GENERATING NODE STRUCTUES BY ADDITIVE MANUFACTURING WITH METAL ARC WELDING – CONCEPT, GEOMETRY, MATERIAL PROPERTIES

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The article describes a new manufacturing method of tube/tube- connections with an additive process. The idea of the procedure is based on the assumption, that a similar manufacturing process like the 3D-printing with plastics can also be realized by using a metal arc welding process, similar to a cladding.

The application of this procedure to the production of tube/tube- connections can remove a lot of problems, which often occur in the traditional manufacturing process, including cutting, assembling, welding. The results of the investigations regarding material, economic and technological factors are promising and give prospects of using the results in industrial applications.

Keywords: Additive process.

1 Introduction

State of the art is the manufacturing of tube connections using semi-finished tubes, which are cut, assembled and then connected mostly by manual welding. Within this production chain the welding process is the bottleneck. Reasons therefor are:

- tube welding demands high experience, knowledge and manual skills from the welder, only a small number of welders is able to fulfill this demand,
- welding is physically demanding and hazardous to health, the number of people, which is willing to do this kind job, is dramatical decreasing,
- standards, i.e. in the offshore industry, demand full penetration connections which are not always producible due to geometric limitations of the cutting and welding process,
- a welding seam is always a geometrical and also a material notch,
- assembly tolerances and thermal deformations may produce high deviations of the node's geometry,
- the possibility of non-destruction tests at tube connections is limited.

With an additive process all of these negative aspects can be removed. The part will be fabricated from melted welding wire in a computer generated, autocratically process. The additive manufacturing does not make the manual welding obsolete. The node will be generated up to a certain length, where a simple circular seam can be used to connect a

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regular tube (Fig. 1).

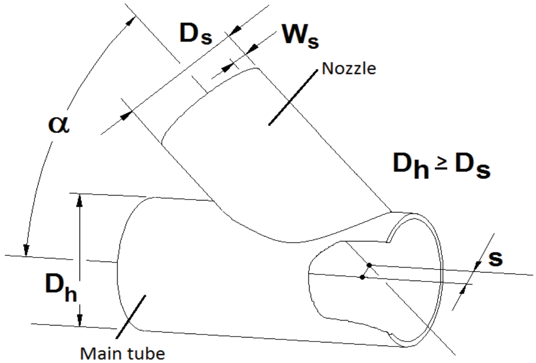

Figure 1. Node with connected tube

Figure 2. Node parameters

2 Concept

2.1 *Kinematics*

While working with the welding arc support structures and false-works- like at 3D-print with plastics- are not possible. The generation of the workpiece can only be based on the effect of gravity and the viscosity of the melted material.

In 3D space a body has a degree of freedom F = 6, which is divided into three position degrees and three orientation degrees. The tool, the welding gun, is normally axially symmetric, which reduces the necessary orientation degree to 2 and demands 5 numerically controlled axes for the machine. To guarantee, that the “line of attack” of the torch is nearly identical with the direction of gravity- maximal deviation of around 15 deg.- these five axes need to be divided into two “kinematic groups”. Both the tool and the workpiece needs to move simultaneously relative to the world coordinate system. Redundancy, i.e. the existence of more movement axes than necessary is desirable but makes the calculations more complicated. In practice this principle works with a tilting table, including the two orientation axes, where the workpiece will be fabricated. A cardanic principle, i.e. the rotation axes are intersecting and in zero position horizontal, is the preferred arrangement. The welding gun, the torch, must be oriented parallel to the direction of gravity and has to be moved simultaneously along the three cartesian axes.

The obvious choice is the use of an industrial robot with suitable tilting table. The arguments for this concept are:

- industrial robots are commercial and well-priced,
- the position accuracy of industrial robots of some millimeter is more than enough for the task,
- three redundant axes are available,
- because of the continuous re-orientation of the workpiece a very big workspace is necessary, multiple times bigger than the volume of the workpiece itself,
- the necessary kinematic transformation is integrated into the robot control and ready for use.

2.2 *Welding equipment*

First choice is *gas metal arc welding (MIG)* with solid wire. The welding wire is continuously pushed through the torch and supplied with the necessary welding current. The current is heating up the wire and creates an electric arc at the contact point to the workpiece, which causes the wire to melt and transfers a particle of it to the part. An inert protective gas prevents the weld pool from oxidation. Instead of the MIG- process other arc welding techniques can be used like flux-cored wire or plasma powder welding. This creates possibilities to increase the efficiency of the welding process and diversity of materials [HOE2017].

3 Data flow and software

Core is the fast and error-free generation of a CNC- program to guide the tool along the welding path. The program contains a (very long) list of interpolation points with some additional information regarding speed and process control.

3.1 *CAD-Modeling*

Point of origin is a parametric solid model within an arbitrary CAD- system. With only eight parameters

- main tube diameter and wall thickness,
- nozzle diameter and wall thickness,
- intersecting angle,
- eccentricity, i.e. the crossing distance of the main tube and nozzle axis,
- nozzle axis rotation around and shifting along the main tube axis (Figure 2)

the connection is completely described and can be interchanged via STEP- format. Double and multi connections can be handled in the same way, each additional nozzle can be described with the same set of parameters. An important feature of additional manufacturing can be specified with the thesis: Manufactured like designed! Apart from normal manufacturing tolerances all geometrical details will be IDENTICAL at the real part. This is a significant difference to the manual joint welding, where the real seam geometry in the best case is SIMILAR to the theoretical model.

3.2 *Geometrical optimization*

It seems worthwhile to complement the CAD- model with some more parameters and to optimize the shape with FEA. The outer shape needs to be untouched, but with

- the shape and dimensions of the transition region between the two intersecting cylinders and
- the variation in wall thickness along the circumference and the nozzle axis

a couple of parameters are available for optimization. This can be done directly and with the same data base within advanced CAD- systems- in our case with CREO®- and can be adapted to different dimensions in no time.

[Mat2017] contains interesting and unconventional ideas for the forming of the transition regions at tube connections. Based on the study of the static design of trees the paper describes stunning simple geometrical principles to minimize notch effects and to increase the fatigue strength. These ideas were used for the geometrical optimization.

3.3 Robot/ CNC-program

Instead of expensive and complex CAM- software the authors use a small, tailored software solution, limited to tube-tube-connections. Only a small set of parameters controls the fully automatic calculation and makes the analysis of variants fast and easy. Core of the software are sophisticated algorithms for automatic calculation of the welding pattern. The software is in constant development, so continuously new algorithms, result of practical experiences and tests, can be implemented and evaluated.

The generation of the structure is based on the main tube, using a standard round tube. For the additive manufacturing the part model has to be divided into a set of two-dimensional layers. These layers can be parallel planes, coaxial cylindrical or concentric spherical surfaces and have always a constant offset between two regions. The term "Morphing" describes algorithms which create interpolations from one to another cutting layer type. Here the distance between the layers is not always constant. The different in thickness can be compensated to a certain extent with the welding parameters and in addition with filler beads.

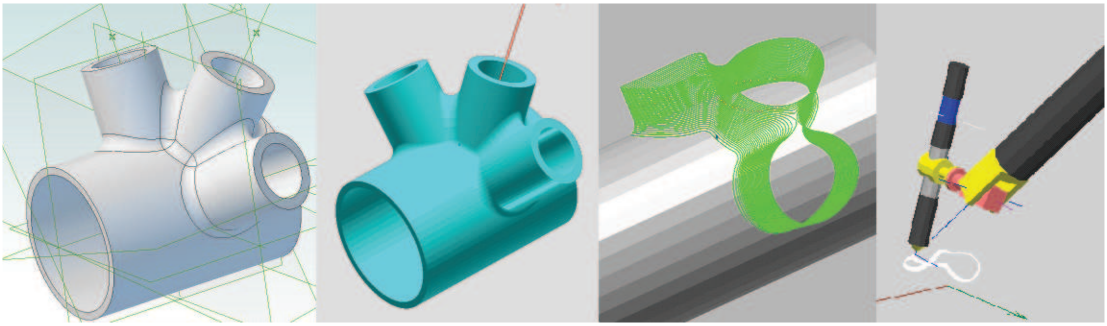

Figure 3. Sequence of manufacturing (CAD-model, STL-export, slicing, process simulation)

Starting with the node dimension in the CAD- system the model will be exported in the data format STL. This is a very simple 3D, surface based format, where the part surface is completely covered with triangular faces. This format makes the calculations simple and transform the 3D-part into a multiplicity of two-dimensional, topologically similar sub problems. After calculating the intersections there is a heap of disordered lines, which need to be sorted into contours and to be grouped into outer and inner regions. The area in between is part of the model and has to be filled with a pattern of welding seams. Of special interest are nodes with multiple intersections, where the nozzles are interfering. During the layer composition contours are constricted and then divided into two independent ones. The topology changes and the software needs to detect and to handle these cases. Based on an existing parametric model within some minutes a machine program in elective CNC- or robot language can be generated. To reduce the size of robot programs- a number of 105 points is not an exception- special algorithms for data reduction and dividing the robot program into a set of subroutines will be helpful.

3.4 *A sample part*

Figure 3 shows the sequence of manufacturing by means of a sample part. The geometrical parameters:

- Main tube Ø177.8 x 8, S355J2H
- Nozzle Ø 88.9 x 12.5
- Intersecting angel 75^0
- Eccentricity 0mm
- Corner radius 14mm outside, 8mm inside.

The part is modeled in the CAD- system (Step 1), exported as a STL- file and loaded into the CAM- Software (Step 2). After selecting an algorithm for slicing the generating of the tool path is done automatically (Step 3). These algorithms are comparably simple but computationally intensive, so calculation times of some minutes are to be expected. Combined with technological data from a data base, filled with our experiences, the result is a ready-to-run robot program (Step 4) which produces parts like seen in Figure 4.

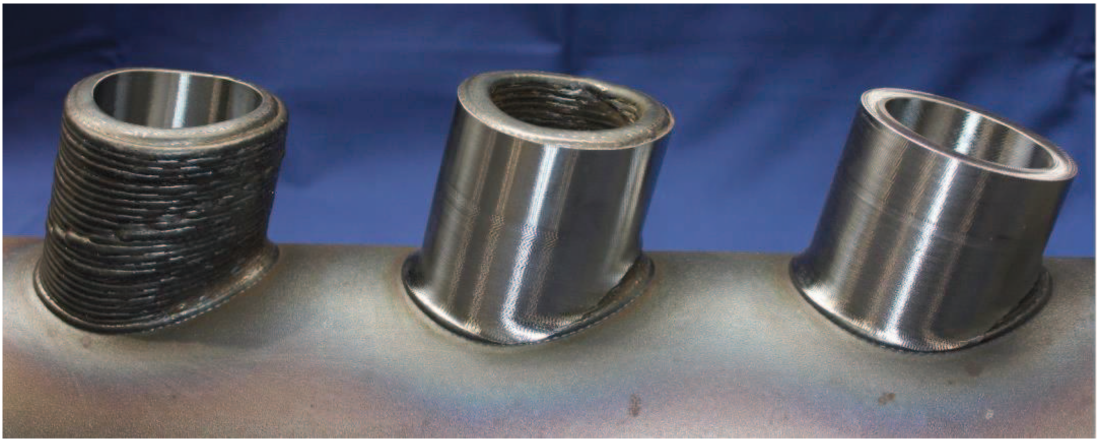

Figure 4. Generated parts in different conditions

4 Processing and process control

We use similar materials for welding (Grade G4Si1, EN 14341) like the main tube (S355J2H). Diameter is only Ø1mm to increase the control range of the welding technology. The welding parameters need to fulfill the following demands:

- certain weld penetration and avoidance of lack of fusion,
- lowest possible heat transfer into the workpiece,
- delicate seam shape for reproduction of also small details,
- high repeatability of the seam width and -height, low weld flank angle for better connection to the neighboring seam,
- no imperfections and no scabs,
- high deposition rate [kg/h], i.e. melted welding wire per time.

A surprising reproducibility of the weld can be displayed. So a lot of manufacturing aspects can be traced back to geometric calculations and parameters. In compliance to [Feld2018] an oscillating weld delivers better welding results than string bead technique, but increases the energy input per unit length and maybe makes the micro-structure more coarse-grained.

The term “inter pass temperature” describes the optimal part temperature for welding, which is normally somewhere between 100 and 150OC. At additional manufacturing a high amount of heat is transferred into the part, so a cooling is necessary to avoid overheating. Cooling down at air takes time, cooling with water [Status] is from the welding point of view is not a technically correct manner.

To prevent overheating and to decrease the time for cooling down the part CO2-snow is used. The snow has a temperature of -78OC and changes directly from solid to the gaseous state. The heat capacity is high, the snow itself vaporizes without any residues into the atmosphere. In addition there is a cleaning effect of the welding seam. Slag and silicates become brittle and spall from the surface of the seam.

5 Material properties and appearance

The material properties of the manufactured parts were checked comprehensively, our results are similar to those in [Feld2018]. At the end a fine grained structure arises with high strength and ductility (Figure 5).

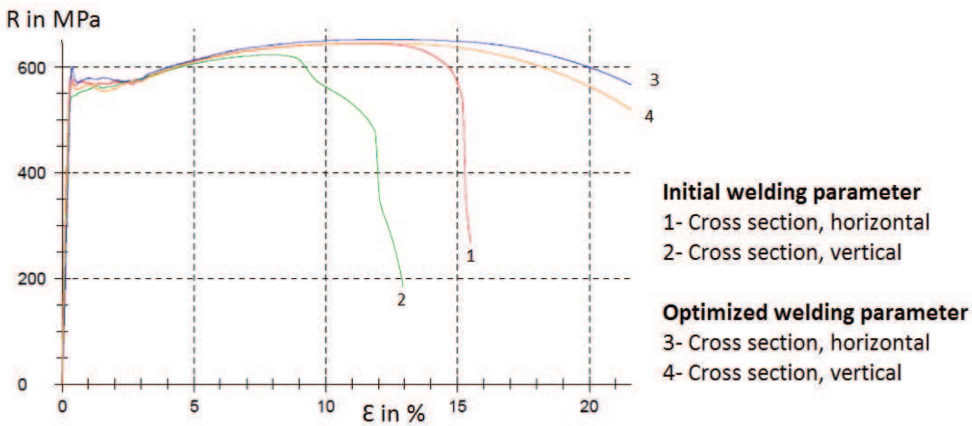

Figure 5. Stress-strain curve

Reasons are on one hand the comparatively high grade of the welding wire with ReL > 420 MPa and KV > 47J at -40°C, on the other hand the heat treatment of the lower by the upper welding seam, which is similar to a tempering. Result is a microstructure (Fig. 6) which is similar to a normalize ones. The surface of the part has a typical scarred shape, but its roughness or better periodic and random deviation is much lower than expected (Fig. 7).

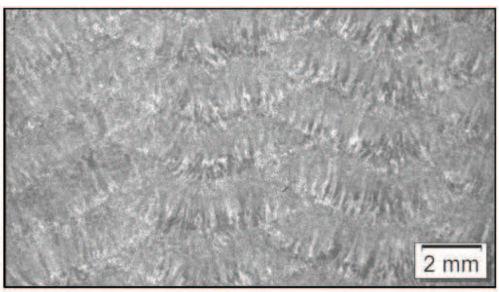

Figure 6. Macro section

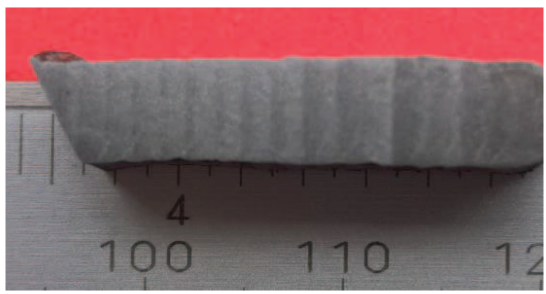

Figure 7. Cross section of generated wall

To remove the scarred shape of the generated parts a final milling procedure is possible. After milling the part is not to differ from cast iron parts or completely milled parts. The combination of welding and milling within one machine and an identical workspace is possible [JOHN2017], [FISC2018], makes the process more flexible, but has technical and economical disadvantages. Using the industrial robot both for welding and milling by a simple tool changing seems the most economical way but fails because of robot stiffness [MUEG2017].

6 Economical aspects

For the sample part in Figure 4, but only with two nozzles, three scenarios were selected. A price calculation has been done based on German personnel and energy costs:
certain weld penetration and avoidance of lack of fusion,

- Scenario 1 - calculation based on our experiences

- Scenario 2 - calculation based on data from a research institute
- Scenario 3 - conventional manufacturing with manual assembly welding
- Scenario 4 - Node 355.6x25, main tube Ø610, 60º

Table 1. Economical calculations

Scenario	1	2	3	4	
Deposition Rate	1.5	3,5	1.2	4	kg/h
Seam volume	664	664	60	19200	cm^3
Pure welding time	208	89	25	2250	min
Manufacturing costs	204	260	214	1623	€
Programming	40	160	0	40	€
Welding wire	11	11	1	300	€
Protective gas	5	5	1	400	€
Cooling gas	25	0	0	0	€
Machine costs	78	39	2	633	€
Mounting/ Checking	45	45	10	250	€
Manual welding	0	0	120	0	€
Prefab.nozzles	0	0	80	0	€
Cost per kg	39	50	41	11	€
Personal cost amount	41%	79%	61%	18%	%

The results are surprising, because the deposition rate has only a small influence to the overall costs. The reason is the fully automatic construction phase which can be taken place for example in the night shift and without an operator. Costs for protective gas and electrical energy are less. However the process steps CAD and CAM are amazing cost drivers at small parts. Slim, fast and robust software is therefore highly important.

7 Conclusion

With the additive manufacturing there is a new possibility available, almost all the described problems can be solved.

Based on technological experiences from overlay welding investigations into additive manufacturing of tube connections were done.

With a combination of CAD and FEA methods the state-of-stress of a connection can be "balanced" by generating corner arcs, by thickening and cutting back. This can be done outside and inside the tube connection, similar to the work of a potter. By additive welding with an industrial robot this can be done fast and easy, so far only possible by casting, which is time consuming and expensive. Modern welding equipment makes the welding process itself very stable and repeatable, a fully automatic manufacturing is possible.

Result of the manufacturing is a homogeneous material structure without inclusions and blowholes, the microstructure of the material is fine grained and normalized. With an additional milling the typical "grain skin" of the parts can be removed, then the parts looks similar to cast iron parts and have at least the same material properties.

The fabrication itself is a highly automated process, including ignition, cooling, measuring and holding the inter pass temperature constant and cleaning the welding seam. This is the key point to make the technology economical, because personnel costs are low.

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