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Use of image correlation to monitor the deformation behaviour of ship propellers during additive manufacturing using build-up welding

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Abstract

Traditionally, ship propellers are manufactured by sand-casting with slight oversizing and then milled or ground to the final shape. However, that manufacturing process, particularly in the production of small-diameter propellers (D < 5 m), can only partially be used competitively by the European industry in today´s market. A new method of manufacturing propellers is therefore needed.
Additive manufacturing technology is already well established in the design and manufacture of marine systems. This article presents a means of monitoring the WAAM of propellers using image correlation methods. The GOM ARAMIS optical measurement system is used for its area measurement capability. The method is applied to two test series, one with flat steel plates and one with a ship propeller blade, using different welding materials.

1. Introduction

The manufacturing process for ship propellers has changed very little in recent decades. Typically, a part is produced as a sand-casting with slight oversizing and then milled or ground to the final shape. Apart from slight geometric changes to increase performance or reduce the noise emitted, hardly any adjustments have been made to the process. At the same time, the highly volatile shipbuilding market is forcing maritime suppliers to react more flexibly to the market and to focus on future-oriented production technologies. Particularly in the production of small-diameter propellers (D < 5 m), the established sand-casting process can only partially be used competitively by the European industry in today's market. However, further developments in additive manufacturing technology are opening new perspectives for the planning and production of maritime systems.
Build-up welding allows ship propellers to be produced layer by layer from the hub to the blade tip using additive manufacturing (see *Figure 1*). This enables near-net-shape production of new propeller geometries with hollow structures and a low component weight, which not only saves resources but also reduces the bending load on the drive shaft.
However, to be able to integrate this technology into existing workflows, the challenges of residual stress, temperature control and quality assurance must be considered. Temperature-related stress in particular causes deformations that have a significant impact on production quality. In addition to the sensor-supported monitoring of welding parameters and temperature, the monitoring of geometric, process-related conditions is essential to master complex process sequences and ultimately carry out optimisations.
For several years, digital image correlation (DIC) methods have proven to be a reliable tool for monitoring strains, compressions and other deformations (Hassan 2021). This technology is capable of recording and measuring geometric changes with sub-millimetre accuracy. For this application, the instrument must provide a measuring volume of at least one cubic meter, which results in a measuring distance of around 1.20-1.60 m due to the geometry. The combination of a camera-based measuring system, which is very sensitive to changes in light, and the ambient conditions during arc welding, such as soot development, flying sparks, high temperature fluctuations and electromagnetic radiation, pose a few challenges for system integration. Thanks to a measurement setup including homogeneously distributed reference points, frequent surface treatment and shielding to the welding arc, it is possible to use the optical measurement method despite the considerable sources of interference in the production environment.

Figure 1. Propeller in the manufacturing process using build-up welding at MMG (Kloetzer-Freese, C.)

A process for the monitoring of the additive manufacturing of ship propellers is presented below. The propellers are manufactured using the Wire Arc Additive Manufacturing (WAAM) process and monitored using the GOM ARAMIS system. The measurement stand has been designed with the measurement challenges of the WAAM process in mind.

2. Related work

Additive manufacturing (AM) technologies have developed rapidly not only because of their ability to produce near-net-shape parts with complex geometries, but also because they offer several advantages over conventional processes in the production of individual parts. In addition to geometric and design freedom, production times, material consumption and, as a result, costs can be significantly reduced for small batch sizes. The development of new manufacturing technologies opens up new perspectives for the production of components for maritime systems, especially in the foundry industry. The additive manufacturing of metallic structures has been extensively investigated in many research projects. Wire Arc Additive Manufacturing (WAAM) is a promising candidate for the production of large metallic components, especially for complex geometries. The WAAM process is an additive manufacturing process in the DED (direct energy deposition) category in the production process for 3D printing or repairing metal parts. Metal layers are applied on top of each other until the desired shape is achieved. *Figure 2* shows the components of a robot-assisted setup (Li et al. 2022).

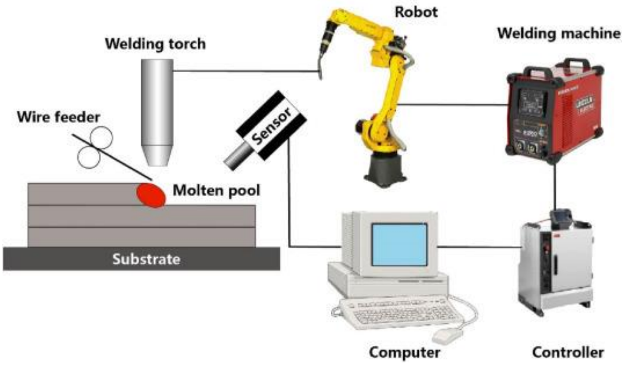

Figure 2: WAAM process (Li et al. 2022)

Specifically for shipbuilding, (Taşdemir and Nohut 2020) provide an overview of WAAM technologies and discuss the feasibility of using WAAM in the shipbuilding industry in the context of material availability and properties, design complexity and cost in selected applications. Further comprehensive reviews of the WAAM process can be found in (Chaturvedi et al. 2021), (Jafari et al. 2021). Only a few researchers, such as (Govindaraj et al. 2021) and (Ya and Hamilton 2018), have focused exclusively on the manufacturing of marine propellers by WAAM in recent years. The manufacturing potential has been highlighted, but the benefits have been limited mainly by the restriction to the original casting geometry. The studies have focused exclusively on additive manufacturing and have not considered the material and deformation behaviour during build-up welding. Geometric changes to the component during deposition welding are only monitored in small areas, and different strategies are used for different tasks, particularly in sensor-assisted robotic welding. In additive manufacturing, sensor systems can be used in offline path planning for position adjustment using correction data for tool or workpiece positioning before the welding process. During the welding process, changes can be recognised as part of seam tracking and the welding and movement parameters can be directly controlled in real time. After the welding process, sensors for fully mechanical arc welding are used online or offline for weld seam inspection. The robot uses the determination of the thermal distortion by the laser online sensor for adaptive welding. The control system adapts the welding parameters to a changing geometry. If this changes - e.g. due to changing tolerances or thermal distortion - the sensor recognises this and causes the welding parameters to be adjusted accordingly. An autonomous system can be realised by combining seam tracking with seam inspection, particularly for multi-layer welding.

Overall, monitoring of all process data is necessary to determine the optimum process parameters. The open source analyzer generates data such as current, voltage, temperature and sound during wire-based arc welding. Geometric data are not provided (Pringle et al. 2020).

(Cunha et al. 2021) gives an overview of scientific publications that deal with insitu measurements with DIC in AM. Methods and results are presented for the application areas of characterisation of defects, evaluation of residual stresses, geometric deformations, validation of numerical models based on in-situ measurements and monitoring and characterisation of components. The integration of in-situ DIC measurements in AM processes reveals several difficulties in practical implementation. Depending on the additive manufacturing process, the challenges include radiation, projected particles, camera position, speckled pattern, curved objects, closed chamber, relative motion.

3. Methodology

The welding tests presented were carried out fully mechanized within a robot-assisted machining cell consisting of a welding system, manipulators and welding fume extraction system. A welding system consisting of the TPS500i welding power source from Fronius was selected for additive manufacturing. The Arc View 2 arc camera from Fronius is used to monitor the welding process. The welding torch with push-pull system is guided by a vertical 6-axis articulated robot type KR500 from Kuka. A DKP400 rotary tilting positioner from KUKA manipulates the workpiece in the workspace. Various arc modifications are used for additive manufacturing of propeller geometries, depending on the required energy density. The Cold Metal Transfer (CMT) process was used in the investigations. This short arc is characterised by an active mechanical return movement of the welding rod during the short-circuit phase. This special type of droplet separation ensures a lower short-circuit current and thus a lower energy input into the component and a reproducible seam geometry. The welding parameters are given in *Table 1*.

Table 1: Welding parameters used in all tests

Parameter	**Value**
Wire diameter	1.2 mm
Current	(110-180) A
Voltage	(10.0 – 15.0) V
Wire feeding rate	(4.0 -7.5) m/min
Robot travel speed	7,0 mm/s
Dwell time	20 s
Shielding gas	Argon 4.6 (99.996 % purity)
Gas flow rate	20 l/min
Nozzle-to-work distance	10 mm
Torch angle	Neutral (0°)
Interpass temperature	300 – 500 °C

Two applications for the different materials were analysed in the tests. In the first application, the three filler wires were welded to a plate using multi-layer welding. In the second application, a propeller blade was welded onto a steel tube with an outer diameter of 120 mm and a thickness of 9.5 mm. The tube is welded to a steel plate and fixed to the surface of a rotary table in a 90° inclined position (see *Figure 3*). Since constraints are necessary for the orientation of the welding torch (PA position) on the workpiece, the welding torch is positioned by means of the robot and the pipe is rotated by means of a tilt and turn positioner. The manufacturing begins with an meandering pendulum bead with a width of 30 mm, as a first layer. This is used to get a higher energy output and make the pipes material more feasable to a stronger welding joint. Afterwards single bead layers in alternating welding direction are added onto each other to form the target geometry. After each layer a short stop must occur so the material can cool down and join together depending on the material, welding parameters and geometry a longer pause may be necessary for the part to acclimatize.

Figure 3: Welding rig prepared for the monitoring (Hack, D.)

To evaluate the welding parameters for each manufacturing application the geometric behaviour of the welded structure is to be monitored. For this purpose a DIC system is integrated into the WAAM process, wich will identify and quantify the areal deformations induced by temperature changes.
However some challenges must be hurdled in order to fully integrate an optical measuring system.

- The welding-arc radiates a bright light of various wavelenghts wich interferes significantly with any optical measurement system.
- Due to the size of the planned propeller the measuring volume must cover at least 1000 mm³ especially considerung the placement of reference targets.
- In contrast to the FDM monitoring mentioned above, the metallic surfaces of WAAM manufactured parts not only lack a naturally occurring stochastic pattern, but also have a high degree of reflectivity, rendering them optically unsuitable for measurement.

3.1 Measurement preparation

Metrologically, the greatest influencing factor in this applycation is the light emission during build-up welding. As the light from the welding arc covers a wide spectrum of wavelength with very high intensity, optical sensors must be protected to prevent over-illumination (see *Figure 4*). The fitting of a protective cover is essential and its implementation must be adapted depending on the application.
In general, the cover should be close to the welding nozzle and, if possible, not obstruct any metrologically relevant areas. The robot arm was used to attach a metal sheet as cover. This ensured constant coverage of the welding nozzle over the entire duration of the process and the protection sheet did not move out of the line of sight between the measuring system and the welding nozzle as the component rotated.

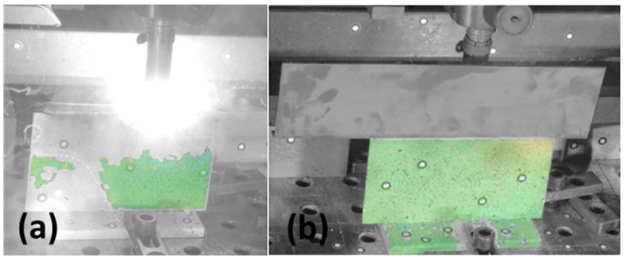

Figure 4: DIC without (a) and with (b) shielding from the welding arc (Stoltmann, M.)

Due to the rotation of the component, the fixed-body correction must be applied throughout the entire process; reference points are used for this purpose. In the processing, they are assumed to be deformation-free objects with whom the movement of the measured object in relation to the camera system is compensated. The heat input not only deforms the welded layers, the support structure (base plate, tube, propeller hub) on which the welding is applied must also be metallic and is therefore subject to thermally induced deformation. Therefore reference points must be applied as decoupled as possible.In this case, the rotary table was utilized. Due to its distance from the welded blade and its high thermal mass, it was subject to relatively small temperature-related deformations and performed the same rotations during the process.
In addition to thermal deformation, all metallic components (carrier structure and application material) additionally have a strong optical influence on the measurement quality.
Due to the high reflective properties of the metals and in order to create the best possible contrast under the already difficult lighting conditions, all components must be primed matt white and provided with a matt black, stochastic pattern for feature detection.
The surface treatment takes place before the first application layer and periodically between welding sections parallel to the computing time. As the welding temperature is around 1000°C, ULFALUX ® high-temperature oven paint with a temperature resistance of 1200°C is used. To prevent sooting of the measured surface, the area adjacent to the welding section must be omitted by about 10-20 mm (see *Figure 5*).
The elasticity of the coating spray was tested beforehand to ensure that it did not mechanically filter the deformation movement. No verifiable negative impacts can be detected.

The speckle size and pattern homogeneity directly influence which surfaces are available for analysis and must therefore be checked for its quality before welding.

Figure 5: Preliminaty testing of the coating agent behaviour and sooting (Stoltmann, M.)

3.2 Measurement System

The GOM ARAMIS 3D 6M (see *Figure 6*) DIC system was used with the following measurement parameters:

Table 2: Properties of Measuring system GOM ARAMIS 3D 6M

Measuring Volume	1250 x 1100 x 1100 mm
Mesuring Distance	1400mm
Camera Angle	25°
Max. Frequency	25Hz
Lighting	External Blue light (Cameras w. Filter)
Camera Resolution	2752 x 2200 Pixel
Pixel Size	4,54µm
Sample Temperatur	-100 °C to +1500 °C
Strain Measurement Accuracy	0,005%

In order to achieve the required measuring volume, the standard ARAMIS system was enlarged using a longer base of 600 mm. The system works with filtered blue light, which is more suitable for applications in a higher temperature range than white light, as the light emission from test specimens has less impact (Berke and Lambros 2014).
Measurements were taken at a fairly low frequency in order to shorten the evaluation process and keep the data volume low. This favors integration into existing production processes.

Figure 6: Measurement setup for the monitoring of propeller manufacturing (Hack, D.)

3.3 Measuring procedure

The reference marks and the speckle pattern are recorded as a reference stage before the welding process. The reference stage describes the initial state in the evaluation, all subsequent images are compared to this.
After these preparations, the welding process starts and is measured simultaneously using DIC. The measurements are carried out in stages, the time intervals depend on the component geometry and the associated heat input per material layer.
To regulate the temperature, short cooling phases of several minutes must take place in sections of ~ 5 to 50 layers. These pauses are also used to apply a primer and speckle pattern to the surface of the added material. Immediately afterwards, the production process and measurement are continued. In the final cooling phase, image acquisition is continued until the component has a maximum temperature of less than 60°C.
The processing of the DIC images includes the manual definition of reference points for sturdy body correction. Furthermore, features in the speckle pattern must be defined as areas or points, which are analyzed for correlation across all recording stages of a production sequence. In the result, the measured deformations are displayed as scaled vectors.

3.4 Accuracy assessment

Since a reference measurement with a higher-precision measuring system is not possible in this specific application and there is no adequate test device that works in an environment with similar conditions, the manufacturer's specifications must be used to estimate the accuracy.
The manufacturer specifies a strain measurement accuracy of 0.005% as the measuring system uncertainty. This is a value relative to the measured deformation, so the inaccuracy increases with higher deformation.
In this test, a maximum amplitude of 13.7 mm (see 4.1 and 4.2) was detected, resulting in a measurement uncertainty of 0.000685 mm, but this value is subject to further uncertainties due to the challenging environmental conditions for measurement.
The factors influencing the measurement such as stray light, temperature fluctuations and air circulation have been minimized as far as possible through regular calibration, measurement of the ambient temperature, use of filtered blue light and shielding from the welding light; it is therefore estimated that the overall measurement uncertainty is in the sub-millimetre range. The required production tolerance of welding based additive manufacturing is 3 - 5 mm, with a sub-millimetre measurement accuracy the production-specific requirements are fullfilled.

4. AM-process Application and Results

The following chapter describes the welding process and the monitoring procedure, and subsequently presents the results. The test setup is divided into a simple preliminary test for process validation from a welding point of view and the application-oriented test by means of prototypical production of a propeller blade. To enable process evaluation, all tests were monitored in parallel using a thermographic camera system and the test specimen geometry was 3D scanned after the tests.

4.1 Preliminary welding test

To analyze the impact of different filler metals, simple welding tests were carried out.
The welds were made on EN 10088-3 1.4404 flat steel plates, 300 mm x 100 mm x 12 mm and on EN 10294-2 hollow bars.

The three welding consumables with different filler metals used are:

- ISO 24373 – S Cu 6328 CuAlNi5Fe3Mn2
- ISO 24373 – S Cu 6338 CuMn13Al8Fe3Ni2
- ISO 14343-A – G 19 12 3 L

The three filler materials were each welded to a subtrate plate. Due to the higher energy input, the first layer was welded in a meandering pendulum bead with a width of 30 mm. The following 5 layers were welded individually. The welding sequence was alternated and reversed after each layer. Filling times were provided to avoid end craters.
All of theses tests have been monitored via DIC and therographic imaging for the duration of the welds and the 30 minutes afterwards as well as pre- and post-welding surfacescans using a structured light measurement system (GOM ATOS Triple Scan). Since a relatively thin base plate is used a high deformations is expected, therefore the nozzle clearance was increased.
The first thing noticeable ist the lack of data for DIC-monitoring on the stainless steel specimen wich is caused by interruptance of the stochastic pattern by the developed soot (see *Figure 7*).
Other than that the different thermal capabilities of the used materials caused a significantly different bend in the base plate dispite the use of the exact same welding parameters and manufacturing strategy.
The deformations of the bronze-wire specimen were substaincially higher then of the steel, with aluminium bronze as the highest (see *Figure 7* and *Figure 8*).

Table 3: temperature induced bending of the base-plate usind different filler materials

Welding-wire material	Maximum Deformation [mm]
Aluminium bronze	13,7
Manganese bronze	13,2
Chromium-nickel steel	10,5

The nozzle usually has a clearance of around 8 - 12 mm above the specimen, a deformation of 13,7 mm would have caused it to collide into the material under normal circumstances.
Temperature induced deformation of the base- and welded material is inevidable. The test shows that these deformations occur significantely different changing the wire materials (see *Table 3*).

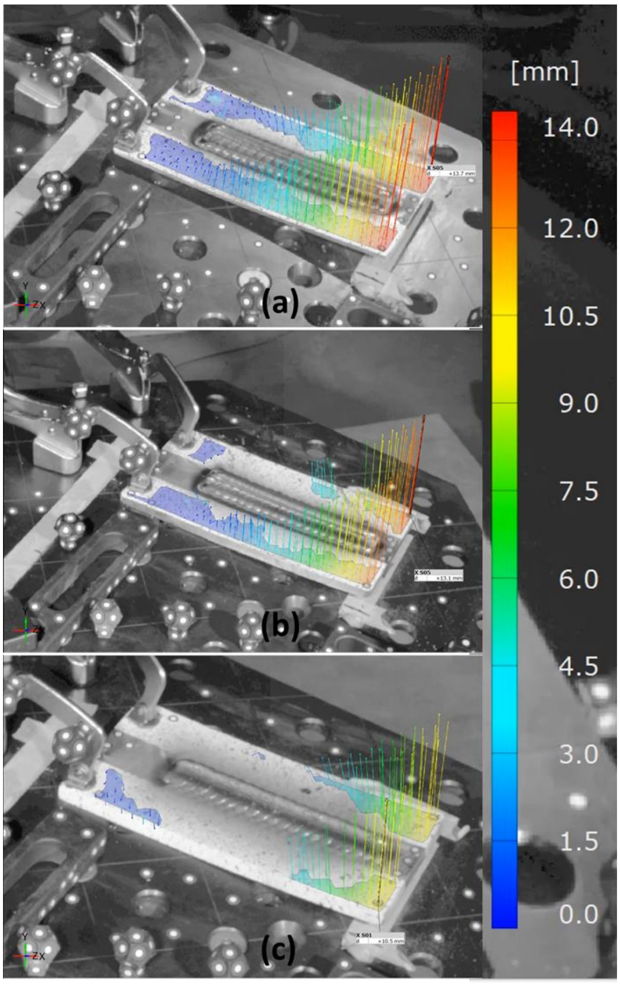

Figure 7: Deformation analysis on plate tests
(a) aluminum bronze, (b) manganese bronze,
(c) chromium-nickel stainless steel (Hack, D.)

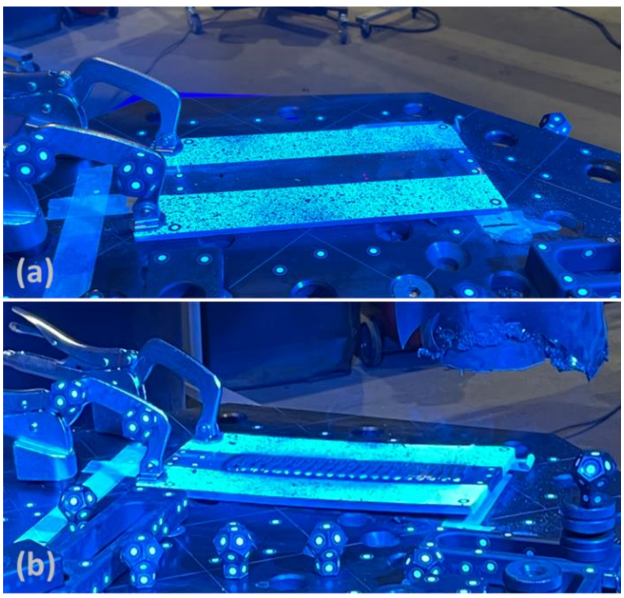

Figure 8: Flat steel plates from aluminum-bronce alloy
(a) before and (b) after first weld layer (Hack, D.)

4.2 Application-oriented test

The welds were made on EN 10294-2 hollow bars 119 mm outside diameter and 9 mm wall thickness. The welding consumable filler metal used is: ISO 14343-A – G 19 12 3 L.

In accordance with the welds on the plates, the first 5 layers were oscillated during build-up welding of the blade geometries and then individual beads were applied per layer. The propeller blade consists of 120 layers and the process was paused for 10 minutes after 50 layers. During this time, the stochastic pattern was applied to the blade geometry. The build-up welding process was then continued and the geometric behaviour of the tube and the patterned blade area was monitored. In order to fully monitor relevant deformations caused by temperature, the images were continued 30 minutes after completion of the process. At this point, the component had a maximum temperature of approximately 60 °C at the wing tip.

The comparison between the thermographic imaging and the DIC shows differences in the areas of the highest measured values. While the highest heat signatures simply occur from the welding area outwards as seen in *Figure 9*, the highest deformations are found at the tip of the base-pipe as seen in *Figure 10*. This phenomenon can be explained by the fixation of the specimen. Any deformation has some impact on the surrounding material, this adds to up to an overal bend of the pipe. Since the fixation is realized on one end the bending can only transpire on the other side of the base-pipe.

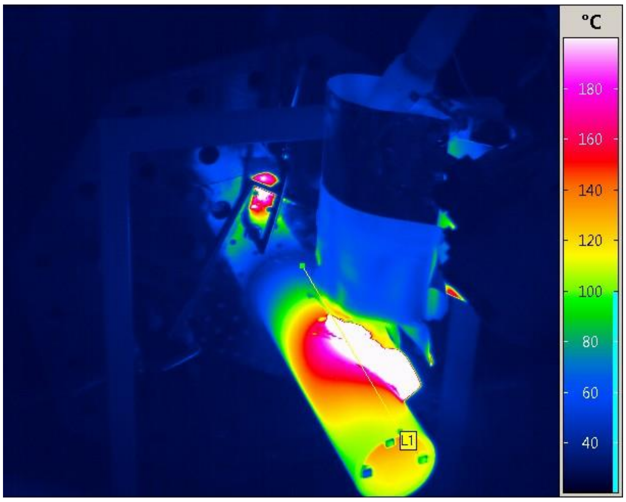

Figure 9: Thermographic imaging of the welding process (Hack, D.)

Additionally to the pipe bending deformations on the wing itself are detected. Whilst the inner area doesn't appear disfigured, a bend of the edges in opposing directions is measured. The frontside edge is bending inwards, yet the backside ist deforming in an outwards direction forming an overall torsion of the wing.

However the maximum deformation measured in this test is 1,4 mm whereas the deformations in the plate tests are maxed at 10,5 mm with the same material. The reasons for that supposedly are the stiffer geometry of the pipe and the larger thermal mass which might favoured heat distribution.

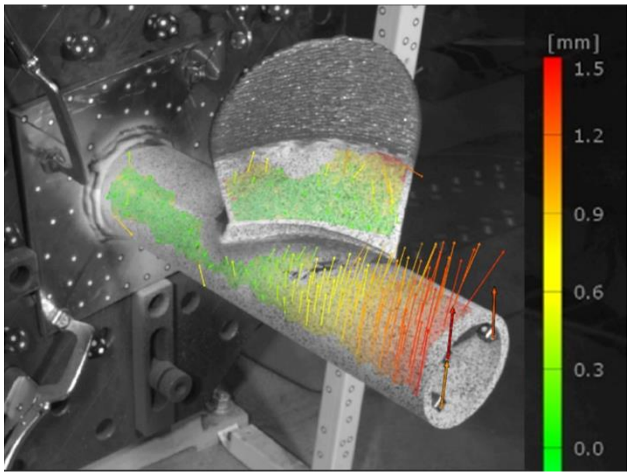

Figure 10: vectorised deformation image of stainless-steel propeller blade from DIC-Monitoring (Hack, D.)

As the temperature decreases, the deformations also decrease. The greatest change can be measured during welding or shortly afterwards. However, the changes become smaller and smaller as the material approaches the ambient temperature.

The actual state of the manufactured part is measured via structured light projection system (GOM ATOS). This measurement takes place at ~ 60 °C specimen temperatur, 30 minutes after the weldung process (direcly after DIC monitoring) and at ~20 °C (ambient temperatur) 8 hours later. The deformations between these two states were found to be only -0.4 mm maximum deviation on the tube and 0.1 mm on the wing surface (see *Figure 11: comparison of actual state measurement 30 min. (~60 °C) and 8 h (~20 °C) after build-up welding of stainless steel specimenFigure 11*).

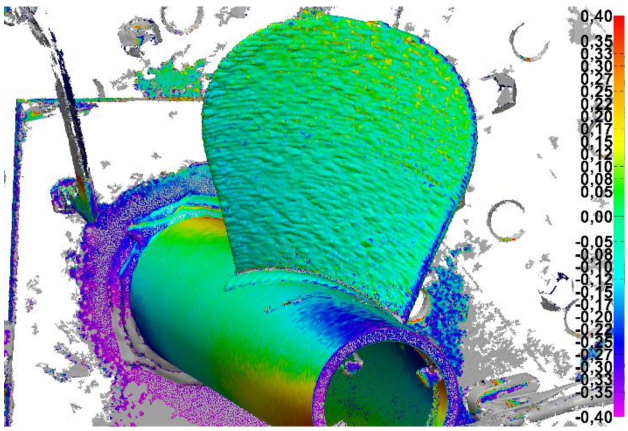

Figure 11: comparison of actual state measurement 30 min. (~60 °C) and 8 h (~20 °C) after build-up welding of stainless steel specimen

5. Discussion

A measurement setup for monitoring the WAAM process with DIC was presented. In addition to a series of tests with flat steel plates, this setup was tested in a series of tests for the production of a propeller blade. The basic structure was monitored during the entire process and the first 50 layers from the 10-minute cooling phase onwards. In addition, thermal data was recorded during the process and the produced blade was geometrically measured 30 minutes and 8 hours after completion.

A thermal camera is used to record temperature differences in the material during the manufacturing process. It is not possible to derive any shape information from the data. Geometrical measurement of the product after manufacture records the shape and any deviations in shape. This data cannot be used to analyse the causes. DIC fills this information gap by recording the changes, including the direction of the material. This means that data on cause (temperature), effect (deformation) and result (geometry) is available for process evaluation.

The information that can be derived from this will prove to be essential in the development of a WAAM process for the production of ship propellers. Compared to monitoring without DIC, it is not only possible to determine what geometric effects certain temperatures have on the product, but also how the material deforms during the process. This information is particularly useful when determining welding parameters and cooling phases in order to find the optimum setting.

In the series of tests with various filler metals, bending and torsion could be detected by DIC regardless of the material. However, analysing the chromium-nickel-stainless steel material was more difficult due to the development of soot. This is due to the welding parameters not being optimised for the material. Soot formation must always be avoided during the production process with WAAM, as this affects the quality of the product. In this respect, the inapplicability of the DIC if there is too much soot is not an exclusion criterion when determining the optimum process parameters. If soot is produced, the process parameters are not suitable - regardless of any deformations.

The very high accuracy with which deformations can be determined results from the manufacturer's specifications. These assume ideal ambient conditions when using the measuring system. When monitoring the WAAM process, the measurement takes place under non-ideal conditions, namely at very high ambient temperatures and in poor lighting conditions. It can therefore be assumed that the theoretical accuracies will not be achieved in practice. However, this high accuracy is not necessary to determine the optimum process parameters; deformation trends are sufficient.

Monitoring during the entire process with DIC to obtain information is recommended. Monitoring can be stopped 30 minutes after completion of the WAAM process, as no further deformations are expected from this point onwards.

Thus DIC using GOM ARAMIS measurement system is suitable to monitor WAAN process and determine optimal process parameter for manufactoring ship propellers. However, due to the long computing times, the method cannot be used in process control.

6. Conclusion

A methodology to monitore WAAM process using GOM ARAMIS measurement system has been presented. The process has to be paused after a suitable number of welds in a cooling phase. To allow deformation detection by DIC, a speckle pattern is coated to the cooled-down weld layer. By using DIC, the process data include geomtrical information auch as deformation direction. Temperature-induced torsion and bending of the product could be verified in tests.

The method presented thus provides the basis for determining the optimum process parameters for the manufacture of ship propellers using WAAM.

7. References

Berke, Ryan B.; Lambros, John (2014): Ultraviolet digital image correlation (UV-DIC) for high temperature applications. In *The Review of scientific instruments* 85 (4), p. 45121. DOI: 10.1063/1.4871991.

Chaturvedi, Mukti; Scutelnicu, Elena; Rusu, Carmen Catalina; Mistodie, Luigi Renato; Mihailescu, Danut; Subbiah, Arungalai Vendan (2021): Wire Arc Additive Manufacturing: Review on Recent Findings and Challenges in Industrial Applications and Materials Characterization. In *Metals* 11 (6), p. 939. DOI: 10.3390/met11060939.

Cunha, Filipa G.; Santos, Telmo G.; Xavier, José (2021): In Situ Monitoring of Additive Manufacturing Using Digital Image Correlation: A Review. In *Materials (Basel, Switzerland)* 14 (6). DOI: 10.3390/ma14061511.

Govindaraj, Ramesh Babu; Junghans, Eva; Andersen, Isak; Lim, Young ki; Lindström, Per (2021): Additive manufactured marine component – Ni Al bronze propeller. In *Procedia Structural Integrity* 34, pp. 20–25. DOI: 10.1016/j.prostr.2021.12.039.

Hassan, Ghulam Mubashar (2021): Deformation measurement in the presence of discontinuities with digital image correlation: A review. In *Optics and Lasers in Engineering* 137, p. 106394. DOI: 10.1016/j.optlaseng.2020.106394.

Jafari, Davoud; Vaneker, Tom H.J.; Gibson, Ian (2021): Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts. In *Materials & Design* (202), p. 109471. DOI: 10.1016/j.matdes.2021.109471.

Li, Yan; Su, Chen; Zhu, Jianjun (2022): Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects. In *Results in Engineering* 13, p. 100330. DOI: 10.1016/j.rineng.2021.100330.

Pringle, Adam M.; Oberloier, Shane; Petsiuk, Aliaksei L.; Sanders, Paul G.; Pearce, Joshua M. (2020): Open source arc analyzer: Multi-sensor monitoring of wire arc additive manufacturing. In *HardwareX* 8, e00137. DOI: 10.1016/j.ohx.2020.e00137.

Taşdemir, Ahmet; Nohut, Serkan (2020): An overview of wire arc additive manufacturing (WAAM) in shipbuilding industry. In *Ships and Offshore Structures* 16 (7), pp. 797–814. DOI: 10.1080/17445302.2020.1786232.

Ya, Wei; Hamilton, Kelvin (2018): On-Demand Spare Parts for the Marine Industry with Directed Energy Deposition: Propeller Use Case. In Mirko Meboldt, Christoph Klahn (Eds.): Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017. Cham: Springer International Publishing, pp. 70–81.