Wire-Arc Additive Manufacturing Toolpath Optimization Using a Dexel-Based Temperature Prediction Model

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Abstract. Wire-Arc Additive Manufacturing (WAAM) has been established as a new technology for industrial use-cases such as low-lot size manufacturing or part repair services. A key aspect when developing such WAAM processes is thermal management during the layer-by-layer metal deposition. To maintain a stable welding process in-depth knowledge about the heat distribution is required. Thus, predicting the heat flux for a given part geometry already in the process development stage using Computer-Aided-Manufacturing Systems (CAM) would be beneficial. However, current state-of-the-art approaches are computationally expensive and time intensive. Therefore, they are hardly applicable for WAAM applications. In this paper, a dexel-based metal cutting and deposition simulation is combined with a temperature prediction model, which is integrated in the toolpath planning algorithm when defining a build-up strategy for a given part geometry. The approach is based on a temperature prediction algorithm, that calculates temperature fields for deposited material volume considering basic material properties. Calculated temperature fields can be utilized for optimizing welding toolpath to achieve stable process conditions across the part geometry.

Keywords: Wire-Arc Additive Manufacturing · Toolpath Planning · Temperature Simulation · Computer-Aided-Manufacturing

1 Introduction

Wire arc additive manufacturing (WAAM) is an innovative metal additive deposition technique that employs the power of an electric arc to melt and deposit metal wire, thereby fabricating workpiece layer by layer [1]. WAAM supports trends towards more sustainability in production and consumption, due to its advantages over conventional manufacturing techniques regarding material and energy efficiency [2]. Campatelli et al. highlight the potentials integrating WAAM processes and conventional milling processes, demonstrating an energy saving of 34% compared to traditional manufacturing

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process chains [3]. One of the biggest challenges when utilizing WAAM technology is the transient temperature field created due to the inhomogeneous welding process. The temperature in the part is increasing during the layer-by-layer build-up phase and, if not managed properly, potentially leading to process quality issues such as weak connections between weld layers or geometrical errors. By carefully regulating temperature, one can optimize the entire process, enhancing its efficiency and ensuring the production of high-quality parts [4]. The induced temperature in the workpiece is mainly influenced by the welding parameters such as voltage or current and the speed of the welding torch manipulator. However, recent research indicates that toolpath strategies also play a major role for practical WAAM systems [5]. To further increase the industrial utilization of this important technology towards sustainable manufacturing systems, temperature related sources of defects need to be identified and eliminated already in early stages of process development.

2 State-of-the-Art Review

Temperature predictions are an essential part of the design of a stable WAAM process. This includes a series of tests and numerical simulations [6]. Various researchers have focused on developing finite element simulation (FEM) models for additive manufacturing processes to analyze thermo-mechanical performance of the WAAM process. Researchers have implemented models to simulate WAAM processes and analyze characteristics such as local and global heat development and the subsequent formation of residual stresses [7–9]. The impact of preheating the substrate and baseplates before building the actual geometry, as well as the impact of cooling periods is investigated [10, 11]. Various heat source models as basis for temperature simulation are implemented [12–14]. Mehnen et al. provide a design study, utilizing FEM to investigate different build-up strategies by implementing the welding toolpath as a moving heat source in the simulation software system [15]. The result of this work highlights the high dependency of the process quality on the selected build-up/toolpath strategy. Required toolpath information must be imported in numerical model by either (a) utilizing specialized tools from simulation software providers [16] or (b) implementing toolpath information by individual import scripts utilizing the application programmable interface (API) possibilities in the respective FEM software such as Ansys or Abaqus [17–19]. In contrast to FEM based models, Böß et al. developed a dexel-based simulation system to predict the weld seam geometry using a quadratic regression model [20]. Researchers also studied the effect of various toolpath strategies for optimized WAAM processes. According to Uyen et al., the choice of trajectory has a significant influence on the cooling behavior and therefore the grain size and mechanical properties of the workpiece [21]. To prevent final part distortion, studies about the impact of deposition toolpaths such as balanced building strategies are discussed [15, 22–24]. Algorithms enabling continuous welding toolpaths eliminating defects occurring from stopping the welding torch are investigated [5, 25]. An approach to optimize toolpaths based on a rapid thermo-mechanical field prediction model utilizing machine learning techniques is used by Zhou et al. [26].

To summarize, past research has mostly focused on optimizing final part defects such as distortions by developing simulation models for thermo-mechanical analysis as well as experimental studies analyzing varying toolpath strategies for the part build-up. While finite element analysis provides positive correlations when compared to experimental data, these kinds of simulation are computational expensive and operate on a fixed domain where initial temperatures and boundary conditions are known. However, in WAAM the domain is subject to change due to the constant material deposition. Additionally, current finite element approaches are limited in their use since toolpath and process information need to be integrated manually, utilizing provided software interfaces. Regarding toolpath strategies, research highlighted opportunities to optimize part quality. Current approaches are focusing on optimized build-up strategies for selective geometries and are based on large experimental data sets. In some approaches, experimental temperature data is collected and deployed as training set for machine learning approaches. However, no simulation data such as temperature prediction is used in the toolpath planning process directly to optimize the overall results. An integrated system, coupling a thermal deposition calculation, a material build-up simulation as well as a toolpath algorithm, could overcome the limitations of current approaches developed in academia and provide novel opportunities for virtual WAAM process optimization.

3 Concept for Wire-Arc Additive Manufacturing Toolpath Optimization

This paper presents an approach for a dexel-based temperature calculation model, enabling automated toolpath adaptions for optimized WAAM processes. The temperature simulation is coupled with the toolpath planning algorithm within one system, thus, providing novel opportunities for process optimization. The envisioned concept expands the functionality of traditionally used CAD/CAM systems along the horizontal process chain when generating numerical codes for WAAM machines. The concept proposed in this work builds on integrating the novel temperature calculation and toolpath planning algorithm by using only one dexel-based data model in the background. Figure 1 provides an overview of the concept and its main components. The proposed concept consists of two main modules: *(a)* the *temperature calculation module*, providing the time-dependent temperature in the deposited material during the welding process and *(b)* the *toolpath optimization module*, which consists of necessary temperature management rule sets to calculate an optimized toolpath. Both models interact and exchange information for an iterative optimization of the toolpath, based on simulated temperature values.

First, a draft toolpath is generated based on the standard CAM inputs such as welding geometry, layer height, layer width etc. In this step, conventional CAM algorithms are used to slice the geometries and provide necessary points and line segments as input for the machine movement commands.

Second, the current toolpath is then the basis for a material deposition simulation, utilizing modern dexel material modelling technique. This method discretizes the space by a three-dimensional dexel field. The boundary of the material is represented by intersection points on the dexels. During process simulation these intersection points are updated to represent the current material geometry. Third, the same dexel material model is now used for solving the respective heat equation in the temperature calculation model. The

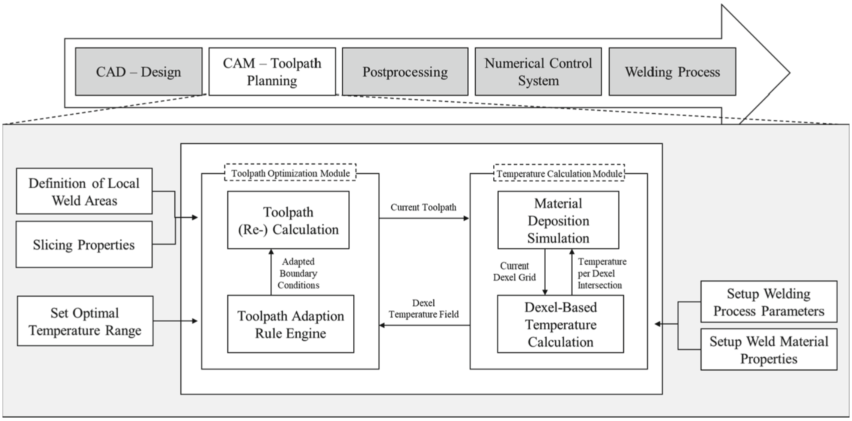

Fig. 1. Concept for WAAM toolpath optimization using dexel-based temperature prediction.

model requires standard material parameters such as heat transfer coefficient, room temperature and welding current/voltage as input and solves the transient heat equation using Lattice-Boltzmann-Method (LBM) [27]. Last, the calculated temperatures for a given toolpath position are provided to the toolpath optimization module. A rule engine consists of WAAM specific process rules, that determine respective actions if the temperature values are too high or low, thus, leading to a potential defect during or at the end of the welding process. The rule engine describes the boundary conditions and potential actions to be taken in such a case and initiate a re-calculation of the toolpath considering the changed situation. From here, the iterative optimization process starts again, given the new toolpath as input for the simulation.

4 Validation

The described concept for temperature dependent toolpath optimization has been implemented as a prototype system and was validated in the laboratory of *TU Wien Institute of Production Engineering and Photonic Technologies* in Vienna. The temperature calculation software has been implemented utilizing existing software frameworks of *ModuleWorks GmbH*. An existing toolpath calculation and deposition simulation environment has been expanded by the described modules in order to demonstrate a proof-of-concept implementation.

4.1 Experimental Setup

The novel functionality of the prototype is demonstrated for a simple two-wall weld geometry, utilizing a 6-axis welding robot and a Cold-Metal-Transfer (CMT) welding power source. For temperature measurement, an *Optris* infrared thermo camera was used. In the demonstration scenario, two walls with same geometry are deposited on a baseplate (H: 10 mm). An original welding toolpath for the robotic setup has been generated with *Siemens* NX CAD/CAM multi-axis-deposition software and was utilized as baseline for the optimization. This baseline toolpath aims to build the two wall geometries consecutively (S235 steel wire, L × W × H: 100 × 5 × 40 mm, number of layers: 16).

This toolpath does not consider information about the expected thermo-mechanical development during the deposition process. It is purely based on the wall geometries and the experience of the CAD/CAM programmer. During the welding process, the welding torch follows the toolpath while inducing heat energy in the baseplate and the already deposited wall structure material. Due to the layer-by-layer additive build-up process, temperature is continuously growing in the local toolpath welding area, potentially leading to defects such as uneven weld geometries, destruction of the material chemistry or postprocess deformations due to the induced stresses.

In the given demonstration scenario, the original toolpath builds both walls consecutively, reaching maximum temperatures of about 1300–1500 °C. With the developed optimization software, an additive manufacturing rule is added in the toolpath optimization module, limiting the maximum temperature in the local weld area to prevent expected welding defects. Whenever the simulation indicates that the temperature in the local weld area exceeds the defined maximum, a toolpath adaption is initiated. The manufacturing rule forces the system to reject the toolpath segment of the overheated layer. Instead, it adds a transfer move to the second wall geometry, which at this moment has a temperature below the defined maximum.

4.2 Results

The newly developed approach has been implemented and utilized in the described demonstration scenario. The original toolpath has been simulated, and respective temperature values for all dexels intersection are generated (c.f. Fig. 2).

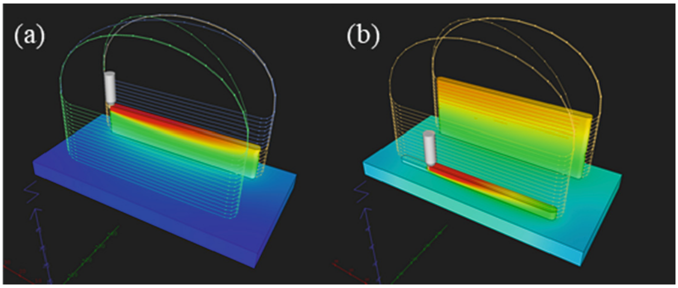

Fig. 2. Toolpath simulation (CLSF input from Siemens NX) with integrated temperature calculation module and colored visualization scheme. (a) Wall 1, Layer 10; (b) Wall 2, Layer 2.

The simulation data was compared to measurements to obtain information about the accuracy of the proposed LBM-based simulation approach. Depending on the camera calibration used, measured (maximum) temperatures in the welding zone vary significantly between 1100–1500 °C. In comparison, simulated temperature values in the currently deposited dexel intersection points illustrate temperatures between 1200–1400 °C. These first results indicate a positive correlation of simulated and measured temperatures of the developed model.

The temperature feedback provided is used as input for the toolpath optimization module. Based on developed optimization rules, the toolpath can be segmented and adapted to achieve optimal heat distribution across the entire toolpath and to prevent defects in the welding zone. In the presented experiment, a maximum has been defined as the initial point for a toolpath adaption. During the build-up simulation of the first wall, the temperature reaches this maximum for the first time right in the middle of deposition layer 10 (of 16). The deployed manufacturing rule forces the toolpath generator to reject the last toolpath layer segment on the current feature, and instead create a transfer move to another geometry whose current top layer is below the maximum temperature defined. From there, a new toolpath segment on the new geometry is created until the build-up is completed, or maximum temperature is reached, starting another optimization loop respectively. Figure 3 highlights the result of the adaptive toolpath planning, the created toolpath segments, and an updated simulation result during the welding process.

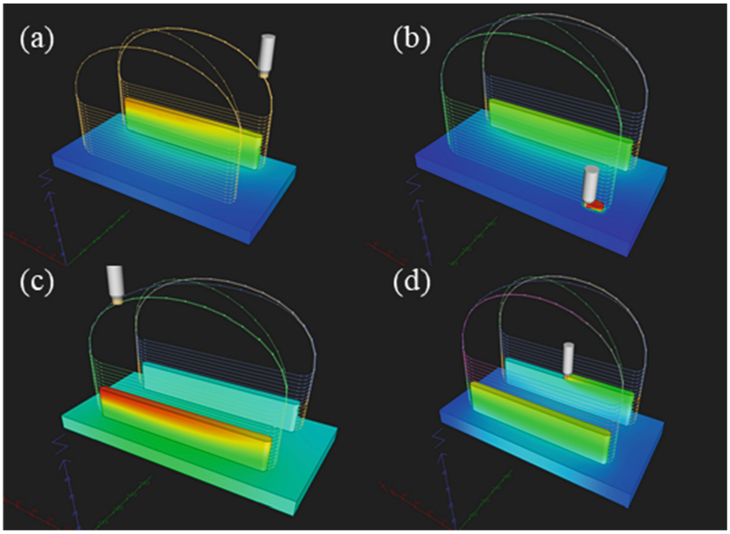

Fig. 3. Adapted toolpath strategy utilizing optimization module. (a) Wall 1, Layer 10 exceeds defined temperature maximum; (b) integration of transfer move to Wall 2, Layer 1 and start deposition simulation; (c) Wall 2, Layer 9 exceeds defined temperature maximum starting another optimization loop; (d) Continued welding on Wall 1, Layer 10 until geometry is finished.

5 Conclusion and Future Outlook

In this paper, a concept for an integrated dexel-based temperature prediction for WAAM toolpath optimization has been presented. The concept is based on a fast and reliable temperature simulation, which is fully integrated within an additive material deposition simulation and a toolpath planning algorithm. First prototype tests indicate that the proposed concept helps to give a quick understanding of the temperature behaviour during the process and demonstrates the usability for the optimization of WAAM path planning already in the virtual process planning stage.

Although this prototype gives a good estimation, further research is necessary in the future. To further increase the accuracy of the underlaying model, different models than LBM could be exploited. Additionally, increased accuracy could be achieved by optimizing the form and shape of the added material in the dexel simulation. More complex toolpath optimization strategies will be necessary leading to additional requirements for advanced collision control systems and dynamically adaptions of welding paths.

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