Modelling, prediction, and optimization of properties of low-carbon steel produced by wire arc additive manufacturing using machine learning

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Motivation

Wire and arc additive manufacturing (WAAM), which utilizes an electric arc source and a metallic wire to deposit metal layers, has received significant academic and industrial attention to produce medium and large-scale components. This is attributed to its advantages including a high metal deposition rate, flexible building volume, and low cost of equipment investment as well as raw material. However, the high heat accumulation and the complex thermal evolution during the deposition significantly impact the microstructure and mechanical properties of a WAAM component. Traditionally, the relationship between process parameters and mechanical properties of the deposit has been explored through dedicated series of experiments. The large number of potential combinations of process parameters and high costs involved, make this approach inefficient.

Prediction models based on machine learning techniques have gained popularity in materials science and additive manufacturing. Such models aim to rapidly predict the properties of WAAM components for different process parameter configurations. However, a significant challenge lies in generating sufficient datasets to train, test, and validate the model's performance This evolution towards machine learning-based prediction models presents a promising avenue for overcoming the limitations of traditional methods in WAAM research and development.

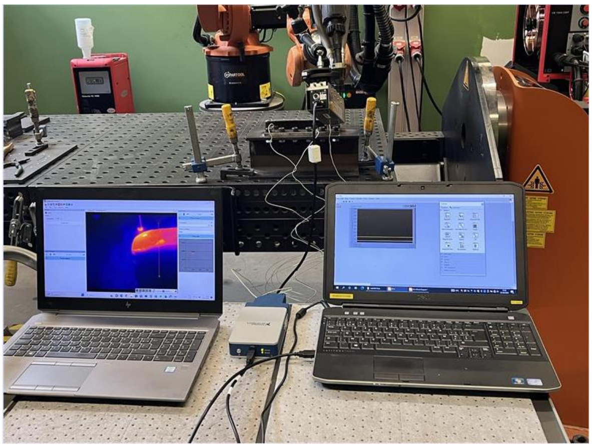

Figure 1 Wire arc additive manufacturing test setup: thermographic measurements of temperature evolution during and following deposition.

Over the course of a four-year project, researchers at Soete Laboratory will concentrate on modelling, predicting, and optimizing properties for low-carbon steel produced through wire arc additive manufacturing (WAAM) by leveraging machine learning to address the challenges outlined above.

Objectives

The objective of this research encompasses four main topics, following a comprehensive literature review.

1. Finite Element Modelling:

In this phase, a thermal-metallurgical-mechanical simulation model is developed to (a) predict the thermal history during the WAAM deposition of mild steel, and (b) to forecast resulting phase fractions and microhardness.

2. Data Preparation:

Subsequent to the modelling phase, a design of experiments approach is applied for simulating experiments. This method is crucial for generating an effective dataset tailored for the prediction model.

3. Prediction Model:

Following data preparation, a dataset is utilized to construct a prediction model, revealing the intricate relationship between process parameters and properties. This process involves the application of various methods to enhance prediction performance, including optimization algorithms and grid searching methods.

4. Optimization Model:

Leveraging the prediction model, the optimal properties of WAAM steel components are determined through the utilization of optimization algorithms. These optimization algorithms encompass techniques such as particle swarm optimization, genetic algorithms, among others.

Approach

This thesis adopts a systematic approach, integrating modelling, data preparation, prediction modelling, and optimization modelling, to comprehensively address the challenges associated with predicting and optimizing properties for low-carbon steel produced via WAAM.

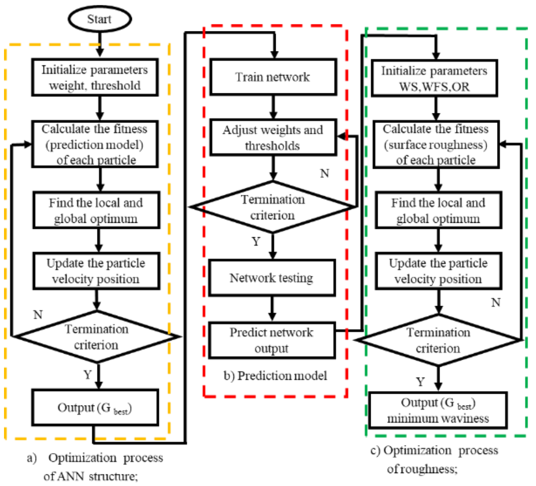

Figure 2 Prediction and optimization hybrid model

Regarding the first objective, the thermal-metallurgical-mechanical model comprises three distinct steps. The initial step involves constructing a heat transfer model for the wire arc additive manufacturing of a steel component. This is achieved using a well-distributed volumetric heat source and the birth-and-death element approach. The accuracy of the thermal analysis model is validated by comparing experimental data with simulation results. Subsequently, a metallurgical-mechanical model is applied to compute the phase fractions and microhardness values based on the predicted thermal history.

In the second step, various design of experiment (DOE) methods is applied for the simulation experiment. Following this, the validated thermal-metallurgical-mechanical model is utilized as a virtual experiment to generate an effective dataset for the prediction model. This multi-step process ensures a comprehensive approach to modelling the thermal and metallurgical aspects of the WAAM steel component, validating the thermal analysis model, and generating the necessary dataset for subsequent predictive modelling.

In the third step, the generated effective dataset will be utilized to train, test, and validate various machine learning models. This section is divided into two distinct parts: 1) ensemble learning for a single prediction model; and 2) the prediction model enhanced by different improvement methods.

Finally, different optimization algorithms are proposed and developed to achieve the optimal properties of the WAAM steel component based on the models. This comprehensive approach ensures a thorough examination of different machine learning techniques and optimization algorithms for predicting and optimizing properties in wire arc additive manufacturing.

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