

hybrid manufacturing of a hollow ship's propeller – investigation from material characterization to implementation*

Christian Klötzer-Freese¹, Tobias Kruse¹, Mohamad Khalil¹, Lars Greitsch¹

¹ Mecklenburger Metallguss GmbH, Waren, Germany

ABSTRACT

The development of new manufacturing technologies is opening new prospects to produce components of maritime systems. Particularly in the production of ship propellers with small diameters ($D < 5$ m), the established sand-casting process can only be used competitively to some extent as a technology in today's market. Additive manufacturing technologies have not only developed rapidly due to their ability to produce near-net-shape components with complex geometry, but also offer various advantages over conventional processes in the area of individual component production. In addition to the geometry and design freedoms, production times, material consumption and, as a result, costs can be reduced enormously for small batch sizes.

Ship propellers in the superyacht sector combine the restrictions of the conventional sand-casting process and the potentials of additive manufacturing. A propeller with four blades and a hollow blade structure is being developed as part of a research project. Together with Fraunhofer IGP and the University of Rostock, investigations were carried out into the WAAM process using copper-based alloys. In addition to the conventional pulsed arc process, the Cold Metal Transfer (CMT) process was used to investigate the three welding filler materials CuAl8Ni2Fe2Mn2 , CuAl9Ni5Fe3Mn2 and CuMn13Al8Fe3Ni2 . Results for a material and process characterization are shown based on buildup welds in the form of wall-shaped structures. Sensitive component areas were then selected to determine process variables for additive and subtractive manufacturing as part of the process development. Testing of different buildup strategies as well as different milling tools is also part of the investigations. To ensure a reduced core drop load on the hollow structure, there is a continuous alternation between buildup welding and milling, both on the external and internal surfaces. A techno-economic comparison between the manufacture of the demonstrator propeller using the WAAM process and sand casting is presented in conclusion.

Keywords

Additive manufacturing, wire arc additive manufacturing WAAM, mechanical testing, path planning.

1 INTRODUCTION

Additive manufacturing technologies (AM) have not only developed rapidly due to their ability to produce near-net-shape components with complex geometry, but also offer various advantages over conventional processes in individual component production. In addition to the geometric and design freedom, production times, material consumption and, as a result, costs can be reduced enormously for small batch sizes. According to Greitsch and Klötzer (2019), the development of new manufacturing technologies opens new perspectives for the production of components of maritime systems, particularly in the foundry industry.

Components of maritime systems that are exposed to salt water are often made from corrosion-resistant copper alloys. Casting processes are usually used for propulsion system components, such as propellers, due to the component size and complexity. The cast blank is mechanically processed into the finished product. With the development of additive manufacturing (short: AM) processes, the possibilities for manufacturing such components are expanding. AM makes it possible to design components with internal hollow structures. This reduces component mass and saves material costs. AM technologies can also increase the flexibility of the manufacturing process, as manual, time-consuming work in one-off production is reduced. However, there are risks associated with the welding process, the resulting material behavior of the material and ensuring/monitoring the quality of the components.

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. Specifically for shipbuilding, Tasdemir and Nohut (2020) provides an overview of WAAM technologies and discusses 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 overviews of the WAAM process can be found in Chaturvedi et al.

(2021), Jafari, J et al. (2021). Few researchers, such as Rauch et al. (2021), Babu et al. (2021) Ya & Hamilton (2017), have focused solely on the manufacture 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 intermediate or downstream machining processes.

2 MATERIALS AND METHODS

The milling and welding tests presented were carried out fully mechanized within a robot-assisted machining cell consisting of a welding system, manipulators, electro spindle 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. Two different arc modifications from Fronius are being investigated for the additive manufacturing of propeller geometries. One is the Pulse Multi Control process (PMC), which is characterized by a pulse process with minimal short-circuit current in the droplet transition. Weld penetration and arc length stabilizers ensure higher weld seam quality and higher welding speeds in the application. The second process is cold metal transfer (CMT). This short arc is characterized by an active, mechanical return movement of the welding rod during the short-circuit phase. This specific type of droplet detachment ensures a lower short-circuit current and therefore less energy input into the component and reproducible seam geometry. The CMT process is widely used in additive manufacturing and is therefore the focus of the following results.

Table 1: Process parameters used for WAAM

Parameter	Value
Wire diameter	1.2 mm
Heat input	0.5 kJ/mm
Robot travel speed	7,0 mm/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

The welds were made on EN 1982 CC33G CuAl10Fe5Ni5-C substrate plates, 350 mm × 100 mm × 30 mm, taken from the riser area of ship propeller castings. The three welding consumables with different filler metals used are listed in Table 2. To keep the filler metal designation as short as possible, only the main alloying element is given below, see filler metal designation in bold in the first column of Table 2.

Table 2: Basic chemical composition of materials used according to filler metal manufacturer

welding consumable: solid wire	Al in wt%	Fe in wt%	Mn in wt%	Ni in wt%
ISO 24373 – S Cu 6327 CuAl8Ni2Fe2Mn2	8.0	2.0	2.2	2.2
ISO 24373 – S Cu 6328 CuAl9Ni5Fe3Mn2	8.5	3.5	0.8	4.5
ISO 24373 – S Cu 6338 CuMn13Al8Fe3Ni2	7.5	2.5	13.0	2.0
Ship Rules – IACS W24-Cu3	7.0 - 11.0	2.0 – 6.0	0.5 – 4.0	3.0 -6.0
Ship Rules – IACS W24-Cu4	6.5 – 9.0	2.0 – 5.0	8.0 - 20.0	1.5 – 3.0

For subtractive manufacturing, a high-frequency milling spindle ES919 from HSD with compressed air-controlled quick clamping device is also installed at the end effector of the robot. The collet chuck with HSK-F63 hollow shank taper can be used to examine various tools for mechanical machining.

The full-size and scaled investigations were carried out using the example of a fixed pitch propeller (FPP), which is shown in Figure 1. The propeller with a diameter of 1.04 m has four blades.

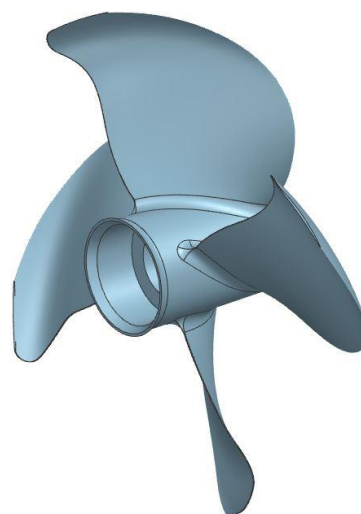


Figure 1: Design of the fixed pitch propeller

The path planning for the additive and subtractive processes was implemented using the DCAM software from S.K.M. Informatik GmbH. In addition to the manipulation of the various tools (welding torch, milling cutter), the path planning also includes the control of the additional axes and process parameters. Finally, the components were measured using stripe light projection with the ATOS 5 from GOM and analyzed using best fit strategies in GOM Inspect Pro.

3 MATERIAL CHARACTERISATION

Wall structures of 300 mm × 200 mm × 30 mm (length × height × thickness) were fabricated to determine the mechanical-technological properties of buildup welded structures. The three filler materials were each welded to a substrate plate using the CMT and PMC processes. Multiple welding beads were placed side by side for each welding layer to provide sufficient wall thickness. The welding sequence was alternated and reversed after each layer. End crater filling times were provided to avoid end craters. The welding parameters are given in the previous section. The first three layers were created with the PMC mode because of its higher energy input into the base material. For the CMT wall structures the process was switched to CMT after the three layers.

To determine the directional dependence of the properties, circular tensile specimens of shape A ($\varnothing = 14$ mm) according to ISO 50125 were taken from the structure in two different orientations. The vertical sampling corresponds to the Z-axis, which also represents the build-up direction. The horizontal samples were taken in the X direction, which corresponds to the direction of movement and welding, see Figure 2.

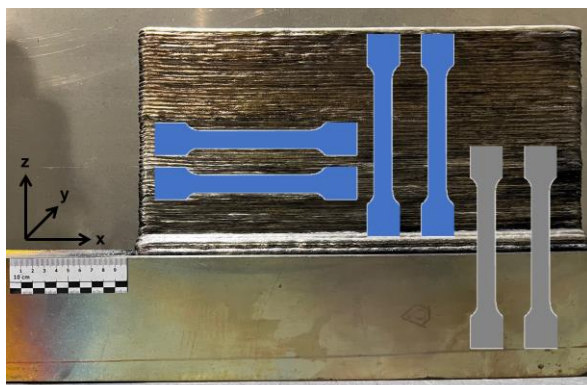


Figure 2: Sampling plan for tensile test specimens from wall structure; blue = additively manufactured area, grey = transition between casted material and additively manufactured structure

In addition to analyzing the static strength and ductility of the filler material, the transition area between the substrate plate and the filler material was also investigated. Due to the homogeneous structure, centrifugally cast parts made of CuAl9.7Ni4.5Fe3.8 were used as substrate plates.

Table 3: Average values of yield strength, tensile strength and elongation at break of the individual specimen orientations in the quasi-static tensile test of CuAl8Ni2Fe2Mn2

Welding process variant and extraction direction	Yield strength $R_p 0,2$ [N/mm ²]	Tensile strength R_m [N/mm ²]	Elongation A5 [%]
CMT horizontal	205	432	40.6
CMT vertical	191	408	43.5
PMC horizontal	219	477	48.4
PMC vertical	200	426	38.4
CMT transition area	201	418	20.5

Table 4: Average values of yield strength, tensile strength and elongation at break of the individual specimen orientations in the quasi-static tensile test of CuAl9Ni5Fe3Mn2

Welding process variant and extraction direction	Yield strength $R_p 0,2$ [N/mm ²]	Tensile strength R_m [N/mm ²]	Elongation A5 [%]
CMT horizontal	393	707	28.3
CMT vertical	384	678	19.8
PMC horizontal	402	694	25.2
PMC vertical	403	684	19.7
CMT transition area	332	637	14.1

Table 5: Average values of yield strength, tensile strength and elongation at break of the individual specimen orientations in the quasi-static tensile test of CuMn13Al8Fe3Ni2

Welding process variant and extraction direction	Yield strength $R_p 0,2$ [N/mm ²]	Tensile strength R_m [N/mm ²]	Elongation A5 [%]
CMT horizontal	398	682	28.8
CMT vertical	396	639	16.3
PMC horizontal	414	683	28.4
PMC vertical	404	675	27.1
CMT transition area	323	647	10.4

In the case of CuAl8 buildup structures, only marginal differences in the strength behavior of the different sample directions can be observed, with the strength level

being significantly lower compared to the other filler metals. The differences in the strength behavior of the different sample directions are more pronounced in the CuAl9 samples. The effect of the welding process and removal direction of the sample on the elongation at break should be emphasized here. The tensile strength of CuMn13 specimens taken transverse to the direction of weld (vertical) tend to show higher values of around $R_m = 680$ MPa than tensile specimens taken in the direction of weld (horizontal). These tend to have lower tensile strengths. The elongations at break A5 are similarly reversed, so that the longitudinal specimens show the better ductility. In the investigation of the transition area to the cast material, the achieved tensile strengths are about 5% lower for all welding consumables. Similarly, significantly lower elongation at break can be recognized. When examining the transition area, fracture occurred in the base material for all materials.

Further investigations on the absorbed impact energy with the Charpy pendulum impact test according to ISO 148-1 for V-notch test specimens, corrosion tendency by means of fatigue immersion tests and investigations on the fatigue properties are listed in Andreazza, P. et al (2023).

4 HYBRID PROCESS CHAIN FOR ADDITIVE AND SUBTRACTIVE MANUFACTURING

The additive manufacturing of large-format components requires an adaptation or extension of the classic process chain. The additive process chain comprises three phases: the development phase (preprocessing), the manufacturing phase (production) and the post-processing phase (post-processing). The first phase, the development phase, consists of CAD design, CAE simulation and data exchange. CAD design and simulation with CAE tools is an iterative process that is repeated several times, especially in additive manufacturing, due to the high optimization potential. At the end of the development phase, data is exchanged in the form of CAD formats (STEP, IGES, STL), which can be further processed in the subsequent process steps. The second phase, the production phase, includes preparation for the WAAM process, process monitoring and intermediate processing. Preparation describes the creation of the robot program through offline programming. The slicing process known from 3D printing also takes place in this step. The layers to be processed in production are created according to the product-, material- and process-specific requirements. This is followed by additive manufacturing and process monitoring, in which the process is monitored to ensure error-free production. Depending on the geometry and material parameters of the welding process, mechanical processing of the intermediate layers is required. The monitoring process guarantees that this is kept to a minimum. In the post-processing phase, mechanical finishing is carried out by grinding, milling, and removing auxiliary structures. Finally, quality assurance is carried out, which documents the finished component in such a

way that the finished component can be delivered with all product documentation.

4.1 Development phase

To prepare a basis for the propeller model with hollow structures, a full propeller was first designed and constructed according to classification guidelines. A mesh study determined the appropriate meshing strategy for the solid propeller for the subsequent strength calculation. Based on this model, a hollow propeller with a minimum wall thickness was initially designed and an adapted meshing was also determined for this. A simulation of the hollow propeller revealed a high stress concentration in the blade root area, which could be reduced by introducing bars. A sufficient strength result was not possible for blades with a single effective wall thickness of 5 mm, which is why the blade wall was thickened to a double weld seam of 8.5 mm (overlapping of two weld strips).

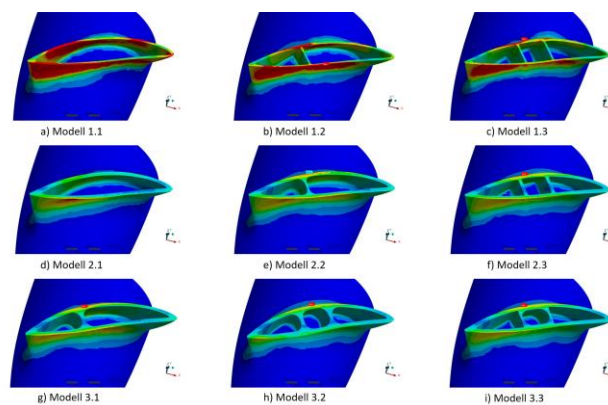


Figure 3: FE simulations of different AM designs

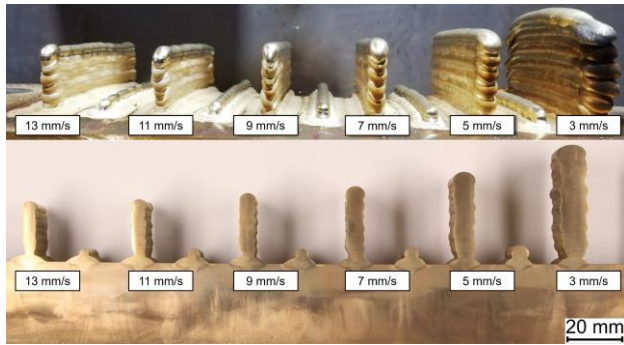
It was shown that large edge fillets between the propeller walls and the inner structure make a significant contribution to the strength of the component, while a simple web thickening achieves significantly less success. The efficiency of the various structures was defined based on a ratio of material increase to strength increase in relation to the hollow propeller. However, the implementation of a hollow structure is also strongly dependent on the local blade section thickness. A hollow structure can rarely be implemented in the blade tip area. Furthermore, parametric modeling is necessary for the transition area between the solid structure and the hollow structure, which also considers the specific material properties and manufacturing options.

4.2 AM Production phase

The geometric shape of a propeller blade is defined in all three dimensions. Welding production is particularly demanding in terms of propeller diameter, number of blades, blade area ratio and pitch ratio. With the aim of maximizing the deposition rate and minimizing post-

processing, the influence of selected parameters on the formation of the seam geometry is particularly important. For this reason, tests were carried out to investigate the influence of the travelling speed of the robot-guided welding torch. With constant welding parameters, the speed of the path movement led to a significant bead geometry for the different filler materials, see figure.

Figure 4: Influence of the feed rate on the weld seam geometry



geometry

The heights and widths of the weld seam in the welded structures were recorded using metallurgical cross-sections. Furthermore, the ratio of the total wall width to the effective wall width was determined based on [Chernovol et. al] to obtain a statement about the extent of downstream material removal.

Table 6: Average values of the width, height and overhang of the weld seams as a function of the feed rate of CuAl8Ni2Fe2Mn2

Feed rate of the welding torch [mm/s]	Height of the weld bead [mm]	Width of the weld bead [mm]	Overhang of the weld bead [mm]
7	1.99	8.02	0.69
9	1.74	7.55	0.68
11	1.53	6.56	0.64

Table 7: Average values of the width, height and overhang of the weld seams as a function of the feed rate of CuAl9Ni5Fe3Mn2

Feed rate of the welding torch [mm/s]	Height of the weld bead [mm]	Width of the weld bead [mm]	Overhang of the weld bead [mm]
7	1.87	8.17	1.06
9	1.63	7.54	0.98
11	1.46	7.94	0.60

Table 8: Average values of the width, height and overhang of the weld seams as a function of the feed rate of CuMn13Al8Fe3Ni2

Feed rate of the welding torch [mm/s]	Height of the weld bead [mm]	Width of the weld bead [mm]	Overhang of the weld bead [mm]
7	1.82	10.87	1.01
9	1.72	9.26	0.75
11	1.56	8.34	1.24

These investigations show that the movement speed of the robot-guided welding torch has a significant influence on the weld seam height and width. Furthermore, the characteristic formation of the seam geometry in aluminum bronzes leads to a uniform bead overhang even with varying feed speeds. With manganese bronze, on the other hand, the movement speed has a significant influence on the seam overhang and therefore also on the waviness of the welded structure.

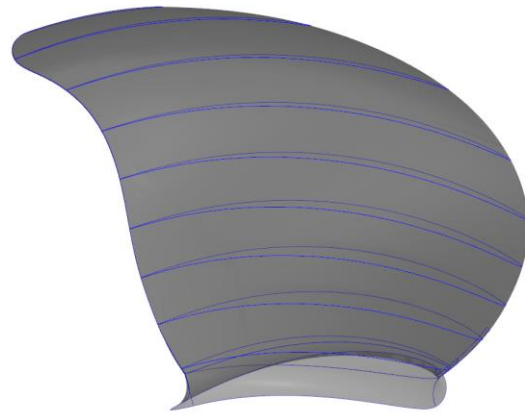


Figure 5: Different blade sections for different propeller radii

The figure 5 shows various blade sections with increasing propeller diameter. In the transition area to the hub, the blade geometry shows greater blade section thicknesses. The blade section thicknesses are smaller in the tip area. Together with the skew and rake of the propeller, these geometries have a significant influence on the path planning for additive and subtractive manufacturing.

4.2.1 Investigation of different path planning strategies

A smaller series of the yacht propeller with a diameter of 0.68 m was selected for testing and investigating different path planning strategies. The blade geometries were welded onto a hollow cylinder (diameter, height, wall thickness) manufactured by centrifugal casting. The first five layers for the connection to the hub body were realized with the same strategy and welding parameters

for all blades. A defined strategy was implemented for each blade.



Figure 6: different path planning strategies for build-up welding using the example of a sheet cut/layer

Strategy 1 includes center lines of the blade cuts and additional parallel paths in the direction of the pressure and suction side of the propeller. The advantages of this strategy are the short production time, low material usage and low surface waviness. On the other hand, the transition between individual paths in one layer was undersized in the blade surface. With the second strategy, the blade section for each layer is created by oscillating in a rectangular pattern. In some cases, no material was provided for the sharp edges of the leading and trailing edges. This led to increased undersize in the outline contour of the blade. In addition, this strategy is characterized by higher post-processing costs and longer production times compared to the other strategies. The third strategy is based on the contour of the pressure side. Additional parallel displaced tracks towards the suction side of the propeller fill the blade sections. This leads to near-net-shape production of the pressure side of the propeller. However, there were also undersize in the transition between the individual paths. The fourth strategy involves extensive CAD operations in advance. Targeted trimming of the contour and surface operations made it possible to implement special filling strategies for the blade cutting contour. Specifically, oscillation between uv-support contours was implemented. This led to a longer production time, but to a uniform oversize in the blade surface and outline contour. The fifth strategy was developed to realize a hollow structure in the propeller. In this strategy, only the respective contour of the blade section was followed. In the case of sharp edges, the strategy led to material overlaps due to non-compliance with minimum distances between two welded paths. This led to increased effort in layer correction through mechanical processing. In addition, the path had to be adapted according to the accessibility of the milling cutter for machining the inner contour.

Table 9: Comparison of the different path planning strategies for additive manufacturing of one blade

strategy	Ratio of welding movement to secondary movements [%]	Secondary times after each layer [s]	Total production time [h]	Total weight [kg]
1	81.9	33	8.19	15.26
2	91.3	83	9.81	17.99
3	85.2	53	10.48	18.12
4	95.3	63	13.01	29.61
5	94.4	53	10.45	20.12

An important parameter for determining the real build-up rate is the ratio of welding movements to secondary movements. The secondary movements are made up of positioning movements, infeed, and lift-off movements of the welding torch. Strategies 1 and 3 have a lower ratio, as each layer consists of several individual welding paths. The increased number of start and end points of the welding paths in a layer can lead to irregularities and errors in the material build-up. Strategies 2 and 4 are filling strategies that require increased non-productive times after each layer. In addition to welding-related non-productive times (gas pre-flow and post-flow times, etc.), these include longer cooling times to maintain the required intermediate layer temperature. The different strategies lead to different production times and component weights in the welded state. Strategy 5, which implements a simple outer contour run for a hollow structure, should be emphasised. With a constant weld seam geometry (track width), this leads to material accumulation in the propeller tip area, as the contours/paths are very close together. In this case, significant adjustments to the path planning or a variable track width of the weld seam geometry must be implemented.

4.2.2 Investigation of tools for robot-assisted milling

The hybrid production of a hollow ship's propeller requires various milling operations. Firstly, the inner contour must be milled during additive manufacturing to ensure a notch-free surface. Furthermore, the component or layer height may need to be corrected during the additive process. This can be caused by manufacturing deviations or deformations due to residual stresses. Finally, the outer contour is machined after welding.

Table 10: selected Tools and parameters for robot-assisted milling

<i>tool</i>	v_c	a_e	a_p	n
<i>solid carbide radius copy milling cutter H8E11118-E12-12</i>	10 mm/s	2 mm	1 mm	12.000 1/min
<i>solid carbide radius copy milling cutter H8E11118-E12-12</i>	30 mm/s	1 mm	1 mm	12.000 1/min
<i>end mill cutter MC268-10.0A3LC-WJ30UU</i>	10 mm/s	1 mm	2.5 mm	12.000 1/min
<i>Circular segment cutter MD838-16E8P301000-WJ30RA</i>	10 mm/s	1 mm	0.5 mm	10.000 1/min
<i>form milling cutter 347463</i>	10 mm/s	0.5 mm	4 mm	8.000 1/min

The tests showed the feasibility of robot-assisted milling for various tools, figure 7. Even in the temperature range $> 100\text{ }^\circ\text{C}$, the tools were able to fulfil the requirements for subtractive machining and the required surface qualities. The milled surfaces were qualified using roughness measurements and reference standards. The specially developed milling cutter for machining the inner contour (form milling cutter No. 347463) increased the process stability. Due to the special shape of the tool, the last layer applied is only machined by a few 0.1 mm and already welded layers are trimmed according to the geometry requirements. This results in a consistent weld seam geometry and prevents irregularities in the bonding behaviour to the already welded layers.



Figure 7: Indexable insert milling cutter for mechanical machining to correct the layer height

5 ADDITIVE MANUFACTURING OF A SHIP'S PROPELLER

The yacht propeller was designed using a hybrid construction method. The starting point is a hub base body onto which the blade geometry was welded. The hub blank was manufactured using the sand-casting process. To realize a defect-free connection of the weld seam to the hub body, 2 mm of material was removed from the cast surface in a machining operation. The hub body was then measured using structured light projection and the actual geometry was imported into the path planning software in the form of an STL file. At the same time, three selected measuring points on the hub body were measured with the assistance of the robot in order to determine the exact position in the clamping fixture. The welding process and associated motion sequences were then planned in the robot-assisted machining cell. Based on the investigations and their analyses in the chapter, variant X was implemented. Different additional allowances were also provided for each blade. Here too, layers 1-3 were welded using a PMC arc. As the hub has a conical outer surface, a different amount of material was applied in the area of the blade geometry. In the 4th layer, the selected hub area had a constant diameter. The individual layers were then applied radially using a CMT arc. To ensure a uniform and optimized heat input into the rotationally symmetrical component, the layers of individual blades were joined together to form a layer information. This meant that all four blades were additively manufactured in each layer. Pre-defined waiting times between the layers ensure that the required interlayer temperatures are maintained. Figure 8 shows the final propeller as-fabricated state by additive manufacturing.



Figure 8: propeller as-fabricated state by additive manufacturing

Finally, the hybrid manufactured propeller was measured by means of fringe light projection and compared with the CAD model. The results are shown in Figure 9. These are typical of the results expected for large multi-axis WAAM parts. A positive value represents an oversize between the actual value and the target value, whereas a negative value represents an undersize between the actual state and the CAD nominal geometry. The effects of thermal behavior due to manufacturing on the accuracy of the WAAM part can also be identified. The different offsets to the nominal geometry in the path planning are also reflected in the measurement results. The additional allowance in the path planning varies between 1 - 4 mm depending on the blade to analyze the influence on the overall result and ensure an optimum allowance. The optimum allowance characterizes a minimum machining allowance while maintaining all tolerances. It should be emphasized that no area of the blade geometry is undersized. The results also show that WAAM can establish itself as a near-net-shape process with minimal post-processing allowance. The final surface of the propeller is produced by downstream processes such as milling and grinding.

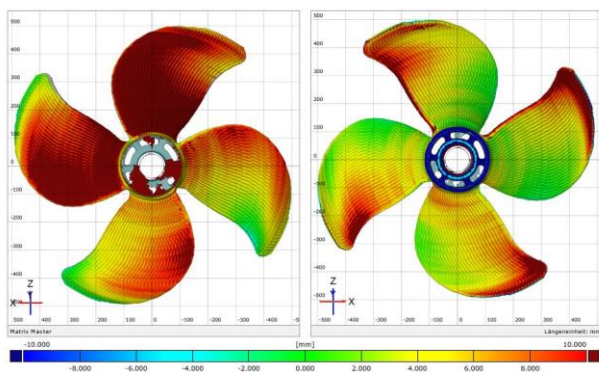


Figure 9: Comparison between CAD model and scan of the propeller for the pressure and suction side

6 TECHNO-ECONOMIC COMPARISON SELECTED MANUFACTURING STRATEGIES

As part of the research project, various manufacturing options were analyzed and evaluated regarding technical and economic criteria. Conventionally, ship propellers are manufactured using the sand-casting process. A detailed description of the production process is shown in Klötzer et al. (2022). A model is required to produce a sand mould. In propeller production with smaller quantities, a wooden model of a blade is generally used to produce the sand-casting mould by moulding the blades. Model plates can be used for smaller propellers. After the mould has been made and a drying phase has taken place, the molten metal is cast. Once the material has solidified, the casting blanks are unpacked from the moulds and cleaned. The components are then machined. This classic production method serves as a reference for evaluating other process

variants. Another manufacturing option is the elimination of the model and the direct additive manufacturing of the sand-casting mould using the binder jetting process. The third variant is the WAAM of the complete propeller. The hub body is welded onto a substrate plate layer by layer, followed by the separate blades. In the fourth option, a hybrid solution is realized. The hub body was manufactured using a casting process and the individual blades were welded on. The following illustrations show the different processes in relation to the conventional sand-casting process for single part production. Times and expenses for internal and external transport were not considered. Also, no costs for the disposal of the destroyed moulds were included.

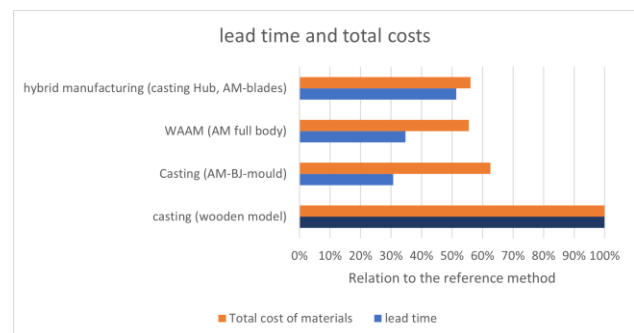


Figure 10: Lead time for different production variants

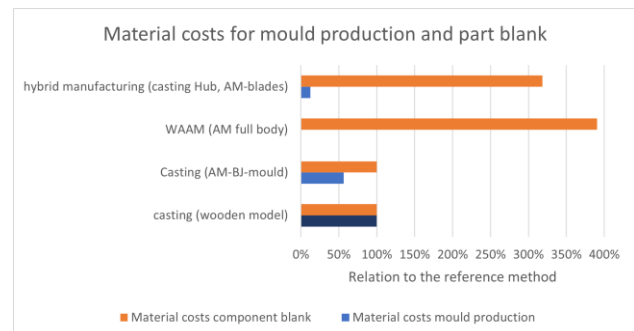


Figure 11: total costs of materials for different production variants

The use of additive manufacturing processes in propeller production has reduced throughput times by at least 50 % for all production options. This is largely due to the production time for the wooden model plates. It was also possible to reduce the total material costs in the context of single-part production for all additive processes. A closer look at this application scenario shows that the costs of an additively manufactured sand mould are lower than those of a conventional sand mould. However, if one considers the material costs for the raw part produced, the material costs for deposition-welded structures are significantly more expensive. This is due to the large price difference between the metal as a block material and the welding wire.

7 CONCLUSIONS

The research project presented here has carried out initial investigations into the additive manufacturing of copper-based materials for use in marine structures. The test specimens were produced in a robotic welding cell using the WAAM process.

Simple wall structures were fabricated by MIG welding with CMT and PMC technology using three filler materials CuAl8Ni2Fe2Mn2, CuAl9Ni5Fe3Mn2 and CuMn13Al8Fe3Ni2 and specimens were tested to analyze the static strength. Different specimen orientations were considered. The welding direction was alternated with two weld beads per layer. All three materials were welded with similar welding parameters, interpass temperatures and arc modifications. The influence of the feed rate on the weld geometry was also investigated using a macroscopic cross section to determine the height, width and overhang of each weld bead. For the additive manufacturing of a ship's propeller, different torch path planning strategies were analyzed and evaluated using parameters. In addition, different milling cutters for machining the inner, outer and intermediate layer contours were demonstrated. Specifically for machining the inner contour, a cutter was developed and tested that minimizes the final weld layer to ensure process stability in the uniform layer structure. In addition, a yacht propeller was manufactured additively with an optimized path planning strategy and the resulting 3D surface profile was optically recorded. Finally, the propeller was used as an example to analyze and evaluate different manufacturing methods in terms of material costs and process times.

The following can be summarized:

- a) The CMT process is suitable for the WAAM process for copper based materials. However, these materials are sensitive to exceeding or falling below the parameter range.
- b) A directional dependence of the strength behaviour was observed. In addition, when the transition area between the cast and build-up welded material was examined, fractures occurred in the cast material for all materials.
- c) The change in feed speed has a significant influence on the weld seam geometry. The values determined are important indicators for a resource-saving overall process. With the aim of near-net-shape production and low machining allowance, the effort required for mechanical reworking is reduced.
- d) FE simulations were carried out for various AM designs. The realisation of a hollow structure for the selected propeller is not recommended due to the low blade section thicknesses.
- e) Various path planning strategies for build-up welding of propeller geometries were presented and compared using parameters.

- f) Various milling tools are suitable for robot-assisted milling of additively manufactured structures by adjusting the parameters.

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