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RESEARCH PAPER

Arc-based additive manufacturing of steel components—comparison of wire- and powder-based variants

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Abstract
Additive manufacturing of components, layer-by-layer, offers several advantages compared to conventional production technologies such as higher material utilization efficiency and increased geometric possibilities. Arc-based additive manufacturing processes have the additional advantage of an almost unlimited assembly space, higher deposition rates, and an improved utilization factor of raw materials. Up to now, the gas metal arc welding variant, cold metal transfer (CMT), and other wire-based process combinations have been used predominantly in this field. Disadvantages of wire-based methods are the restricted availability of different types of wire consumables, the wire feed rate directly coupled to the heat input, and the lack of possibility to create multi-material structures with one heat source in-situ. Within this work, the 3D plasma-metal deposition (3DPMD) method, based on a plasma powder deposition process is introduced. 3DPMD has some advantages compared to the established plasma powder process and wire-based CMT process. Basis for this evaluation is the production of geometrically complex structures by the different methods (CMT & 3DPMD) and their subsequent characterization. Structures are fabricated using welding robots with the path control directly generated from the CAD files. In summary, 3DPMD offers increased flexibility in terms of material selection as well as the possibility to build graded structures. By using subroutines realized from a special postprocessor, it is possible to generate metal structures with standard welding robots directly from the CAD drawings. Microstructures and properties are directly related to the process and therefore material-process-property relationships are discussed within this work.

Keywords Additive manufacturing · Plasma · CMT · 3DPMD · SDSS

1 Introduction

The manufacturing of workpieces by the layer-by-layer application of shapeless material by a production process is referred as additive manufacturing (AM). In the past, the technology has been applied especially for small series and prototype production [1]. Especially the demand of aerospace industry to design lighter and customized components opened up entirely new markets for AM. One way to reach this, is the bionic adaption of the parts. Classic subtractive manufacturing processes cannot produce nature-like parts. Only additive manufacturing processes can produce complex freeform structures and open up the possibility for implementation of the bionic optimization in the production process.

An annual increase in global sales of 35% (2014) in the AM sector to US$ 4.1 billion shows the willingness of the industry to use AM technology. The technologies currently dominant in the market for the AM of metal parts are selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM). These beam-based methods are based on the principle of layer-wise remelting of high purity metal powders. The high demands on the quality of the powder with regard to grain size, degree of agglomeration, and moisture lead to a very complex and price-intensive development and production. For this reason, the available material spectrum is very limited. Characteristic of the methods are low layer thicknesses (up to 200 μm), slow building rates (up to

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105 cm^3/h), limited component size and space, the need for additional laser protection or vacuum devices, and high investment costs [2].

1.1 Arc-based additive manufacturing

In the case of robot-assisted arc-based additive manufacturing, the described disadvantages of the beam-based methods are not or only relevant to limited extent. The heat-reduced and process-controlled gas metal arc welding process ColdMetalTransfer (CMT) is a widely applied method in the field of additive manufacturing [3–6]. The characteristic detection of the short circuit with the subsequent reversal of the wire direction leads to a high-dynamic resolution of the short-circuit bridge. This enables a more sputter-free, more stable, and heat-reduced process compared to the standard dip transfer arc welding. After the termination of the short-circuit bridge, the wire direction is reversed again and the sequence restarts [7]. Advantages of the arc-based process with wire are the high build rate up to 1500 cm^3/h [2], the available large material diversity, as well as the low process complexity.

One approach of component optimisation is the consideration of the real loads. In addition to the possibility of optimizing the components design, there is also the option to a targeted adaption of the material properties. A classic example of this is the improvement of the wear resistance of surfaces by coating through plasma-transfer arc welding (PTA). A mechanically constricted tungsten inert gas (TIG) arc melts the base material powder in PTA welding. The metal powders are supplied by a powder conveyor and transported via a carrier gas and can be regulated independently to the process. In coating, classically up to two materials (matrix material and reinforcing particles) are fed into the process and processed in one layer [8]. An example of this is the introduction of tungsten carbide as reinforcing particles into an iron-based matrix. The advantages (build rate > 2000 cm^3/h, low demands on the powder quality, great material diversity) also make the process interesting for additive manufacturing.

1.2 3D-plasma-metal deposition

The newly developed process variant 3D plasma metal deposition (3DPMD), based on a classical PTA process, is able to generate three-dimensional objects. 3DPMD is a robot-supported and arc-based process that combines the advantages of the classical PTA with new technology (Fig. 1).

The generation starts with the virtual slicing of the CAD part into defined layers. Based on the respective contour information of the layer, a robot program is generated automatically, which contains both—the path movement and the necessary welding commands. During the subsequent AM-construction process, up to four powders, which can be different in terms of material and powder fraction, can be mixed within one layer, respectively, in the same melt pool. This allows a targeted adaptation of local properties (microstructure, mechanical-technological properties, porosity, etc.) to the real loads.

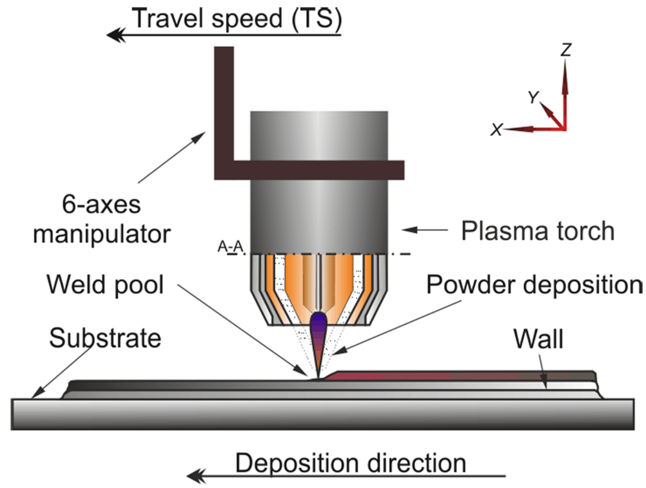

Fig. 1 Process setup 3DPMD

The aim of the work is to qualify the newly developed process 3DPMD and to compare it with the already well established wire-based CMT process. For this reason, the external shape, the heat input, and the properties are determined and evaluated by means of a common demonstrator.

2 Materials and experimental procedure

In addition to the external shape and the process behavior, a significant evaluation criteria for the process comparison is the amount of heat input and the thermal history of the component.

In order to detect possible tempering effects, property changes, etc., the temperature sensitive austenitic-ferritc superduplex alloys 1.4410 (powder) and 1.4501 (wire) were used within this analysis.

Very high cooling rates lead to an increased ferrite content, with in turn causes insufficient corrosion resistance and low toughness. On the other hand, with slow cooling, the risk of unwanted precipitation and embrittlement increases [9]. A state with 50% austenite and 50% ferrite structures is striven for the used superduplex alloy [10]. This is achieved by observing the limits of cooling rates, energy input per unit length, interpass temperatures, and the heat-treatment. Due to the extreme microstructural differences as a function of the thermal history, the super duplex material is highly suitable as indicator material in this research. Therefore, the mechanical-technological properties of the generated component are not of primary interest and are only used for reference reason [11].

An outlet nozzle of a seawater desalination plant was used as the demostrator part. The component in the dimensions 100 × 100 × 100 mm is shown in Fig. 2. Due to the highly corrosive properties of seawater superduplex (SDSS) steel is preferred with its good pitting resistance and good weldability.

Figure 1 shows the test setup for 3DPMD and consists of a power source PlasmaStar 500 (I_{max} = 500 A) in combination with the welding torch PlasmaStar MV230 (I_{max} = 230 A, two separate powder feeds). A Plasmastar PF II disk conveyor with a feed rate up to 250 g/min is used for powder supply. The conveyed powder has a particle fraction from 45 to 150 μm. High-purity argon was used as shielding gas at 12 l/min and as plasma gas at 1.5 l/min. The distance between the plasma anode and the workpiece was 10 mm and the electrode set back was 2 mm. The welding torch moved with a relative speed of 47 cm/min. A six-axis-articulated arm robot REIS RV20–16 was used as a manipulation system.

The power source Fronius TransPulse Synergic 5000 CMT with the welding torch Robacta Drive CMT W was used for the CMT tests. The welding parameters for CMT were based on an internal database for an optimum weldment. As input factors of the database, we use the constant process parameters. For comparability between the processes, these were a constant weld area, constant layer thickness, and the constant building rate. The wire-feed speed was WFS = 2.9 m/min. As shielding gas, high-purity argon with 16 l/min was used. As contact tip to work distance (CTWD) 18 mm (standard) was selected. The welding speed was 41 cm/min.

The heat input into the manufactured part was calculated using the energy input per unit length [12]. The cooling behavior and the interpass temperatures are determined by the direct measurement by means of CrNi-Ni thermocouples type K according to EN ISO 13916:1996 [13]. A 3D laser scanner was used for the characterization of the surface structure. For the determination of the mechanical and technological properties, various metallographic cross-sections were prepared, polished, and electrochemically etched with NaOH. Subsequently, several images of the macro- and microstructure were analyzed. The ferrite content was determined with a magnetinductive measurement system, Fischer Feritscope MP3, over the entire cross-section. In addition, a mapping of the micro hardness of every layer was carried out with a Durascan 70 automated hardness indenter.

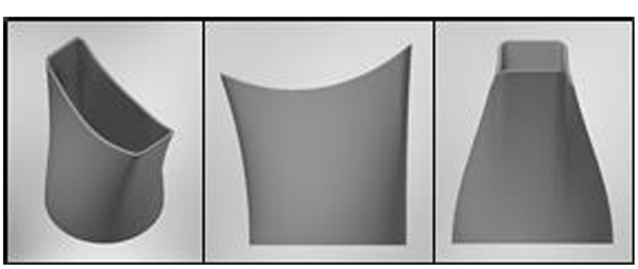

Fig. 2 Demonstration part

3 Results and discussion

The requirement of a constant build rate (1500 g/h) and a constant layer thickness (2.5 mm), leads to different welding speeds of the processes. Through these adaption, the weld bead area and the cooling behavior keep constant and the comparability of the results will guarentee. The construction time of the whole 3DPMD part was 2400 s. The lower speed of the CMT process is reflected in an increased building time of 2700 s. The parameters used are summarized in Table 1.

The detailed profile analysis shows a more homogeneous shape of the 3DPMD component, Figs. 3 and 4. Obviously, the CMT part is characterized by a higher macro roughness and a more unstable layer characteristics. The 3DPMD surface

Table 1 Test parameters

Parameter	3DPMD	CMT
Layer thickness	2.5 mm	
Building rate	1500 g/h	
Building time	2400 s	2700 s
Welding power	2370 W	1254 W
Welding speed	47 cm/min	41 cm/min
CTWD	10 mm	18 mm
Shielding gas	Ar 12 l/min	Ar 16 l/min

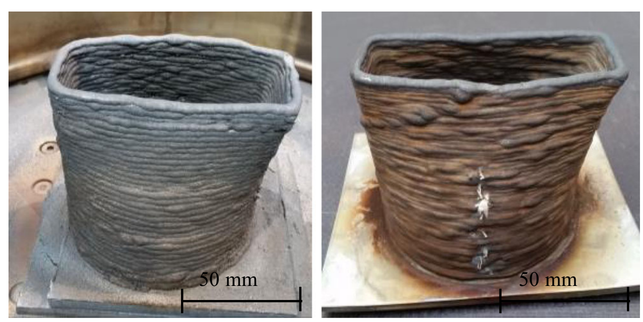

Fig. 3 Generated part (left: 3DPMD; right: CMT)

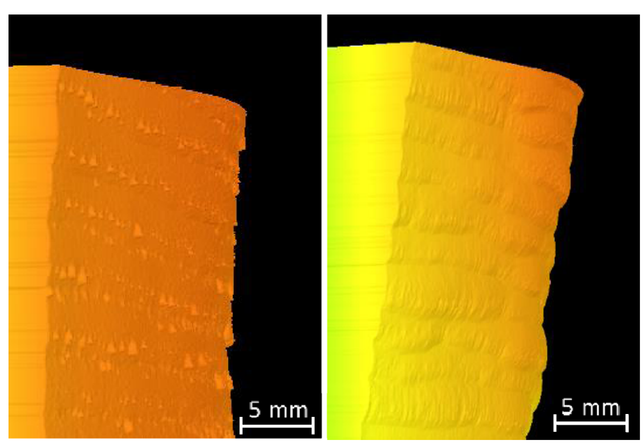

Fig. 4 3D surface texture (left: 3DPMD; right: CMT)

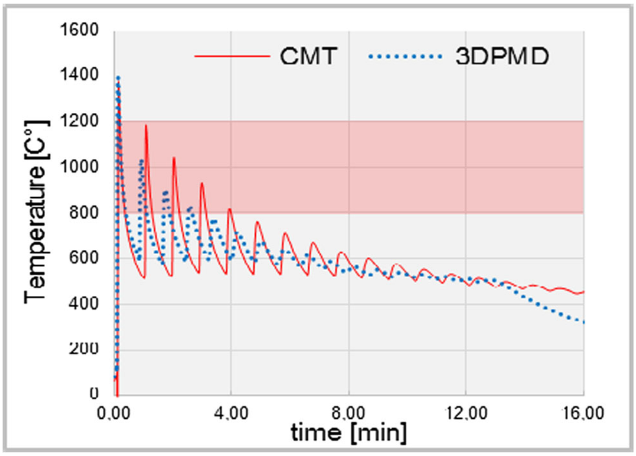

Fig. 5 Cooling chart of the processes

shows adhesion of partially molten powder particles. Therefore, the micro roughness is higher, than using CMT.

The disadvantages of the longer building time and the rougher surface structure of the CMT are compensated by a better material utilization ratio (formula 1) of $\chi_{CMT} = 99\%$ compared to $\chi_{3DPMD} = 80\%$. χ is the ratio between the amount of the fed raw material- powder or wire, ($m_{\text{raw\_material}}$) and the mass of the built component (m_{part}).

$$\chi = \left(m_{\text{raw\_}material}/m_{part}\right) \times 100(\%) \qquad (1)$$

Numerical simulations of the flow and powder behavior at the powder outlet of the plasma nozzle (3DPMD process) indicate that by adapting the bore geometry (angle, diameter) to the AM-process, the material utilization rate can be increased to more than 90%.

Figure 5 shows the cooling behavior of austenitic-ferritic superduplex alloy during welding with CMT and 3DPMD. Weldability is evaluated by the cooling time in the range from $t = 1200$ C – 800 C (red highlighted area) [14]. With cooling times of $t_{12\text{–}8,\text{CMT}} = 228$ s and $t_{12\text{–}8,\text{3DPMD}} = 150$ s, the recommendations of $t_{12\text{–}8} = 8\text{–}10$ s are widely exceeded for both methods [9]. However, this procedure is ideally suited as an indicator for comparing the heat input of the two processes (Fig. 6).

Detailed analysis of the temperature gradient (maximum-minimum temperature) of the individual layers show, that the gradient is significantly higher in CMT welding compared to 3DPMD.

In the case of the same build rate as the CMT process, the dilution with the base material in the 3DPMD is lower.

Figure 7 shows the microstructures of different regions in the parts. The bright areas are the austenitic structures and ferrite appears dark. The structure of the 3DPMD component (Fig. 7a–c) is characterized by a primary austenitic matrix with residual ferrite. The magnetinductive measurements showed a ferrite content of 13%. The structure of the CMT part (Fig. 7d–f) has a much higher proportion of ferrite in the austenitic matrix. This resulted in an average ferrite content of 30%. An explanation for the low ferrite content is the transformation of ferrite, which precipitates in austenite, due to the very low cooling rates [15]. However, both values do not correspond to the technical specification of the manufacturer. This gives a theoretical ferrite content of 33FN for the material 1.4410 and 55FN for the alloy 1.4501. Detailed investigations of the structures of the weld were not carried out, since the material served merely as a pointer material. The evaluation of the hardness maps (Fig. 8) shows no difference between the two processes. For both methods, an average hardness value of 264 HV 1 was obtained. However, the values are corresponded with other studies [16] but lower compared to unwelded base material (316–345 HV1) [15, 17].

Table 2 presents a summary of the results.

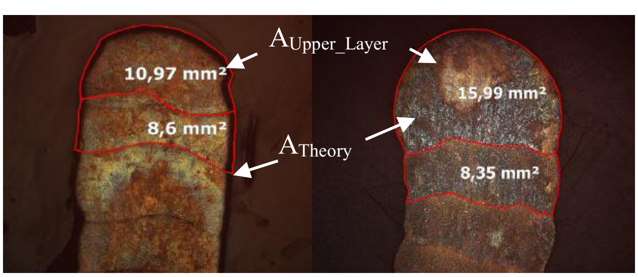

Fig. 6 Definition of the areas of the different welds (left: 3DPMD; right:CMT)

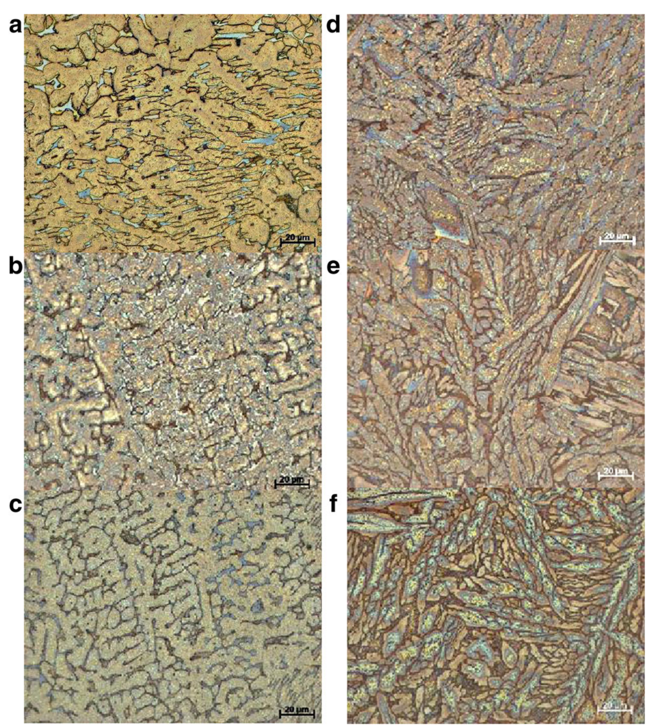

Fig. 7 Build-up of the welds. **a** 3DPMD, top of the part; **b** 3DPMD, middle of the part; **c** 3DPMD, below the part; **d** CMT, top of the part; **e** CMT, middle of the part; **f** CMT, below the part

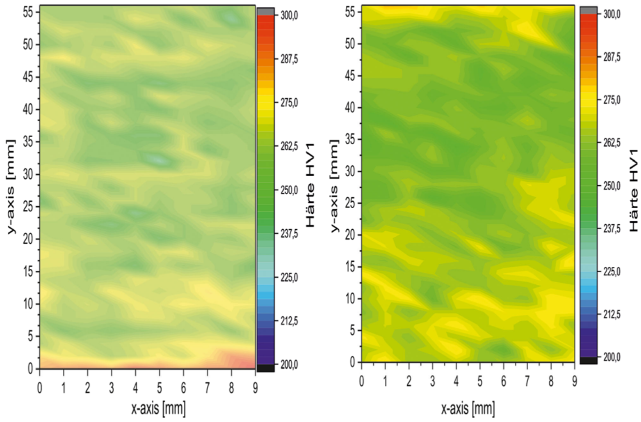

Fig. 8 Hardness mapping (left: 3DPMD; right: CMT)

Table 2 Overview of the results

Parameter	3DPMD	CMT
X- material utilization rate	80%	99%
MR- degree of dilution	23%	49%
t_{12-8} – cooling rate	150 s	228 s
Ferrite content	13%	30%
Hardness (aver.)	264 HV1	

4 Conclusions

The suitability of the 3DPMD process as an AM process has been demonstrated. The used process parameters shows the possibility to realized large structures with 3DPMD in a adequate time:

- Layer thickness, 2.5 mm
- Build rate, 1500 g/h
- Building volume, 200 cm^3/h

It was determined that the heat input and the degree of dilution of the CMT process are higher, and the surface structure is less homogeneous than the one by 3DPMD. The results of the hardness measurements are independent from the process and at the level of the base material. A disadvantage of the 3DPMD is the lower degree of material utilization. By adapting the anode geometry and optimizing the flow conditions of the process gases, significant improvements can be expected here. A great advantage of the 3DPMD is the flexible and independent feeding of various additional powders during the welding process.

References

1. Brandl E, Baufeld B, Leyens C, Gault R (2010) Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications. Phys Procedia 5:595–606. https://doi.org/10.1016/j.phpro.2010.08.087
2. NN: "x-Technik - Additive Fertigung", journal, 01/2015; Link: x-technik IT & Medien GmbH; http://www.x-technik.at/fachbereiche/additive_fertigung.php#anchor_ausgaben
3. Almeida S, Williams S. "Innovative Process model of Ti6Al4V AM unsing CMT". Proceedings of the 21st annual international freeform fabrication, 2014. Austin
4. Martina F, Mehnen J, Williams SW, Colegrove P, Wang F (2012) Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. J Mater Process Technol 6:1377–1386
5. Guenther K, Henckell P "Wire based additive manufacturing with GMAW – Research on temperature and time towards homogeneous material properties". Conference proceedings, IIW 2017, Shanghai. Doc. I-1306-17/XII-2359-17
6. Röhrich T, Riemann A "The potential of the wire-arc based 3DMP process for rapid manufacturing". Conference proceedings, ICWAM 2017, Metz, WIRE-AM-02
7. Schoerghuber M (2016) "Using innovative CMT process for industrial applications". Conference proceedings, Kolkata
8. Matthes K-J, Richter E (2006) "Schweißtechnik –Schweißen von metallischen Konstruktionswerkstoffen". 3.Auflage, Hanser Verlag
9. NN (2006) "Hinweise zum Schweißen ferritisch - austenitischer Stähle (Duplex / Super-Duplex)". ESAB- OK-Handbuch – Teil Duplexstähle
10. Standard EN ISO 1011-2 (2001) Welding—Recommendations for welding of metallic materials—Part2: Arc welding of ferritic steels. Beuth Verlag GmbH
11. Strassburg F (2000) "Schweißen nichtrostender Stähle". DVS-Verlags GmbH
12. Muthupandi V, Srinivasan P, Seshadri S, Sundaresan S (2003) Effect of weld metal chemistry and heat input on the structure and properties of duplex stainless steels. Mater Sci Eng 358(1-2):9–16. https://doi.org/10.1016/S0921-5093(03)00077-7
13. Standard EN ISO 13916 (1996) "Guidance on the measurement of reheat temperature, interpass temperature and preheat temperature". Beuth Verlag GmbH
14. DVS 0946 "Empfehlungen zum Schweißen von nichtrostenden austenitisch-ferritischen Duplex- und Superduplexstählen". Deutscher Verband für Schweißen und verwandte Verfahren e.V.; DVS Verlag, Februar 2004
15. Taban E (2008) Toughness and microstructural analysis of superduplex stainless steel joined by plasma arc welding. J Mater Sci 43(12):4309–4315. https://doi.org/10.1007/s10853-008-2632-z
16. Posch G, Chladil K (2017) Material properties of CMT—metal additive manufactured duplex stainless steel blade-like geometries. Weld World 61(5):873–882. https://doi.org/10.1007/s40194-017-0474-5
17. Kaluc E, Taban E (2011) Welding behaviour of duplex and superduplex stainless steels using laser and plasma arc welding processes. Weld World 55(7–8):48–57. https://doi.org/10.1007/BF03321307