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Robot Based Wire Arc Additive Manufacturing System with Context-Sensitive Multivariate Monitoring Framework

Raven Reisch[a,b,*], Tobias Hauser[b], Tobias Kamps[b], Alois Knoll[a]

[a]*Technical University of Munich (TUM) - Chair of Robotics, Artificial Intelligence and Real-Time Systems; Boltzmannstraße 3, 81379 Munich, Germany*
[b]*Siemens Corporate Technology; Otto-Hahn-Ring 6, 81739 Munich, Germany*

* Corresponding author. Tel.: +49 157 82627222; *E-mail address: raven.reisch@tum.de*

Abstract

Large scale, metal parts are commonly manufactured by milling with a buy-to-fly-ratio of up to 10. A resource efficient alternative is the production by Direct Energy Deposition (DED) based Wire Arc Additive Manufacturing (WAAM). In this study, a WAAM system is divided into four elements (welding source, kinematic structure, control system, monitoring system) and a review is accomplished for each. Requirements are defined based on these reviews and additional needs and a robot based WAAM setup is proposed. To validate the WAAM setup, first experiments are conducted regarding the influence of the orientation of the welding torch respectively of the lead and the tilt angle on the geometry of a deposited wall. Finally, a framework for a seamlessly integrated monitoring system in hybrid manufacturing for enhanced data analysis is introduced. The framework is based on a digital twin of the workpiece in production which serves as base for proactive, context sensitive process adaptions.

Keywords: Hybrid Manufacturing; Wire Arc Additive Manufacturing; Robot; Monitoring System; Digital Twin

1. Introduction

Large scale metal parts in aerospace industry are commonly manufactured by milling with a buy-to-fly-ratio of up to 10 [1,2]. This results in a waste of resources such as unused material or high costs due to machine hour rates and tool wear. A promising technology to reduce this ratio in production of large-scale metal parts is Wire Arc Additive Manufacturing (WAAM). Additive Manufacturing (AM) is a rising technology based on the joining of material to create 3D structures usually layer upon layer.

WAAM is an AM technology based on an arc welding process. Hence, the part is built up layer upon layer by melting a metal wire with an electric arc. By using wire instead of powder as it is done in Selective Laser Melting (SLM), this process allows high build-up rates and low production costs. However, the WAAM process has disadvantages regarding the accuracy of the process and the achievable component complexity. The surface quality does not meet the precision requirements of functional surfaces [3,4]. Thus, complex structures with requirements for high accuracy cannot be produced [5]. For this reason, reworking by a subtractive manufacturing step is needed. The combination of additive and subtractive processes is assigned to the term hybrid manufacturing and will be called equivalently in this paper. In order to avoid cost-intensive retooling times, hybrid machines are used. They allow both additive and subtractive manufacturing on the same machine tool [6]. This allows components to be manufactured on one production machine by first producing near-net-shape parts by AM and then reworking them in a milling operation.

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In specific for the aerospace industry, it is necessary to prove the high quality of the produced parts [7]. AM allows to check the part attributes already during the process at each voxel. In the end, first-time-right printing is desired, i.e. a successful production process at the first attempt. Trial-and-error approaches, which are particularly common in AM, must be avoided [8]. The reduction of scrap in production can reduce the total production costs in AM by up to 30 % [9].

In this paper, the setup of a robot based multi axis WAAM system with the capability of being enhanced to a hybrid manufacturing system is presented. It is used for the manufacturing of large scale AlSi12 parts e.g. for aerospace applications. A multivariate monitoring system is proposed based on a set of defined quality demands. The proposed monitoring system is regarded as key element of a seamlessly integrated data chain, aiming at the industrialization of WAAM.

First, we review WAAM setups and monitoring systems in Section 2. Section 3 is dedicated to the definition of requirements for and the setup of our hybrid manufacturing system including a multivariate monitoring system. To validate our setup, we show first results regarding the influence of the orientation of the welding torch on the geometry. In section 4, we introduce a framework of a seamlessly integrated monitoring system for enhanced data analysis and control methodology which allows proactive, context sensitive process adaptions. Section 5 concludes the paper with a final summary and an outlook to future work.

Nomenclature

AM	Additive Manufacturing
CMT	Cold Metal Transfer
CNC	Computerized Numerical Control
DED	Direct Energy Deposition
DoF	Degree of Freedom
GMAW	Gas Metal Arc Welding
HMI	Human-Machine-Interface
IPC	Industrial PC
MAG	Metal Active Gas
MIG	Metal Inert Gas
NC	Numerical Control
SLM	Selective Laser Melting
WAAM	Wire Arc Additive Manufacturing
d	Distance nozzle-substrate
s	Stick-out
α	Lead angle
β	Tilt angle

2. Related work

WAAM setups generally consist out of four elements: the welding source, the kinematic system, the control system and the monitoring system.

The welding source is providing the power for melting the wire by an arc. In general, Gas Metal Arc Welding (GMAW), including Metal Inert Gas (MIG) and Metal Active Gas (MAG) welding, is suitable for this process. An overview of WAAM technologies is given by Rodriguez et al. and by Cunningham et al. [8,10]. In specific, Cold Metal Transfer (CMT) shows promising results in the production of large-scale metal parts. It is based on an oscillating wire feed rate resulting in a low heat input and thus in less residual stresses. [11]

Regarding the kinematic system, two kinds of system configurations can be seen in research [12]. On the one side, systems are based on the kinematic structure of a cartesian machine, which results in axes along X, Y and Z to position the welding torch respectively the tool, and optionally a tilt-turntable to orientate the part along the X(A) and Z(C) axis. For instance, Karunakaran et al. have extended the spindle set of their 3-axis CNC milling machine by a welding torch for the WAAM process [13,14]. Artaza et al. designed a gantry system for WAAM applications [15]. On the other side, the setup of the WAAM system can be robot based [12,16]. Using an industrial robot with six axes, the tool respectively the welding torch can be positioned and oriented flexibly complying with the working space of the robot. To avoid support structures, the robot can be combined with a tilt-turntable too [17]. Hence, the system has up to eight axis and can be positioned and oriented in all manners. An implementation of hybrid manufacturing by means of a robot is carried out by Li et al. [18].

Regarding the control system, a controller for the kinematic system as well as a controller for the welding source is used. They interact with each other in order to allow a stable process. Especially in start and stop sequences, a suitable strategy must be implemented [19]. Gonzalez et al. determined four main parameters for the WAAM process which include parameters of the welding source as well as parameters of the kinematic system: Intensity, welding speed, arc length correction and dynamic correction [20]. Tests conducted by Liberini et al. also show the interaction between parameters of the kinematic system such as welding speed and those of the welding source such as voltage which are both affecting the heat input [21]. Based on this control setup and the main parameters, closed-loop control strategies can be implemented e.g. to ensure uniform weld seam geometry and process stability [12,22–26].

The monitoring system is gathering and analyzing the process data in-situ. Hereby, anomalies can be detected, the quality can be evaluated online and offline and process traceability can be achieved. In GMAW, the path speed, wire feed rate and shielding gas flow as well as the welding current and voltage are essential data for process monitoring [8,27,28]. In WAAM, the dimensions of the weld pool and the weld seam are also determined using optical sensor technology [29]. Further research on the geometric analysis of the weld pool can be found in the publications of Zhang et al., Font comas et al. and Xiong et al. [30–32]. The dimensions of the weld seam can be determined by means of a profilometer, as Xu et al. have proven [33]. The temperature has a high impact on the WAAM process and the weld bead properties and should therefore be monitored as well [33–36]. Further approaches for in-situ analysis of the WAAM process can be seen in the field of acoustics. For instance, acoustic signals provide information about the intensity and stability of the arc [37]. Cudina et al. and Chen et al. derive a correlation between the acoustic emissions of the welding process and the welding current and voltage [38–40]. Zhao et al. perform a spectral analysis during the process to assess the quality of the welding process based on the light emissions of the arc [41]. To mirror the welding process digitally, a multi-sensor approach is necessary [39]. Rodrigues et al. point out the need for the development of multi-parameter based, non-destructive test systems to identify the origin of defects and to increase the reliability of defect detection [8]. For instance, Artaza et al. combined a pyrometer, a welding camera and a laser scanner as well as an oxygen meter [15]. Chen et al. combine current and voltage values, acoustic emissions and optical data from a camera using a fuzzy-based method to evaluate the status of the weld penetration [39]. Zhao et al. combine spectral data with images from a camera and current data [41]. Xu et al. use current and voltage sensors as well as two laser profilometers for their monitoring system [33].

3. Hardware and Software setup

In the following subsections, requirements for the hybrid manufacturing system are defined. Based on these requirements, a WAAM setup is proposed. Finally, first results regarding the influence of the orientation of the welding torch on the geometry of a wall are discussed.

3.1. Requirements

The main goal of the contemplated hybrid manufacturing system is the safe, flexible and fast manufacturing of large scale, high quality, near end shape parts with low costs. Therefore, the system should be capable of absolving manufacturing tasks with WAAM and milling technology (R1). The welding system must allow to change the welding mode in order to adapt the energy input into the part depending on the interlayer temperature to reduce thermal stresses in the part and hence distortion (R2) [35]. The kinematic system must allow multi-axis-deposition (R3). This flexibility in positioning and orientation is needed as the deposition is dependent on the orientation of the torch and of the substrate [42]. To assure a horizontal orientation of the weld bead, the part mounting must include two degrees of freedom (DoF) (R4). Six DoF are to be used for the tool holder system in order to reach all DoF in position and orientation (R5). According to the literature, the achievable accuracy in WAAM is low in comparison to SLM [43]. However, the post processing by milling should result in a surface quality of roughing which requires accuracies of up to 0.1 mm (R6). The system must possess a certain stiffness to allow the milling of aluminum alloys such as AlSi12 (R7). A seamless interaction between welding source and kinematic setup is needed to guarantee a stable process and access the process parameters for monitoring and control reasons (R8).

The monitoring system must gather and analyze the process data in real-time and make it accessible online and offline (R9). For that reason, the monitoring system must allow to monitor the process with same quality at any time in any orientation in order to enable a reliable detection of anomalies (R10). Five main process defects to be detected are defined. A cause-defect relationship was derived based on the literature and empirical knowledge [8,16,33,44]. Each defect mentioned in Table 1 must be detectable either by measuring the defect itself or by monitoring the causes which might lead to the defect (R11).

Table 1. Defects and their causes in Wire Arc Additive Manufacturing

Defects	Causes
Porosity	Hydrocarbon occlusions and other contamination in wire/ substrate
	Instable arc
	Instable gas flow
	Substrate pre-conditions
Distortion	Residual stresses
Cracking	Residual stresses
Deviations in weld bead geometry	High energy input
	Instable arc
	Deviations in deposition volume
	Positioning/orientation errors
Delamination/ lack of fusion	Contamination of part/substrate surface
	Low energy input
	Residual stresses

Lastly, we introduce general requirements of the system which accelerate the transfer of the WAAM technology to industry. Costs are one of the main barriers in adapting new technologies in the industry. Hence, the price of the setup must be as low as possible to facilitate the transfer to industry (R12). The system must fulfill industry standards for safety and connectivity (R13-14) and must be adaptable to the user's needs (R15). Finally, a high ease of use is needed (R 16).

3.2. System architecture and setup

Based on the defined requirements, the following setup is proposed consisting out of four subsystems (process and kinematic setup as well as control and monitoring system). In Fig. 1, the proposed setup can be seen. Here, the inner part of the WAAM cell including the welding equipment and the kinematic setup is shown.

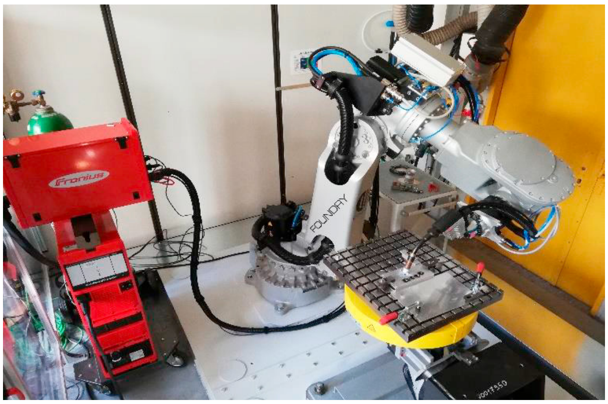

Fig. 1. WAAM system cell consisting out of the 6-axes robot, the tilt-turntable, the Fronius welding source and the welding torch

Process setup: The welding source is provided by Fronius and is suitable for MIG/MAG welding as well as for Pulse and CMT (R2). The cooling system of the torch is water-based.

Components:
- Welding Source Fronius CMT 4000 advanced
- Wire feeder VR 7000
- HMI RCU 5000i

Kinematic setup: The kinematic setup is based on an eight DoF system with an industrial robot and a tilt-turntable to fulfill the defined requirements in terms of DoF, flexibility and costs (R3-5, R12). In addition, a tool head changer system is implemented to enable the usage of a milling spindle and the WAAM torch on the same machine (R1). Robot milling is possible due to the high stiffness of the heavy load industrial robot and its control (R1, R7).

Components:
- 6-axes robot COMAU NJ130 2.0
- 2-axes tilt-turn table COMAU PTS-ORB-1000
- Tool head changer system TC180 by rsp

Control system: To achieve the required accuracies and to offer high usability, a Numerical Control (NC) with PLC and hence industrial safety standards, enhanced accuracy options and G-code functionality based on the "Run-myRobot" algorithms provided by Siemens is used (R6, R13, R16). Via Profinet, a connection to the drives of the kinematic system, the control of the Fronius system, an industrial PC (IPC) with human-machine interface (HMI), an I/O module and an edge device is set up (R8). The Fronius control is handling the WAAM process while the Sinumerik is coordinating the robot movements and synchronization. The I/O module offers analog and digital inputs and outputs to connect sensors to the system (R14). The edge device allows to enhance the automation system by additional features such as cloud connectivity and communication protocols such as USB or TCP/IP e.g. for further sensors. (R8, R9, R15). By using common G-code and the HMI, a high ease of use is achieved (R16). The system architecture is shown in Fig. 2.

Components:
- Numeric Control (NC) Sinumerik 840D SL with PLC
- Industrial PC with Simatic HMI
- Sinumerik Industrial Edge Device
- I/O Modul Simatic ET 200SP

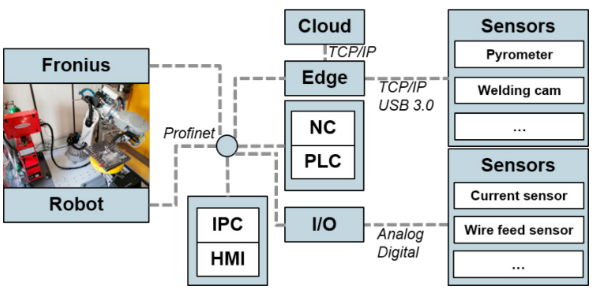

Fig. 2 Control system architecture of the proposed WAAM system

Monitoring system: To monitor the WAAM process in-situ and detect the beforehand mentioned anomalies, a multi-sensor system is set up (R9). Multivariate sensor frameworks use different data sources and are therefore more stable to detect specific anomalies. The proposed sensors are either based on electrical, optical, thermal or acoustic measurement methods to guarantee high monitoring quality with focus on different aspects of the system at any time (R10-11). However, the proposed optical measurement methods face challenges regarding direction independent monitoring. In addition to these sensor data, the monitoring system has access to the real-time information of the kinematic system. Low frequency process data of the welding source can also be transferred.

Components:
- P1000-S3 current and voltage sensor by HKS
- Wire feed speed sensor DV25ST-S3 by HKS
- Gas sensor GM 30L 10B-S3 by HKS
- Welding camera C200 by Cavitar
- Laser profile scanner MLWL132 by Wenglor
- Spectrometer USB2000+XR1-ES by OceanOptics
- Pyrometer LT-CF4 by Optris
- Thermal imaging camera FLIR T200 by Flir
- Microphone Presonus PRM1 by Presonus

3.3. First results and discussion

In the following section, we present first WAAM results with the proposed setup, AlSi12 wire with a diameter of 1.2 mm and Argon as inert gas. Therefore, we test the setup with different orientations of the welding torch. The orientation is defined by the lead angle and the tilt angle. The lead angle α represents the angle between the welding torch and the perpendicular of the substrate surface. Hence, α = 0° represents a neutral orientation and a negative value represents a forehand orientation of the welding torch. The tilt angle is defined as the angle between the weld track and the welding torch on the plane of the substrate surface. The neutral orientation can be seen at β = 0° when the welding torch is aligned to the weld track direction. The lead angle as well as the tilt angle are illustrated in Fig. 3.

In total, ten walls consisting out of ten single lines with a length of 65 mm each were built up on a substrate in horizontal orientation.

The first two layers were added in pulse mode. Thus, a

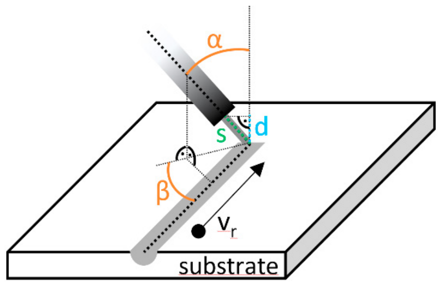

Fig. 3. Orientation of the welding torch (lead angle α and tilt angle β) along the weld track with distance d between nozzle and substrate and resulting stick-out s. v_r is showing to direction of the robot speed.

high energy input was achieved in order to heat up the substrate as it acts as a temperature sink [36]. Afterwards, the CMT mode was used for the next eight layers to reduce the heat input. Before each experiment, the temperature of the cleaned substrate was checked in order to guarantee the same pre-conditions. The process parameters remained the same for all experiments. The robot speed (350 mm/min) as well as the correction parameters (0 %) were fixed, while the wire feed rate and hence the current and voltage was decreased with each additional layer to avoid overheating. The experiments were conducted in an automated manner and thus, same cooling times between the layers were kept. The nozzle was positioned d = 13 mm above the substrate in the first layer of each experiment, resulting in a changing stick-out s of the wire depending on the lead angle α. s can be calculated by equation (1):

$$s = \frac{d}{cos\,(\alpha)} \qquad (1)$$

Thus, the stick-out distance varies between 13.0 mm and 14.3 mm in the first layer. After each layer, the torch was lifted 2.2 mm which results in a slightly changing stick-out along the process.

To investigate the influence of the lead angle, the tilt angle was fixed to 0° and the lead angle was set to a constant value between 0° and -25° in experiments #1 to #6. Positive lead angles bigger than 0° were not considered as the cleaning function of the plasma in aluminium welding is reduced in a backhand orientation of the welding torch. The influence of the tilt angle was investigated by fixing the lead angle to -15° and setting the tilt angle to a constant value between 0° and -90° in experiments #7 to #10.

The wall height as well as the width of the 10^{th} layer were measured with a calliper gauge at three points in the middle of each wall to exclude uneven start and end zones. During the measurements, the walls were still attached to the substrate. Hence, potential effects after the removal in terms of distortion due to residual stresses are not taken into account.

Table 2. Resulting wall width and height depending on the lead and the tilt angle as well as mentioned anomalies

#	Lead angle (α) in °	Tilt angle (β) in °	Stick-Out (s) in mm	Wall height in mm	Width of 10^{th} track in mm	Process stability
1	0°	0°	13.00	21.1-21.5	4.5-4.7	Stable arc
2	-5°	0°	13.05	20.8-21.2	4.6-4,8	Stable arc
3	-10°	0°	13.20	20.3-20.9	4.6-4,7	Sputters, unstable arc
4	-15°	0°	13.46	20.0-20.3	4.5-4.7	Stable arc
5	-20°	0°	13.83	19.6-19.9	4.7-4.9	Sputters, Stable arc
6	-25°	0°	14.34	18.7-19.2	4.6-4.9	Sputters, unstable arc
7	-15°	0°	13.46	19.4-19.6	4.4-4.8	Stable arc
8	-15°	-30°	13.46	20.0-20.3	4.4-4.7	Stable arc
9	-15°	-60°	13.46	20.3-20.5	4.3-4.6	Stable arc
10	-15°	-90°	13.46	18.8-19.2	4.4-4.8	Stable arc

The lead and tilt angles, the stick-out as well as the resulting geometries and process behaviours are provided in Table 2 for the experiments #1 to #10. The resulting weld tracks can be seen in Fig. 4.

The walls show deviations in height and width depending on the lead angle. A more neutral lead angle results in a higher wall than a less neutral angle. The width of the 10^{th} track slightly increases with a bigger absolute lead angle. With decreasing lead angle, instabilities in the process such as sputters and an unstable arc can be seen, resulting in a discontinuous, uneven track surface. These observed instabilities mostly take place in the first layer. Best results regarding sputters were achieved with lead angles of 0°, -5° and -15°. The 10^{th} track shows the smoothest surface for α = 0°, followed by -5° and -15°. In experiment #7 to #9, the deviations in the wall height cannot be matched to the tilt angle. Instead, an increasing inclination of the walls can be observed with bigger tilt angle. As Table 2 shows, the width of the 10^{th} track remains roughly the same for the examined tilt angle configurations in experiments #7 to #9. Here, the process is characterized by a stable arc, no sputters and an invariant smooth surface of the upper track.

In conclusion, only minor effects of the lead angle on the wall geometries and the process stability can be seen when using suitable process parameters. Regarding the best results with a lead angle of 0°, -5° and -15°, the differences between these lead angles are negligible in our experiments and no major advantages in the process and surface quality can be seen. As the deviations in geometry as well as in process stability and quality are small in CMT mode, a neutral lead angle of the welding torch meets the requirements for the WAAM process and in addition simplifies the path planning.

The conducted experiments with changed tilt angle show inconclusive deviations regarding the wall height and minor deviations in the width of the 10^{th} track. However, with regard to experiment #9 and #10, the changing tilt angle results in an

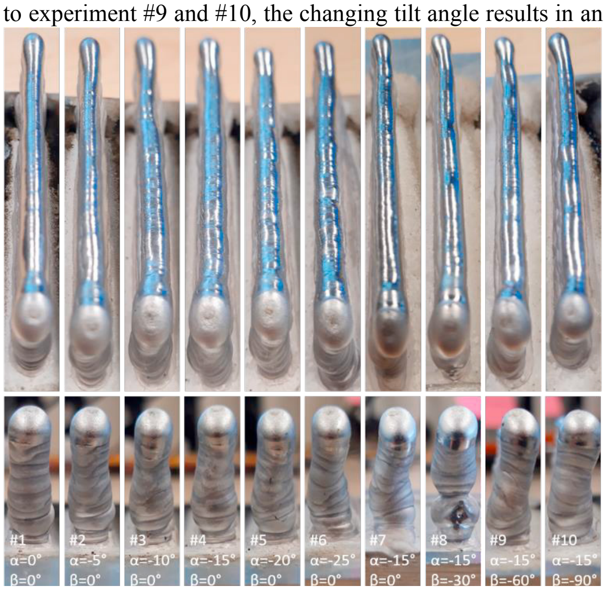

Fig. 4. Influence of different lead angles (0°, 5°, 10°, 15°, 20°, 20°, 25°) on the wall geometry (height and width), inclination of the wall and surface smoothness

inclination of the wall.

Here, the weld bead respectively the working zone of the arc apparently doesn't stay exactly above the previous track along the build-up of the wall. The position of the deposition and for this reason the weld track shift in direction of the wire feed. Due to the shifting of the working zone, the stick-out changes dynamically during the process. Further experiments must be conducted to investigate this effect. However, regarding a potential automated path planning, the shifting effect results in an undefined deposition location and is therefore not desired. For that reason, a tilt angle of 0° is considered as suitable both for the process and the path planning.

4. Seamlessly integrated monitoring system

In this section, a framework for a seamlessly integrated monitoring system based on a digital twin in hybrid manufacturing is presented. Its goal is to improve the process quality, to provide process knowhow along the tool chain and make a step towards "first-time-right" printing. First, the interaction of related elements along the process chain and the setup of the architecture of the seamlessly integrated monitoring system is explained. Then, the data processing during the manufacturing process is mapped to the proposed control architecture regarding real-time and performance requirements.

4.1. System architecture

As Fig. 5 illustrates, the manufacturing process chain can be divided into three major phases (Engineering, Manufacturing and End Product).

The process starts with the engineering phase which includes the design and the process planning step. First, a digital model of the part is designed according to hybrid manufacturing specific guidelines. The process planning is done automatically by dividing the digital model into segments depending on geometrical and material characteristics. A suitable deposition strategy and associated process parameters is assigned to each segment with the help of an expert system based on a process database. Milling

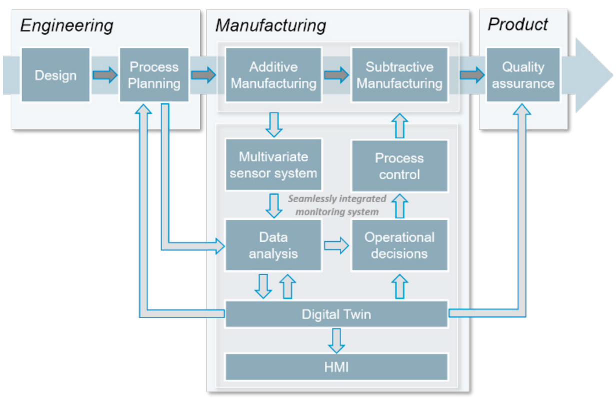

Fig. 5. Framework of a seamlessly integrated monitoring system

operations are added to achieve the required accuracies of all functional surfaces. The planned paths of all segments are merged to obtain an optimal sequence regarding qualitatively and economically aspects. In order to validate the obtained sequence and to conduct collision checks, the kinematic setup is digitalized by creating a machine simulation. In Fig. 6, the beforehand proposed hardware setup is modelled and simulated in the software Siemens NX as an example. The planned paths are then processed by a post-processor to create the machine code i.e. G-code for the manufacturing process.

Via cloud connection, the relevant information is transferred to the machine tool and the system starts the manufacturing process based on the machine code. The process is monitored online by measuring all relevant process data with the aid of the proposed multivariate sensor system. Within the multivariate sensor system, process data is collected. As described in section 3, the sensor technology must be selected depending on the quality characteristics to be investigated. Single sensor signals can be used as input for closed-loop-controls. The collected data is pre-processed and compressed to reduce the amount of data. Then, the data is analyzed, interpreted and screened to detect anomalies. For this purpose, the significance of the sensor data within the multimodal sensor system is evaluated and data fusion takes place. In addition to the current process data, the machine code as well as material properties are included. For data interpretation, semantically interpreted data from the process history is used. This process history is stored in a digital twin, which is built and updated by using the data previously interpreted in the data analysis. Hereby, a digital spatial and temporal context for all process data is created. It can be used for enhanced data analysis methods e.g. in multivariate time series analysis. Hence, the digital twin allows to include information about the process history in the data analysis and thus to implement a context-sensitive monitoring and if needed compensation strategies. These compensation strategies are operational decisions which are initiated context-specifically by a system intelligence. They proactively adjust process parameters in the next

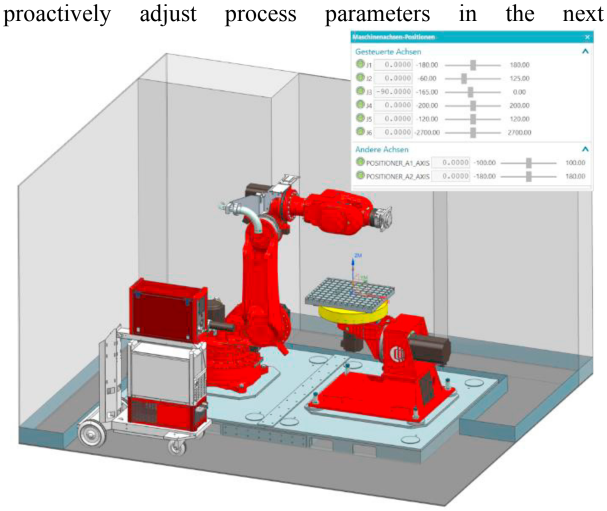

Fig. 6. Machine Simulation of the proposed WAAM setup with 6 axes robot and 2 axis tilt-turntable

manufacturing steps e.g. to compensate distortion in the part in production by reducing the heat input in sub-areas of the next layer or to eliminate surface unevenness by varying the wire feed speed to influence the geometry of the weld bead. Adjustments of parameters of the closed-loop controls may also be applicable. The outcomes of these adjustments and compensation strategies are monitored by the sensor system. The results are evaluated with the help of the digital twin and stored as knowledge elements for future process planning as shown in Fig. 5. Based on the geometry and the metallurgical data of the created digital twin, the pre-calculated milling forces of the subtractive manufacturing step can also be updated and the accuracy in the manufacturing process can be increased. The system intelligence hence decides on the type and extent of interventions and evaluates them subsequently in order to improve them in the future e.g. by reinforcement learning strategies. At any time, an HMI informs the operators in charge and the manufacturing execution system about the process.

Finally, quality assurance takes place. As the digital twin contains information about the geometrical and metallurgical characteristics of the part, defects such as cracks and pores as well as geometry deviations are mapped. Current quality characteristics of the part can be evaluated online automatically. For the final assurance, the digital twin can be screened offline to check for anomalies in the data as the link between the digital twin and the quality assurance in Fig. 5 underlines. Furthermore, conclusions can be drawn from the digital twins of several parts about correlations between machine and process parameters, process data and part quality. These conclusions can be reused for the process planning of future parts. The digital twin can be used in addition for quality checks as part of the Life Cycle Management. Parameter optimization and thus process improvement can be achieved by automatically creating a process database for the aforementioned expert system in the engineering phase.

4.2. Distributed Computing

The presented functionalities of the monitoring system have different requirements regarding performance and real-time capability. For this reason, a hierarchical data processing structure based on three levels (process control level, edge computing level and cloud level) is proposed.

At the level of process control, performance is limited due to the defined control cycle. Here, data with a high frequency and a small data size, such as those generated by current and voltage sensors, are processed in hard real time either by searching for characteristic patterns using evaluation methods with low performance requirements or by reusing them as input variables for real-time closed-loop control. The pre-processed data is then forwarded to the edge computing level.

The Edge Computing level enables decentralized data processing with increased performance but doesn't meet hard real-time requirements. It is connected to the process control level and the cloud level. The pre-processed data is combined with additional sensor data such as data from a welding camera or a profile scanner. These data require sophisticated analysis methods such as edge detection or pattern recognition by neural networks. For instance, an image evaluation for pore detection is only carried out if a process anomaly has previously been detected in the electrical data. The interpreted data is sent to the cloud level and is used to influence controls at the process control level by adjusting controller parameters e.g. to adapt the control to material properties or certain thermal circumstances.

The cloud level offers high performance capacities and a not clearly defined latency. Here, the digital twin of the part in production is created and compared with the digital model from the engineering phase. If necessary, information is returned to the edge level to influence the following process steps in a context-specific way. The interpreted data is classified, and quality characteristics are assigned to the process data.

5. Summary and Outlook

In this study, requirements for a hybrid manufacturing machine were defined. Based on them, a robot based WAAM setup was proposed, which can be enhanced by a milling spindle to obtain a hybrid manufacturing machine. To validate the WAAM setup, first experiments were conducted regarding the influence of the orientation of the welding torch respectively of the lead and the tilt angle on the geometry of a deposited wall. A changing lead and tilt angle results in deviations in height and minor deviations in the width. Regarding process stability, best results were seen with a tilt angle of 0° and a lead angle of 0°, -5° and -15°. Finally, a framework for a seamlessly integrated monitoring system in hybrid manufacturing for enhanced data analysis was introduced. The framework is based on a digital twin of the workpiece in production which serves as base for proactive, context sensitive process adaptions. Next steps will be done in the area of anomaly detection based on the proposed multivariate monitoring system as well as in control engineering topics for WAAM.

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