pulsation current Ipuls = 100 A;
- Speed of the filler wire Vsarma = 0 cm/min.

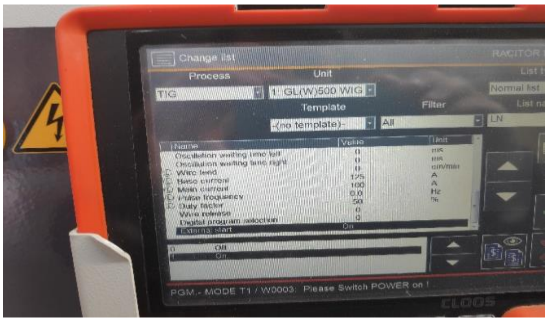

Figure 4. Setting up GTAW parameter values into the robotic system console

The values of the welding parameters for the start list LS1 in the console developed program of the robotic system are as follows:

- Welding speed Vsud = 14 cm/min;
- Oscillation frequency Fpend = 2,84 Hz;
- Pulsation frequency Fpuls = 5 Hz;
- Base current Ibaza = 125 A;
- Pulsation current Ipuls = 100 A;
- Speed of the filler wire Vsarma = 0 cm/min.

The values of the welding parameters for the end list LE1 in the console developed program of the robotic system are as follows:

- Welding speed Vsud = 14 cm/min;
- Oscillation frequency Fpend = 2,84 Hz;
- Pulsation frequency Fpuls = 5 Hz;
- Base current Ibaza = 125 A;
- Pulsation current Ipuls = 100 A;
- Speed of the adding wire Vsarma = 0 cm/min;
- Power failure time Ired = 2 sec.

3. ROBOTIC PILOT WELDING OF THE HEAT EXCHANGER ASSEMBLY

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

It was started from the software program implementation into the robotic system console for welding a copper pipe on the tubular plate, as shown in fig. 5. In order of achieving this goal, a specific approach have been followed.

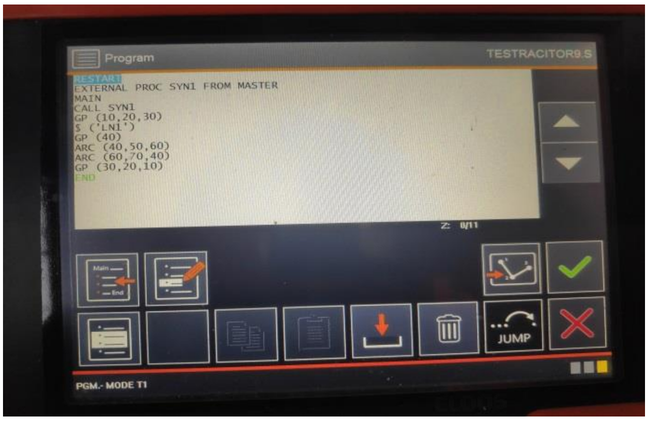

Figure 5. Software program implementation into the robotic system console for welding one copper pipe

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. [7]

Using the robotic system, the next step was to reach the center point of the copper pipe as shown in Fig.6.

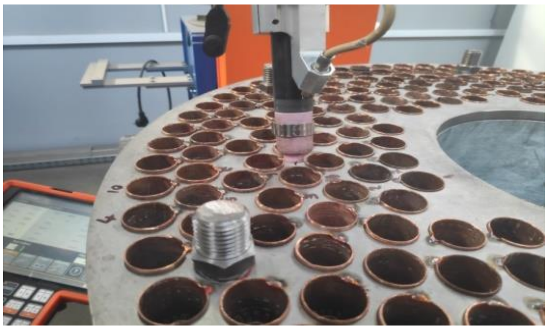

Figure 6. The center point of a pipe using the robotic system

Starting from the copper pipe center, the next step was to seek and to save four points located on the diameter of the pipe in the memory of the robotic system, the starting point remaining the same with the ending point during the welding process.

Figure 7. The first two points on the arc length of a pipe for the software program of the robotic system

The distance of 1 mm was established between the wolfram electrode and the edge of the pipe. [8] 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 60º angle in reference to the tubular plate, in the horizontal position 1G, with the spinning plate of the robotic system in a horizontal position at a 0º 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.

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 m^3 at a 200 bar pressure.

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 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.

3.2 The simulation of the pilot welding process

Regarding the welding process simulation and thus the testing of the developed software program, the heat exchanger assembly has been set in the centering and fixing device located on the spinning plate of the robotic system, with an upfront tubular plate orientated upwards, making sure that the part has a circularity and a flatness of maximum 0,5 mm.

The reinforcement of the copper pipes in reference to the tubular plate has been verified so that it will be in between the admitted limits of 0,5 mm and 2 mm.

Considering the used programming technique at paragraph 3.1 for a singular pipe, the software program was implemented for welding a circular row of pipes located on the second row of the tubular plate, from inside to outside.[9]

The obtained assembly has been repositioned with the upfront of the plate upright. Each end of the 288 subassembly exchanger elements had each element mechanically cleaned with abrasive paper and chemically cleaned with zinc chloride. The cleaned pipes have been introduced into the Ø28,5 holes of the assembly fixed to device until the end of the pipe had a reinforcement of maximum 2 mm in reference to the exterior surface of the frontal plate.

The developed software program for the front tubular plate was executed, without having the electrical arc active. 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.[10]

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.[11]

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 in the 3.2 subchapter and the software technique developed in the 3.1 subchapter, 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.[12]

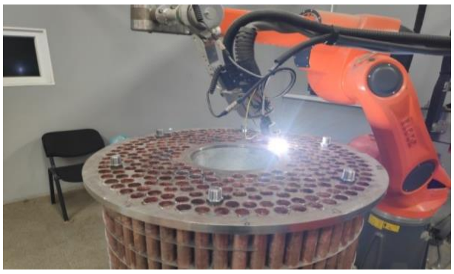

Figure 8. The pilot welding of a circular row of pipes to the tubular plate

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 rows were performed uniformly and without any surface nonconformities.

Figure 9. The pilot welding result

3.4 Pilot welding process analysis and validation

The optimal length for the pipes was confirmed to be maximum 436 mm or minimum 434 mm. Those dimensions assure the sufficient reinforcement of both ends of the pipe by the right assembling between the two tubular plates, allowing the welding process to be continuous, uniform and without deviations.

A deviation from this dimension or having a poorly assembling of the system will lead to nonconformities regarding the aspect and dimensions of the welding seams, therefore resulting areas without tightness.

The results of the part pilot welding have concluded with the confirmation of the fact that the GTAW welding process can be performed successfully without filler material. The 125 A welding current proved sufficient to assure a homogenous and a sufficient melted metal pool for the welding process.

The only issue that can disturb the welding process is the local excessive overheating of the part. The issue can be solved with an alternative order of welding for the sectors of the ten pipes.

4. CODE IMPLEMENTATION INTO THE ROBOTIC SYSTEM CONSOLE FOR WELDING A TUBULAR PLATE OF THE HEAT EXCHANGER

4.1.Defining the console program points

The program implemented into the robotic system console for welding of the assembly tubular plate contains a total of 211 lines of code programming. Using this program, out of the total of 288 pipes located in the assembly of the heat exchanger, 258 pipes have been welded. The pipes located near the six stiffening rods have been welded separately. Therefore, a designated program was developed for robotic welding the 30 pipes left.

Having the purpose of making the trajectory of the robotic system more efficient and avoiding collisions with possible obstacles, there were defined four intermediary point: P7, P8, P9 and P10. Those points will be used during the entire time while the program is running, before the start of the welding process and after it.[13]

Regarding the welding of each individual pipe for a selected sector of ten pipes, five points have been saved into the console memory of the robotic system. Therefore, for the pipe 1 there were defined the following points, according to the technique used in subchapter 3.1: P11, P12, P13 and P14.

In order to avoid the overlapping of the start point with the last point and risking to obtain nonconformities for the welding seam, an additional point located at 5 mm from the starting point, P15 was defined in the software program.

For pipe 2 from the designated sector of ten pipes, the following points have been defined: P21, P22, P23, P24 and P25, similar to pipe 1.

For pipe 3 from the designated sector of ten pipes, the following points have been defined: P31, P32, P33, P34 and P35, similar to the other two pipes.

In this manner, we define all points for all the ten pipes from the selected sector. As a result, for pipe 10 the following points have been defined: P101, P102, P103, P104 and P105.

The points will be implemented into the robotic system console in order to weld the front tubular plate. [14]

In this manner, ten pipes sector was implemented into the robotic system through defining a number of 50 points as above.

In order to rotate the robotic system plate each time by 60º, five translation points were defined:

- point P111 rotated by 60° in reference to point P21 was defined into the robotic system console;
- point P211 rotated by 12° in reference to point P21 was defined into the robotic system console;

- point P311 rotated by 24° in reference to point P21 was defined into the robotic system console;
- point P411 rotated by 36° in reference to point P21 was defined into the robotic system console;
- point P511 rotated by 48° in reference to point P21 was defined into the robotic system console.

4.2. The beginning sequence analysis of the first software program

During the software program first execution phase, the “go point” function allows the robot to go through the defined trajectory by passing through the intermediate points P7, P8 and P9 saved into the console memory, as discussed in the subchapter 4.1.

Before starting the welding process, a call is made for the normal list LN1 into the robotic system software program in (9), which is composed by the start list LS1, the end list LE1 and all the values of predefined parameters in chapter 2. The beginning sequence implementation inside the robotic system console is shown from (1)-(9).

```
RESTART                                  (1)
VAR REP                                  (2)
EXTERNAL PROC SYN1 FROM MASTER           (3)
MAIN                                     (4)
CALL SYN1                                (5)
DCO (1,2,3)                              (6)
GP (7,8)                                 (7)
GP (9)                                   (8)
$ ('LN1')                                (9)
```

4.3. Code sequence interpretation referring to sector S11

Five sectors defined as S11, S211, S311, S411 and S511 are represented in Fig. 10 with the green, blue, yellow, orange and white colors. Being able to rotate the robotic system plate, each of those five sectors will be translated six times from 60º to 60º in the follwing order: S11, S311, S511, S211, S411. This defined welding order prevents the overheating of the tubular plate.

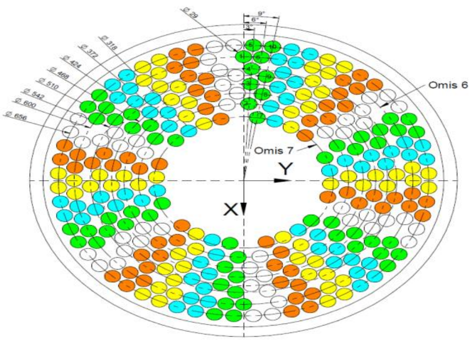

Figure 10. Representation of the S11, S211, S311, S411 and S511 sectors of the tubular plate in different colors

Into the console software program, a “for” type loop has the role of calling six times, six different sectors composed of ten pipes, starting with sector S11 using the 50 predefined points according to the subchapter 4.1.

```
FOR REP:= 1 TO 6 DO BEGIN                (10)
GP (11)                                  (11)
ARC (11,12,13)                           (12)
ARC (13,14,15)                           (13)
GP (8)                                   (14)
GP (21)                                  (15)
ARC (21,22,23)                           (16)
ARC (23,24,25)                           (17)
GP (8)                                   (18)
```

The sequence continues similarly for the 10 points of the sector by calling a point on the diameter of the pipe according to the subchapter 3.1, as seen in (11), calling the ARC function like seen in (12) and (13) which have the role of following the pipe outline with the welding gun in reference to defined points by the instructions and calling an intermediate point at the end of the welding as seen in (14).

At the end of the welding process of a sector, point P111 is called by instruction (24) through the “Change” function, and the robotic system plate is being rotated again to 60º and the welding process of the 10 pipes sector is started again.

```
GP (8)                                   (19)
GP (101)                                 (20)
ARC (101,102,103)                        (21)
ARC (103,104,105)                        (22)
GP (8,10)                                (23)
CHANGE (21,111)                          (24)
END                                      (25)
```

This process repeats itself 6 times for all the pipes represented with the green color in Fig.10. At the end of six welding cycles defined in the “for” loop of the program sequence, the loop will end in (25) through the “end” instruction.

4.4. Code sequence interpretation referring to sector S311

Further, the program inside the robotic system console will call the intermediary point P8 through instruction (27) and then the translation of point P21 in point P311 by using the change function through instruction (28). All the yellow color pipes will be welded as in Fig.10. As to the previous sector, through the “FOR” loop as seen in instruction (29) and the CHANGE (21,111) instruction, six sectors with 10 holes will be translated from 60º to 60º.

```
DECH                          (26)
GP (8)                        (27)
CHANGE (21,311)               (28)
FOR REP:= 1 TO 6 DO BEGIN     (29)
```

4.5. Code sequence interpretation referring to sector S511

In regards of the S511 sector, the situation is different compared to the other sectors because of the proximity of some pipes in reference to the stiffening rods. The difference is that the 5 pipes located around the stiffening rods will not be welded using this current software program. So, pipe 4, pipe 6, pipe 9 and pipe 10 from sector S511 will be welded afterwards, with a different dedicated software program.
Also, in the case of sector S511, pipe 1 does not exist in the structure of the assembly and a stiffening rod is replacing pipe 5. In conclusion, for each of the six sectors, there are to weld only 4 pipes: pipe 2, pipe 3, pipe 7 and pipe 8.

The code sequence inside the software program for sector S511 and the translation of it will be executed with a same principle to the previous ones. The entire sequence is represented between (30) - (51):

```
DECH                          (30)
GP (8)                        (31)
CHANGE (21,511)               (32)
FOR REP:= 1 TO 6 DO BEGIN     (33)
GP (21)                       (34)
ARC (21,22,23)                (35)
ARC (23,24,25)                (36)
GP (8)                        (37)
GP (31)                       (38)
ARC (31,32,33)                (39)
ARC (33,34,35)                (40)
GP (8)                        (41)
GP (71)                       (42)
ARC (71,72,73)                (43)
ARC (73,74,75)                (44)
GP (8)                        (45)
GP (81)                       (46)
ARC (81,82,83)                (47)
ARC (83,84,85)                (48)
GP (8,10)                     (49)
CHANGE (21,111)               (50)
END                           (51)
```

4.6. Code sequence interpretation referring to sector S211

The software program approaches sector S211, according to the welding order predefined at the subchapter 4.3. The robotic system will weld sectors of 10 pipes, after which the robotic system plate will rotate at 60° while being in a ”FOR” loop through the “CHANGE (21,111)” instruction, restarting the welding process for the next sector.

All the pipes represented in Fig. 10 with blue color will be welded with the robotic system following this process. The code sequence for sector S211 and the translation for it is similar to the one used for sectors S111 and S311.

4.7. Code sequence interpretation referring to sector S411

According to the welding order in subchapter 4.3, the last sector to be welded is sector S411, represented with orange color on Fig. 10. Except for pipe 6, all the component pipes for this sector will be welded by using again a “FOR” loop and the translation at 60º implemented through the “CHANGE (21,111)” instruction.

Pipe 6 from sector S411 will be welded separately alongside with the other four pipes of sector S511, as they are in a same case. Therefore, the code sequence used for the robotic GTAW welding of sector S411 and the translation of it are almost similar with the ones for sectors S111, S211 and S311. Also, from the code structure perspective, the sequence from (52) - (55) is missing. This sequence executes the pipe 6 welding and it was excluded due to the proximity of the pipe in reference to the stiffening rod.

```
GP (61)                       (52)
ARC (61,62,63)                (53)
ARC (63,64,65)                (54)
GP (8)                        (55)
```

4.8. The used technique for welding the remaining pipes

The second software program console was developed for the robotic system to weld pipe 6 from sector S411 and pipes 4, 6, 9 and 10 from sector S511.

The code for the developed software program in order to weld the remaining pipes from sectors S411 and S511, primary and translated, has a number of 41 lines.

The software program was developed according to the same principles and structure as presented in the subchapters 4.1 - 4.6. The code development was performed for first to weld pipe 6 from sector S411 and then to weld pipes 4, 6, 9 and 10 from sector S511.

After the software program has ended its execution, a translation at 60° is performed through the console by rotating the robotic system plate after which the software program is executed again.

The welding process was repeated for all the remaining pipes from the translated sectors S411 and sector S511. Finally, all of the 288 pipes were welded on the front tubular plate.

5. CONCLUSIONS

Following the possibilities of technology improvement research carried out for manufacture a heat exchanger assembly by replacing the soldering with the robotic GTAW welding of copper pipes, it was resulted a significant reduction of the process time.

In order to replace the heat exchanging assembly process of soldering with the robotic GTAW welding, a major financial investment is needed for a CLOSS CST FLEX S 8 axis robotic system.

The robotic GTAW welding was performed without filler material, using type 5.0 protective argon gas, with a quantity of 5 m^3 for each part.

The cost reduction was possible due to the fact that the workers that were executing the soldering needed to be qualified and trained, while the operator of the robotic GTAW welding system needs only to be trained. We must also add the necessity of an existing programmer with a high qualification which can implement the code for the robotic system software program.

Regarding the front tubular plate robotic welding, four intermediate points were defined, 50 points for one single sector of ten pipes and 5 translation points of the robotic system plate. By having to perform the robotic welding process, only 59 points were saved into the console.

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