Weld Data Collecting for Use in Welding Simulations and Digital Twins

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***Abstract*— Today´s industry produces a lot of pipes; for cooling, chemicals and other purposes. The piping can be in a large variety of dimensions and materials, with stainless steel being a common choice due to its resistance to corrosion. Ships, submarines or powerplants, can have several kilometres of piping, with high demands and requirements on quality and safety. Over the lifetime of a pipe, maintenance or replacement may be necessary, often requiring welding to join sections. Due to economic considerations, much of the fabrication is conducted in workshops, necessitating precise tolerances and robust processes, but also causing problems when on-site installation is needed. This study aims to collect measurement data for subsequent use in welding simulations and the development of digital twins for expected final design. Tree pipes were welded with orbital TIG-welding and during the welding, temperature was measured with type-k thermocouples around the diameter of the pipe. Before and after the welding the length of the pipes was measured in four places. Test data collected includes temperature profiles and shrinkage during welding. The tests revealed longitudinal shrinkage in the weld zone ranging from 0.12% to 0.18% of the length of the pipe, with higher heat input resulting in increased longitudinal shrinkage. In the future, this measurement data can be used for verification purposes in the development of digital twin models by comparing actual welding outcomes with simulation results, aiding the prediction and resolution of geometric tolerance challenges during production, and installation. This paper proposes an approach to collect data for future simulation and prediction of deformation and shrinkage in piping systems during welding using digital twins.**

Keywords- welding; orbital welding; simulation; TIG; design.

I. INTRODUCTION

Much of today’s industry is depending on pipes both for production and for their products. Hence, piping could be a significant part of the production time for a plant or product. As an example, time consumption for pipe machining and installation in ship construction accounts for 9-18% of total hours of which half of the working hours are used for assembling and welding various flanges and pipes [1]. In brewery processing plants, much brewing equipment is factory-built. However, many of the small-bore pipes and their interconnections are brought from manufacturers and joined on-site [2].

For joining pipes into systems of pipes, welding is one of the most used joining techniques. Welding is a critical joining process in the manufacturing process. Circumferential welding joints are commonly used in marine engineering, nuclear power plant and aerospace industry. For hight-strength welding of these structures, Tungsten Inert Gas welding (TIG) is a popular joining technique [3].

For pipework, the preferred method is automatic orbital welding. If properly programmed, an orbital welding machine is capable of consistently produce high-quality welds [4]. For the welding in biopharmaceutical, brewery, and related industries the welding without filler material is the most common, even though welding with filler material exists. Since TIG-welding is using a non-consumable tungsten electrode to produce the heat for the weld the filler material is added separately to the heat input [2]. When using welding as a joining method there will be a Heat Affected Zone (HAZ). The HAZ that results from the welding operations should be minimized [2].This is because the heat from the welding can change the structure of the material and affect the material properties.

Joining with welding can sometime be difficult. Some factors leading to poor welds is pipe geometry as pipes are manufactured to outer diameter (OD). Wall thickness and ovality tolerances that affect the alignment of pipe ends [8]. With better and stronger materials, the focus has moved to greater fabrication challenges like structures fabricated from thinner and lighter sections, which were previously masked by mass [2].

On-site welds are often inaccessible from the inside, so site welding is more difficult to control. Inadequately welded joints can compromise product quality [2]. Also, the fabricators centroid misalignment may be an important factor for the product quality. Good orbital welding requires matched pipes, which are correctly aligned and a minimum overlap of 95%, preferably in the range 90-100 ± 10% [2]. Figure 1 below shows the orbital TIG welding head mounted on a pipe. The picture is taken during the welding.

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Figure 1. Orbital TIG Welding head mounted on a pipe during experiments.

Pipes are manufactured in two distinct ways – as welded pipes or seamless pipes. Commercially pipes are sold with manufacturing tolerances in ovality and wall thickness. This results in pipes and tubes that are neither circular nor of even wall thickness [2].

As the requirements continue to increase, the challenge of keeping a fabrication process within tolerance becomes more difficult. At some point it is no longer feasible to approach each individual assembly of parts with identical settings and process parameters. Small differences at the part level makes every assembly unique and to reliably achieve a good outcome, each assembly will require small adjustments. This is commonly referred to ass mass customization, meaning that each product is approached individually rather than interchangeably [5]. In all production, tolerances could be a challenge during assembling. In a piping system with several joints and bends, there will be many possibilities for quality and geometrical problems. Most companies are fully aware of the fact that a change is costlier in production than in the design phase [6]. To minimise the cost for geometrical variation, geometry assurance can be helpful.

Geometry assurance can be described as a set of activities that contributes to minimizing the effect of geometrical variation in the final product. Activities take place in all phases of the product realization loop. The phases where geometrical assurance is to take place is design phase, pre-production phase, production phase [7]. To foresee, and thereby also possibly reduce, this kind of problems in a final assembly, methods to predict geometrical variation are crucial tools [8]. To verify the geometry inspection, inspection points are used. In early production series and prototypes those are often more in numbers to gain knowledge and understanding of the product. Later production has often fewer inspection points to reduce resources thanks to quicker inspection procedure and simplified analysis of measurement data. By reducing the number of inspection point there are a risk of losing to much information about the manufacturing process. This risk can be much lesser by using a structured method for the inspection point reduction [9].

Figure 2 below shows an example of a piping system for a submarine.

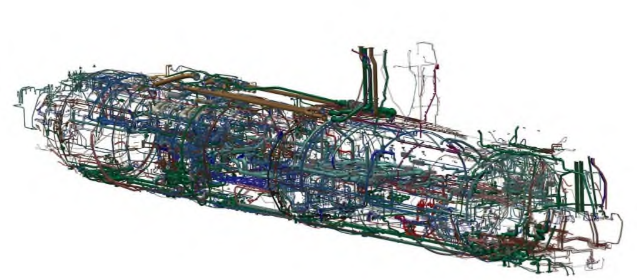

Figure 2. Piping system for a submarine. There are about 10.000 pipe components in a submarine like the Swedish A26 that must be able to handle high pressure, liquid, and toxic gases. Picture Copyright SAAB AB[10]

With a digital twin, mirroring a piping system, with all the weld joints, it should be possible to predict the weld temperatures, shrinkage, and deformation from the weld zones in the whole system by simulating the welding. Differences in shrinkage and deformation due to changes in heat input during welding should be possible to simulate for the whole piping system. With potential shrinkage in the weld zone there is a possibility of large amount of shrinking and deformation for the whole piping system. If the welding order will affect the shrinkage and deformation in a welded piping system, this can be studied during simulation.

Hence, the research questions that guide the work in this paper are;

- RQ1: Will it be possible to collect temperature data from welding that later can be used for welding simulation in a digital twin?
- RQ2: Will it be possible to measure longitudinal shrinkage on a thin wall stainless pipe after orbital welding so that the data can be used in welding simulation?

The paper is organized as follows. The method is described in Section 2. In Section 3 the results are shown. Section 4 contains discussion and in Section 5 conclusions and future work are presented.

II. METHOD

The research is case based [11] and using applied cases/experiments to justify the conclusions. The process approach for simulation and testing is shown in Figure 3 below. Before and after welding there will be measuring to see how the part changes. Optimisation will be done when needed and this will be mirrored in a digital twin in later work. For this paper, the part marked in the red zone in the sketch of the process, are made.

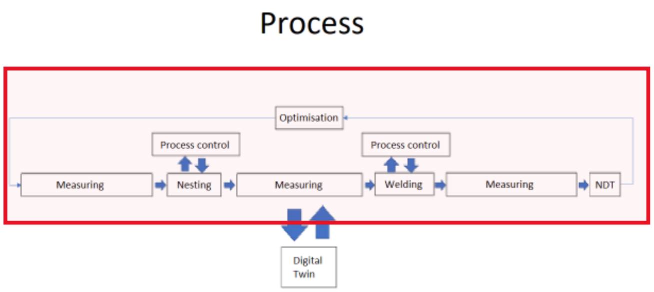

Figure 3. Process.

The pipes are measured before and after welding to see the longitudinal shrinkage in the pipe from the welding. Also, the temperatures are measured in chosen places during the welding. From this information the process will be optimised for each weld with new welding parameters. After each welding the weld will be checked visually (NDT - Non destructive testing). Then the information can be used in a digital twin.

A. Material

The base material used in this experiment are stainless steel 316L (1.4404). The welded material is a pipe with the outer diameter 88.9 mm and a wall thickness of 2 mm. The pipe is seamless for less interfering with the weld.

B. Welding equipment

The welding is done with automatic orbital TIG-welding. The welding Machine is an AMI model 415A from Arc Machines Inc. The backing gas used was Formier 10 with the flow rate of 10 l/min. The welding head for the weld test is an Arc Machine Inc. model 15 shown in Figure 4 below.

Figure 4. Welding head, Arc Machines Inc. Mod. 15.

Figures 5 and 6 below show the placement of the thermocouples during welding. Figure 5 shows test 1 and Figure 6 test 2 and 3. Welding direction is clockwise. The first thermocouple is placed 10 mm from the weld centre. Then the following thermocouples are placed 15 mm, 20 mm and 25 mm from the weld centre. 25 mm is only in test 2 and 3.

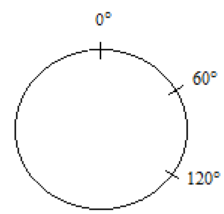

Figure 5. Placement of thermocouples. Test one.

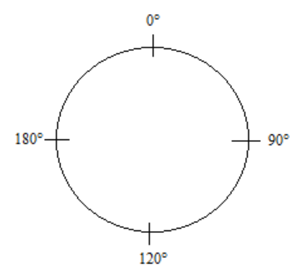

Figure 6. placement of thermocouples. Test 2 and 3.

C. Measuring

The measuring of the length of the pipes are done before nesting, after nesting and after welding. The procedure is shown in Figure 7 below.

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Figure 7. Measuring of pipe.

D. Welding parameters

Tables I and II below shows the welding parameters used during the welding.

TABLE I WELDING PARAMETERS

	Volts (V)	High Amp	High Pulse	Low Amp	Low Pulse
Test 1	8.3	100	0.15	47	0.13
Test 2	8.3	100	0.15	47	0.13
Test 3	8.3	108	0.15	55	0.13

TABLE II WELDING PARAMETERS

	Downslope	mm/min	Energy (kJ/mm)
Test 1	0	80	0.40
Test 2	0	80	0.47
Test 3	0	80	0.52

E. Thermal conductors

For this experiment thermocouples of type K was used. Type K thermocouples consists of two wires of dissimilar metals joined together at one end, called the measurement ("hot") junction. The other end is connected to the signal conditioning circuitry traces, typically made of copper. The junction between the thermocouples metals and the copper traces is called the reference ("cold") junction. The Voltage produced at the reference junction depends on the temperatures at both the measurement junction and the reference junction [12] (see Figure 8).

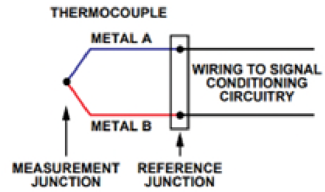

Figure 8. Thermocouple.

F. Welding case

Two 300 mm seamless tubes of stainless steel 316 with a wall thickness of 2 mm are welded together using an automatic orbital TIG-welding machine described above.
The welding is performed at room temperature of 23 degrees Celsius. The welding is done without welding wire. The welding starts at 12 o´clock and the pipe is turning one and a half lap during welding. The arc from the weld will always be at 12 o´clock. The choice of welding one and a half lap around the pipe is because of the straightness of the finished pipe. Figure 9 below shows welding direction.

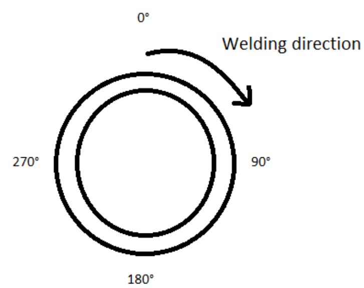

Figure 9. Welding direction.

III. RESULTS

The results from the welding show that there is 0.12% to 0.18% of shrinkage in the weld zone when measured before and after welding. It also shows that with increased heat input the shrinkage will increase. Tables 3-5 show the measuring results from the longitudinal shrinkage in mm with results of 0.7-1.1 mm in shrinkage. Tables 6-8 shows temperature results from welding in degrees Celsius, with maximum temperatures measured from 520 degrees Celsius to 640 degrees Celsius for the different weld tests.

The straightness of the pipes after welding is shown in Figure 11 and all the pipes were after welding straight.

TABLE III MEASURMENTS SHRINKAGE

Test one						
(mm)	0°	90°	180°	270°	Mean value	Mean shrink.
Measurement before welding	589,5	598,1	598,1	598,4	598,3	0,12%
Measurement after welding	597,6	597,6	597,5	597,5	597,6	0,7 mm

TABLE IV MEASURMENTS SHRINKAGE

Test two						
(mm)	0°	90°	180°	270°	Mean value	Mean shrink.
Measurement before welding	604,5	604,6	604,2	604,6	604,5	0,15%
Measurement after welding	603,8	603,3	603,3	604	603,6	0,9 mm

TABLE V MEASURMENTS SHRINKAGE

Test tree						
(mm)	0°	90°	180°	270°	Mean value	Mean shrink.
Measurement before welding	598,1	598	598,2	598,5	598,2	0,18%
Measurement after welding	597	596,6	597,1	597,6	597,1	1,1 mm

TABLE VI MEASUREMENT TEMPERATURE

Test 1			
Weld start 315°, this weld was visually OK			
Placement of thermocouple	0°	60°	120°
mm from centre of weld	10	15	20
Temperature in Celsius lap 1	582	427	322
Temperature in Celsius lap 2	604	491	394

TABLE VII MEASUREMENT TEMPERATURE

Test 2				
Weld start 0°, this weld was visually OK				
Placement of thermocouple	0°	90°	180°	270°
mm from centre of weld	10	15	20	25
Temperature in Celsius lap 1	443	351	276	176
Temperature in Celsius lap 2	520	442	265	-

TABLE VIII MEASUREMENT TEMPERATURE

Test 3				
Weld start 0°, This weld was visually not OK				
Placement of thermocouple	0°	90°	180°	270°
mm from centre of weld	10	15	20	25
Temperature in Celsius lap 1	493	487	330	284
Temperature in Celsius lap 2	639	392	304	-

Figure 11 shows the straightness of the pipe after welding.

Figure 11. Straightness in pipe after welding.

IV. DISCUSSION

The results show a longitudinal shrinkage of 0.12%-0,18% witch if several welds are added can end up in a total longitudinal shrinkage of several millimetres and even centimetres. For large systems of pipes this will be a significant aspect during design and construction. To be able to simulate this in the beginning of the design, will be worth a lot of time in the end of production, as predictions of outcome and hence also compensation may be made early, something that is enabled via the research in this paper.

The literature review indicates that there is a need for geometry assurance in larger sections of piping systems on ships, submarines, powerplants and other facilities. One way of doing this is to simulate the welding. To be able to do this

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comparation data is needed. In this paper we looked specifically at welding joints, with orbital TIG welding experiments, with the aim of collecting data for later simulation of weld joints via digital twins and adding the possibility to adapt design parameters already before the production is performed. The shrinkage in the weld test behaved as expected, even though there is a small possibility that there are problems with the measuring equipment that will give small differences.

The temperature was measured with thermocouple type K, those were calibrated at zero degrees Celsius and at one hundred degrees Celsius with good results, within two degrees Celsius. Still there is a small possibility for errors if there for example is an air pocket between the thermocouple and the base material during welding. The pipe was, as shown in Figure 11, straight after the welding.

V. CONCLUSIONS AND FUTURE WORK

Data from weld test shows that there is longitudinal shrinking in the weld area during welding of pipes in 316L, with a diameter of 89.9 mm and wall thickness of 2 mm. The shrinkage from the tests is 0.12-0.18% of the length and with a large amount of weld joints, this can be significant for the possibility of mounting the part. In a piping system this can add up to several millimetres or even centimetres.

Future work is development of simulation models that will mirror the actual welding for digital twinning purposes. Through those simulations prediction of deformations and shrinkage during welding can be performed. When constructing the simulations verification will be made by comparing the simulations with the experiments in this paper. When the simulation models are made, they will be inserted in models of sections from piping systems. This way it will be possible to simulate how several welds in a piping system will affect the end product and plan the production from the data given in the simulation. Different geometries, materials and numbers of welds can then be simulated in advance to help plan production. By doing those simulations before welding, the time and quality in production will increase and it will be easier to prefabricate piping systems with less time for on-site welding.

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