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MariClad - Repair of ship propellers using additive manufacturing methods

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Abstract. This project aimed to develop reliable and reproducible technologies for the repair of large-volume maritime components using the additive manufacturing processes arc direct energy deposition (DED-ARC), laser wire direct energy deposition (DED-LW), and laser powder direct energy deposition (DED-LP). With the help of these additive manufacturing processes, defective maritime components were to be reconditioned by applying material directly to the affected area. The DED-ARC process was carried out using a filler material similar to casting alloy $CuAl_8Ni_4Fe_2Mn_2$. The large-volume structure of the components demonstrated a process free of irregularities, eliminating the need for any subsequent heat treatment. Using the same filler material, layers free of irregularities were generated with the DED-LW process. For this type of additive manufacturing, heat treatment was found to be necessary to reduce residual stresses. For the DED-LP process, the powder alloy $CuAl_{10}Fe_5Ni_5$ was atomized using an in-house metal powder production plant. The aim was to produce a metal powder that was as spherical and free-flowing as possible. The samples produced using DED-LP were free of internal irregularities and did not require heat treatment. Following the successful completion of the research project, corresponding parameter sets are available for all three additive manufacturing processes. These developed parameter sets enable the repair of defective maritime components made from multi-material aluminum bronze.

1 Technical and technological objectives of the project

This project aimed to develop reliable and reproducible technologies for the repair of large-volume maritime components using the additive manufacturing processes of arc direct energy deposition (DED-ARC), laser wire direct energy deposition (DED-LW), and laser powder direct energy deposition (DED-LP). With the help of these additive manufacturing processes, defective maritime components, particularly propeller tips, could be reconditioned by directly applying material to the affected part of the propeller. This repair was to be carried out using a similar welding wire for wire-based additive manufacturing processes and a powder made from shavings of the bulk material for the laser powder energy deposition process.

A key objective was to reduce the repair and downtime of ships. For the development of repair technology using wire-based additive manufacturing processes, welding parameters and build strategies had to be developed that would enable a shaping build-up weld. By varying process parameters such as welding speed, welding voltage, laser power, and wire feed, the generated deposition welds must have a homogeneous microstructure free of irregularities. This was verified by both destructive and non-destructive testing conducted on standardized samples. Due to the nature of the additive manufacturing process, residual stresses occur in the material. The aim is to keep these residual stresses as low as possible.

2 Results

2.1 Requirements analysis

The selection of cast copper alloys for ship propellers is standardized by the relevant classification societies regarding chemical composition and minimum mechanical requirements. Currently, most ship propellers are manufactured from a nickel-aluminium multi-material bronze. Based on the chemical composition of the bulk material, the $CuAl_8Ni_4Fe_2Mn_2$ welding filler material, similar in type specified in DIN EN ISO 24373:2018-11, was selected for the wire-based additive welding processes.

For the additive manufacturing process based on a powder of the same type, remnants of a decommissioned ship's propeller with the bulk material being $CuAl_{10}Fe_5Ni_5$ were used. Internal characteristic values and quality features were defined for the production of the powder, as the corresponding standards and guidelines of the classification societies for additive manufacturing do not directly specify laser powder cladding or DED, primarily focusing on the laser powder bed fusion process. The metal powder should have a spherical structure and good flowability, with no adhesion of small particles to larger grains, known as satellites. The powder should have a particle size between 80 µm and 160 µm.

2.2 Direct energy deposition – Arc

The tests with DED-ARC were carried out using a Fronius TPS 600i welding power source with a standard 0° torch mounted on a KUKA KR 70 robot. The parameters were determined using simple geometries.

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The primary parameters varied were welding current, wire feed, and welding speed.

Table 1. Examples of parameter sets for DED-Arc

Wire feed speed	Welding current	Welding voltage	Welding speed
5 m/min	190 A	18,9 V	0,6 m/min
5 m/min	163 A	20,2 V	0,6 m/min
6 m/min	193 A	21,2 V	0,75 m/min

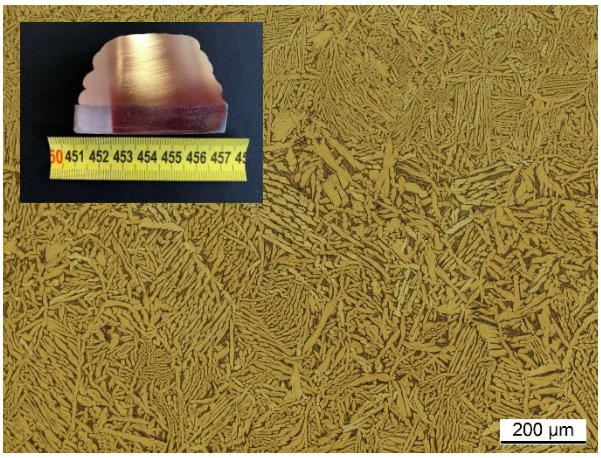

Fig. 1. Microsection of sample "163 A | 20,2 V" with primary α-phase

The analysis of the pure weld metal shows a fine-grained dendritic microstructure consisting of α-phase and β'-phase, where the α-phase occurs primarily, see Figure 1. Due to the layer offset by 90° various dendrite growth can also be seen in the micrograph. The material characteristics of the pure base material serve as the reference value for the tensile test. There are no significant differences regarding the tensile strength R_m and the yield strength $Rp_{0.2}$. However, the layer generated using DED-Arc shows a significant increase in elongation at break A. This can be explained by the low Fe content in the filler material, as the intermetallic κ phase in the form of Fe_3Al can form to a lesser extent here, which is a very hard and brittle phase. This is also reflected in the impact energy, as seen in Fig. 4.

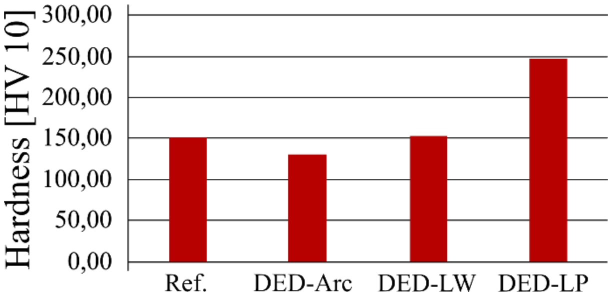

Fig. 2. Results of Vickers hardness testing

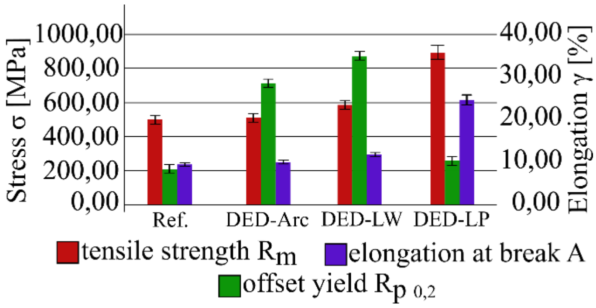

Fig. 3. Tensile test, n = 3

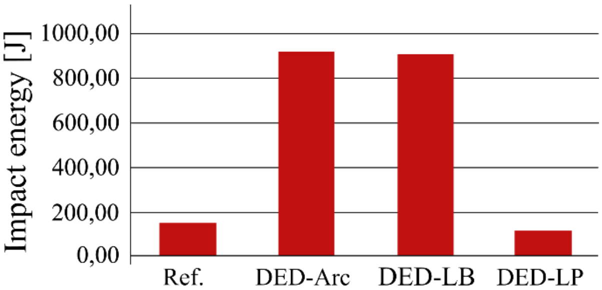

Fig. 4. Charpy impact test at room temperature, 23,9 °C

2.3 Laser wire direct energy deposition

The CoaxPrinter processing head (Precitec GmbH & Co. KG, Gaggenau-Bad Rotenfels) was used for DED-LW tests. This processing head has a coaxial wire feed and is designed for a maximum laser power of 6 kW, depending on the filler material used. A Trumpf TruDisk12002 (Trumpf SE & Co. KG, Ditzingen) disk laser was used as the laser beam source. The wire feeder unit Master-Feeder-System MFS-V3.1 from ABICOR Binzel was used to feed the 1.2 mm thick filler material. The processing head together with the wire feeding unit was mounted on the KUKA KR70 industrial robot.

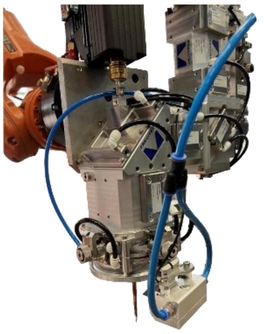

Fig. 5. KUKA KR70 robot with the Precitec CoaxPrinter processing head used for DED-LW

The parameters were developed using individual small, overlapping tracks. Essentially, parameters such as laser power, welding speed, and wire feed rate were varied. However, the laser power was only varied up to a maximum of 4000 W to avoid intense back reflections and an increased thermal load on the processing head.

Table 2. Examples of parameter sets for the DED-LW process

Wire feed speed	Laser power	Welding speed	Line energy
1,2 m/min	3.800 W	1,00 m/min	2,28 kJ/cm
1,5 m/min	3.800 W	0,40 m/min	5,70 kJ/cm
1,0 m/min	3.800 W	0,75 m/min	2,80 kJ/cm

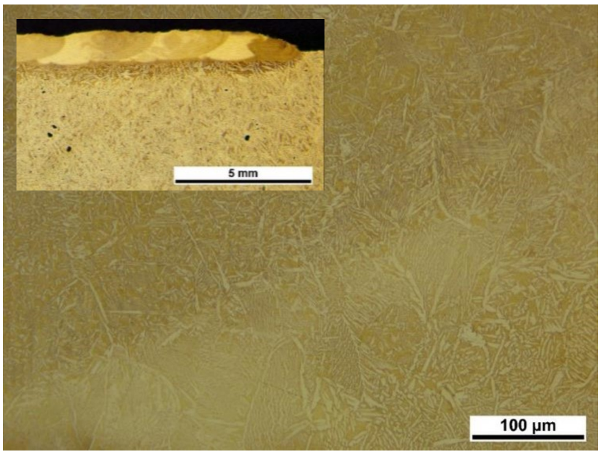

Fig. 6. Microsection of sample "Line energy = 5,70 kJ/cm" with very fine α-phase

In the first macro section, a layer bonding defect occurred. Adjusting the welding speed and reducing the wire feed speed can prevent this irregularity (see Figure 6). However, this led to a reduction in the layer height as well as the deposition rate. The following analysis of the macro section and microsection revealed no internal irregularities, so no further parameter adjustments were necessary. The microstructure is composed of fine dendrites, with the α phase outweighing the aluminium-rich β' phase. A comparison of the microstructure with the DED-LW sample shows that the dendrites are even finer in the DED-LW sample. This is reflected in the hardness values, see Figure 2.

2.4 Powder atomization for DED-LP

The BluePower AU1000 gas atomization system was used for powder production. Each atomization was carried out using a graphite crucible with a volume of 1,7 Liters. A free-fall nozzle was used. Both the melting of the material and the atomization were carried out using argon gas. On average, around 4500 g of metal shavings could be recycled with each atomization, as the maximum filling quantity of the crucible was exhausted. The metal residues were then molten at 1350 °C. Depending on the nozzle outlet and atomization pressure, different powder fractions could be produced. Thus, with a small outlet and high pressure, rather fine powders were produced. Outlets with a 1.5 mm to 2.0 mm diameter and a pressure of approx. 20 bar tended to produce coarser powder fractions. After atomization, an average of 4400 g of powder was removed from the system. The remaining approx. 100 g remained in the crucible as slag. After removing powder components that were too large and too small by sieving, a total of approx. 3900 g per each atomization of powder could be used for further processing using DED-LP.

Fig. 7. Crucible with bronze shavings (left) powder atomization (middle) DED-LP process (right)

The investigations of the different powder fractions showed that all powders have a spherical shape, and no satellites adhere to the larger particles.

2.5 Laser powder direct energy deposition

Like the DED-LW process, a very fine structure of dendrites was also formed during laser powder cladding Compared to the macro sections of the previous processes, the layer produced appears optically more matt.

Table 3. Examples of parameter sets for DED-LP

Powder feed rate	Laser power	Welding speed	Line energy
14,5 g/min	3.000 W	0,8 m/min	3,0 kJ/cm
11,0 g/min	4.000 W	0,8 m/min	3,0 kJ/cm
8,5 g/min	4.000 W	0,8 m/min	3,0 kJ/cm

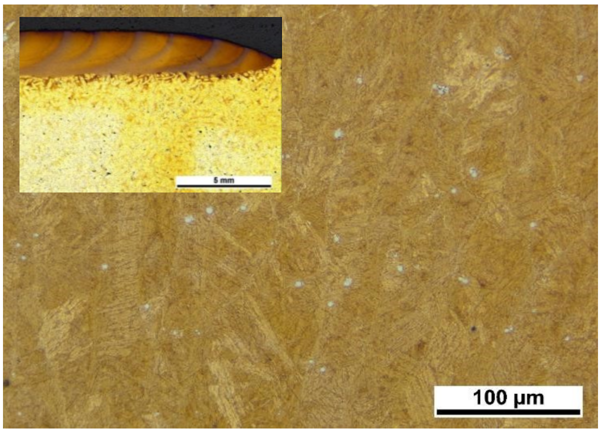

Fig. 8. Microsection of sample Powder feed rate = 11,0 g/min with very fine α-phase

No irregularities were detected during the evaluation of the macro sections and microsections, see Figure 8.

The assessment of the microsection showed that very small κ phases had also formed in the powder of the same type, like cast iron. These κ phases are very rich in iron and are formed due to the increased Fe content of the starting material. Compared to the samples with wire, the samples with the same type of powder have a higher β' phase and a smaller α phase. The primary β' phase, also known as β' martensite, results in high strength and low ductility of the material due to the structure of the martensite. This is also reflected in the mechanical properties, see Figure 2 to Figure 4. The reason for this high proportion of martensite lies in the rapid cooling rate/quenching temperature of the locally generated molten bath.

3 Discussion

After completing all investigations, the final parameter sets were developed for all three DED processes. These sets enable a wide spectrum of repair possibilities for defective maritime components made of multi-material aluminium bronze. In contrast to the initial objective that all three processes should be suitable for manufacturing large-volume components, it became apparent that DED-LW is only suitable for limited part sizes, at least with the system components used at SLV M-V GmbH. The main obstacle is the increased, sporadic interruption of the process when generating individual layers. However, the DED-LW process is particularly suitable for repairing small local irregularities on large or small objects where a high degree of shape accuracy must be maintained, such as the repair of a propeller hub, see Figure 9.

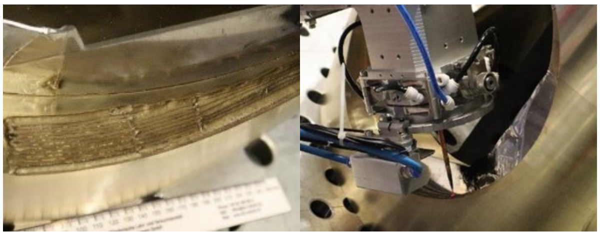

Fig. 9. Repair of a propeller hub (left); finished generated layer using DED-LW (right)

On the other hand, both Wire Electric Arc Energy Deposition and Powder Laser Energy Deposition demonstrated a low error rate when creating individual layers, indicating that these processes are well suited for manufacturing or generating large-volume components. Analysing the mechanical characteristics of the manufactured samples using different developed parameters reveals significant differences. In the DED-Arc process, higher values were achieved for impact energy and elongation due to the similar filler material. Yet the hardness and tensile strength could be significantly increased when using DED-LP.

During research, new questions arose that could not be fully answered within the project framework. These relate to powder development and the DED-LP process. One of the examples is, that it was not possible to clarify what influence the addition of certain elements would have on the mechanical properties using the DED-LP process. Furthermore, no investigations could be carried out using different processing optics such as broad beam optics. The use of such components could further increase application quality and performance, as well as minimize production costs.

Planned lectures and trade fairs:

- 77th IIW Annual Assembly and International Conference on Welding and Joining 2024, Rhodos, Greece
- DVS Congress 2024 in September
- Conference 14th Rostock Welding Days 2024 in November