Robot based Wire and Arc Additive Manufacturing (WAAM) as a Solution to Produce 3-d parts

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ABSTRACT

The current use of additive manufacturing is limited almost exclusively to the field of high performance materials, here mainly powdery materials manufactured in the SLM process. There are two main reasons which hinder this application in other sectors, which are not so cost intensive. First, there are significant investment costs to install the production technology, and second, the cost of the powdered materials is enormous due to their manufacturing processes. Wire-based processes are also possible but expensive in the field of laser technology. The use of MSG welding processes currently takes place in combination with machine tool concepts, which however, only offer a limited space for component production in all cases.

For classically weldable metals, arc welding is a good option for the rapid production of complex structures. With the available energy-reduced short and pulsed arc processes, it is possible to use a superimposed single bead welding for three-dimensional component production.

The example of MIG welding shows that using robots which move both, the component and the arc process, it is possible to produce thin-walled, three-dimensional structures. Using two KUKA robots, it will be shown which process strategies are necessary to successfully build up a 3d-part. Building on this, the future development effort and the potential of these processes are shown. Investigations on manufactured components are exemplary presented. For this purpose, results of microstructure development and mechanical properties are presented and discussed. The results show that thin-walled components in the range of 2-6 mm wall thickness can be produced reproducibly and show partly anisotropic property profiles. Both linear welding as well as rotationally symmetric components can be produced with reasonable effort, so that in this technique a very large potential for the production of large structures of different materials is seen. The process strategy how such a manufacturing process step by step must be performed and which tasks relating to the automation of such processes are still unresolved are presented and discussed. The presentation of results also deals with the variable materials portfolio, in particular the possibilities of producing hybrid material components.

1 INTRODUCTION

Wire and Arc Additive Manufacturing (WAAM) is a promising way of combining the disadvantages of conventional casting technology with the disadvantages of machining monolithic wrought materials and thus achieving cost-optimized production of large structures, e.g. from aluminium materials [1-4]. Welding technology can not only be used advantageously as a manufacturing process, but the available materials in the form of wire-shaped filler materials can strongly expand the portfolio of casting alloys and offer a wide range of applications with regard to the mechanical properties of the materials. By means of available arc processes, three-dimensional structures can be created by recurring over-welding of the individual layer, which can then be finished with a minimum cutting and milling volume [5].

The introduction of this technology in the corresponding application areas is dominated by two main machine concepts. On the one hand, this is a strategy based on a machine tool concept, whereby the arc process is integrated into a 3- or 5-axis machine tool and, through the development of a special machining strategy, enables the generative production of components up to 3 m^3 in size [6]. The accuracy to be achieved on the component is specified as +/- 3mm, which is achieved by the very good repeat accuracy of this machine concept. Disadvantage is that this accuracy has to be bought with an increased investment volume and an extension of the component size beyond the machining area is not possible. The advantages are the market availability and the welding process related high rates of application compared to the available powder-based additive manufacturing processes.

The second possible machine concept is essentially based on robot welding, whereby both the welding process and the component can be guided by jointed-arm robots. This concept exceeds the space limitations of a processing machine, so that a generative production of large components on a meter scale is possible and does not represent a significant increase in investment costs compared to a classical robot welding set-up. The greatest challenge here is currently the production strategy, which requires a symbiosis of robot control and CAD data processing in order to produce an additive component [7-11].

First successes could be shown here with regard to the production of large Al structures, whereby up to 6 m large components were produced from Al alloys [12]. The greatest challenge here at present is the production strategy, whereby so-called slicer programs are used to divide the CAD target geometry into a slice model and then to produce the near-net-shape component using layer-wise welding [13]. Due to the deviations in the height profile of the weld seam and its direction-dependent shaping and the lack of process-integrated feedback possibilities into the robot control for path correction, there is currently no optimal solution [11, 14].

2 ROBOT BASED WIRE AND ARC ADDITIVE MANUFACTURING (WAAM)

The robot-based welding test rig (see Fig. 1) consists of two jointed-arm robots in such a way that they have an overlapping field for a common TCP space. The workpiece is held by a KUKA KR 125 robot with a load capacity of 125 kg and can be used as an endlessly rotating table or as a linear traversing unit. The MIG welding torch (Arbicor Binzle) is guided by a KUKA KR 15 with a load capacity of 15 kg. The components are mounted in a soundproof chamber, which is equipped with a suction device to remove the welding fumes generated during the welding process. The welding power source is connected to the KR15 via a robot interface, so that the welding process can be controlled from this robot. With this system, linear paths can be executed to produce flat components and circular paths to produce rotationally symmetrical components. The paths are programmed in such a way that the melt pool is always guided in the horizontal position and the 3D structure is thus built up by tilting the component. The WAAM-generated components are mounted on an aluminum base plate, which is clamped to the KR 125. The necessary height offset is transferred to the robot controller by analyzing the layer height as a step value, so that simple structures can be set up even without complex software tools.

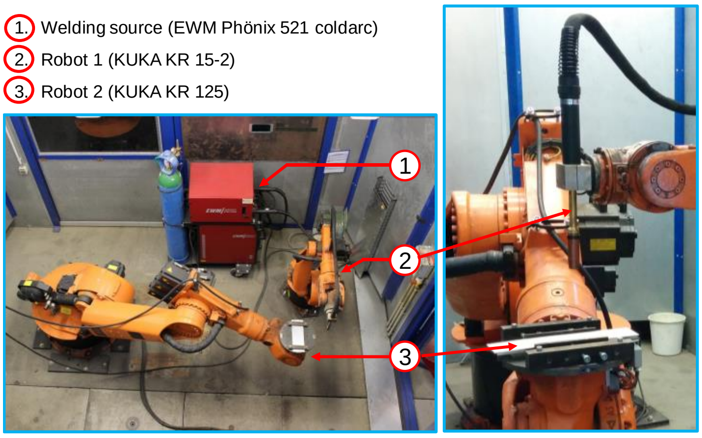

Figure 2: WAAM chamber at Institut für Werkstoffkunde (materials science) of Leibniz University of Hanover

3 MATERIAL SELECTION OPTIONS

For the selection of the materials, the target value in terms of component properties is of great interest. On the one hand, there is the requirement for the highest possible strength and, on the other hand, the requirement to achieve the best possible formability, i.e. high ductility. In most cases, an optimum combination of strength and ductility is required in order to meet the designer's requirement profile. The range of available filler materials in the field of aluminium materials means that there is a large selection to choose from. Three materials were selected, which are listed in Table 1.

Table 1: Materials used to create MIG generated 3D parts

Filler material		Chemical competition in mass%											
alloy		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ga,V	Ti	Zr	Al	Be
Al 2319[(1)]	**AlCu6MnZrTi**	0,2	0,3	5,8-6,8	0,2-0,4	0,02	-	0,1	0,05-0,15	0,1	0,2	Rest	0,0003
Al 3103[(2)]	**AlMn1**	0,5	0,7	0,10	0,9-1,5	0,3	0,1	0,2	-	Ti +Zr 0,1		Rest	0,0003
Al 5087[(3)]	**AlMg4,5MnZr**	0,25	0,40	0,05	0,7-1,1	4,5-5,2	0,05-0,25	0,25	-	0,15	0,1-0,2	Rest	0,0005

[(1)]… MIGAL.CO GmbH; [(2)]… EWM AG; [(3)]… MIGAL.CO GmbH und DRAHTEC GmbH

4 OPERATION STRATEGY

The filler materials used had a wire diameter of d = 1.2 mm. For the welding tests, a fully electronically controlled MSG welding power source from EWM AG was used, which can be used for both cold arc and impulse welding (Phoenix 521).
The program for creating the samples is only executed on the KR 15. For flat structures, it is designed so that the robot moves the welding torch from one end of the workpiece to the other and back. After each layer produced, the torch is moved upwards by the previously determined layer thickness. The program pauses between the individual layers to avoid overheating of the component. This is realized by a FOR loop in the program. Each loop pass contains a back and forth movement. This will raise the height per loop pass twice according to the order height. The program also controls the start and stop of the welding power source (see Fig. 2).

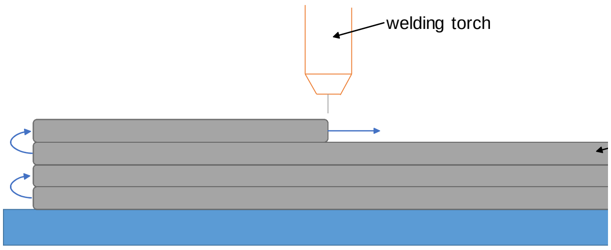

Figure 3: Structure of a three-dimensional flat structure for taking samples for mechanical testing

Tensile specimens (DIN 50125 - Form E) in horizontal, diagonal and vertical directions, related to the welding direction, were taken from the approx. 300x300x6 mm (length x height x width) flat structures by means of abrasive water jet cutting and milled to a specimen thickness of 2 mm in order to determine the mechanical properties in the tensile test. Samples were also taken for metallographic analysis to perform macro- and microstructural analysis (see Fig. 3).

Figure 4: Sample plate circumference per alloy (left); example of a 300x300 mm flat structure made of Al 5087 (middle); representation of the samples taken to perform the mechanical test.

5 RESULTS AND DISCUSSION

The robots used for this work are equipped with a KR C1 controller, which does not allow coordinated work in the same networked work area. For this reason, the existing input and output signals were used to establish a connection between the robots and the welding power source. The planned workpiece is positioned in the coordinate system of the KR 125, in which the second KR15 robot approaches defined positions with its TCP. Since the KR 125 can rotate and tilt endlessly, it is possible to produce simple rotationally symmetrical components in the KR 125 coordinate system by moving the TCP (in which the wire tip of the welding torch lies) sensibly through the KR 15.

For the planar components, the KR 125 holds the aluminum base plate statically at rest, and the KR 15 performs the feed motion and the layer offset in the z direction. It is already evident here that the robot systems used do not meet the requirements of the WAAM requirements, since the programming effort increases extremely with the complexity of the component, and there is also no possibility of transferring CAD data directly to the controllers. It was not possible in these investigations to use possibilities with software-based slicer programs and a conversion into G-code, since a digital networking of the coordinate systems of the two robot systems used cannot be realized.

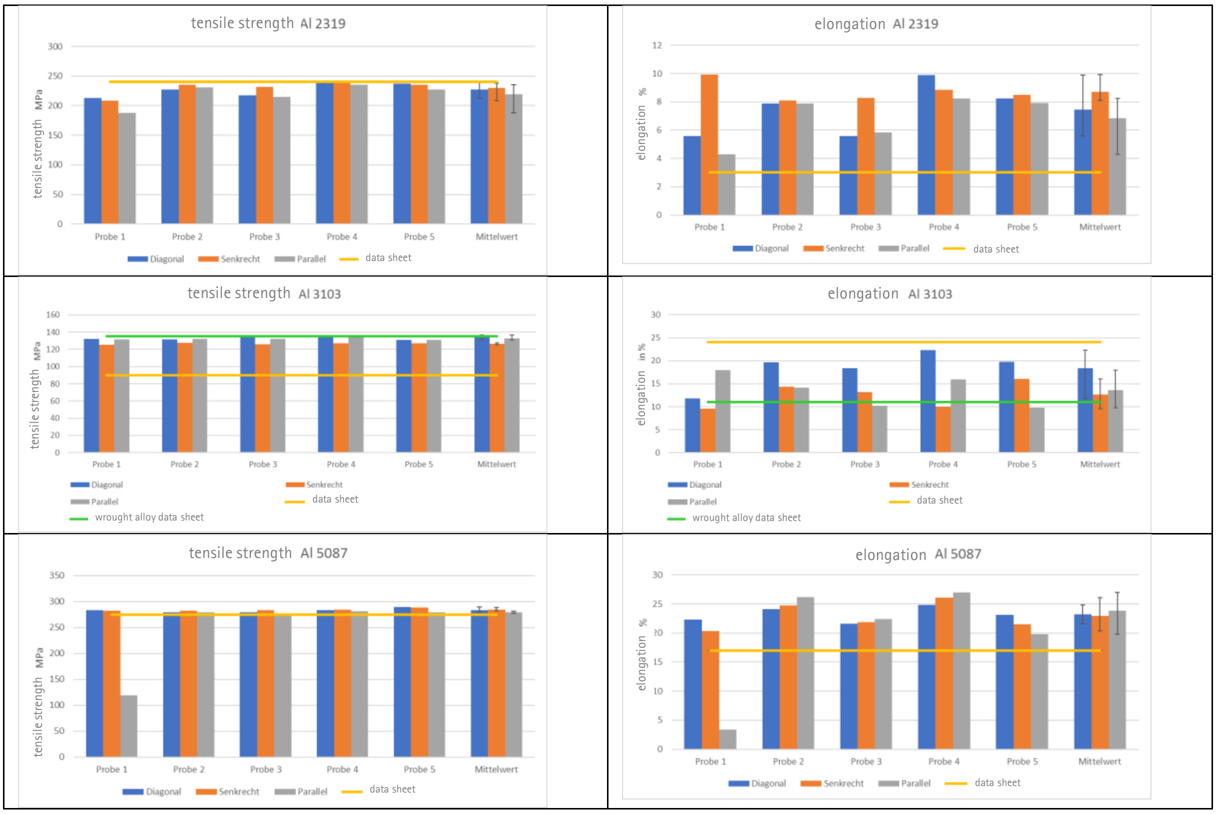

Figure 5: Mechanical properties of the WAAM material of the three alloys used.

<u>Al 2319 (AlCu6MnZrTi)</u>

The results shown in Figure 4 show that the tensile strength specified in the manufacturer's data sheet is almost reached. The achieved yield strength is below the specifications, whereby the "as welded" state without heat treatment is the measured variable and the manufacturer's specifications refer to the heat-treated state. This can be clearly seen from the measured strain, which at approx. 8% is significantly higher than the manufacturer's data. This circumstance leads one to expect a further improvement of the mechanical properties with regard to tensile strength and yield strength, if one assumes a simultaneous reduction of the elongation to the 4% specified by the manufacturer. However, this is not yet included in the scope of these investigations. The hardenable alloys of the 2000 series, which are described as difficult to weld, thus show a not insignificant potential in the application area of aerospace technology to also be used as WAAM components. An anisotropy of the properties is not determined.

<u>Al 3103 (AlMn1)</u>

For this alloy, the tensile strength values specified by the manufacturer (see Fig. 4) are far exceeded, so that the WAAM components can be given a higher strength, which can even correspond to the property profiles of the work-hardened variants. This is also achieved for the yield strength and the values are above those specified by the manufacturer. Only the plastic deformability does not reach the target value, but lies in the comparison between the manufacturer's specifications and the values for work-hardened material, so that a property profile can be assumed that can be used quite well here. The direction-dependent specimen taking shows a strong influence on the elongation properties of this alloy, since the elongation in diagonal direction is strongly increased here. The reason for this may be the high grain boundary proportion in the body alignment.

Al 5087 (AlMg4.5MnZr)

For the characteristic values shown in Figure 4, it can be said that the requirements are fully met. Both the tensile strength and the yield strength meet the manufacturer's specifications in full. At the same time, the WAAM-generated components show increased plasticity, as the elongation values exceed the specifications by approx. 10%. Anisotropic property behavior is not detected here, which can be of great advantage for WAAM component planning.

6 CONCLUSIONS

The results show that the WAAM technology with the use of robots as guiding system is possible both for the guiding of the process and for the guiding of the workpiece position and represents a quite meaningful way for the fast production of 3D components. However, essential parts of the process chain still have to be developed for commercial use. The process must run so comfortably that the CAD data of the component is fed directly into the WAAM system and the process then runs completely automatically. This requires on the one hand a clever transfer into the path programming of the robots and on the other hand the use of the arc as a sensor for feedback of the layer height directly through the welding process. These two essential factors should enable an industrial implementation of the WAAM process even for large components.

Especially for the WAAM process, the large and directly available variety of filler materials offers itself for use. In the context of this work it was shown that for different Al alloys the WAAM process can be successfully carried out with relatively simple on-board means and thus satisfactory component properties can be achieved. Mechanical properties have been achieved which essentially meet the specifications of the manufacturers of the filler materials or even bring better properties. An advantage for the WAAM process is the temperature effect of the previously deposited weld metal caused by the heat of the subsequent weld seam.

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