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A metamodel based on basis spline hyper-surfaces for thermal simulation of the wire arc additive manufacturing process

Mathilde Zani[1,a], Enrico Panettieri[1,b] , Marco Montemurro[1,c*]

[1]Arts et Métiers Institute of Technology, Université de Bordeaux, CNRS, INRA, Bordeaux INP, HESAM Université, I2M UMR, F-33405 Talence

[a]mathilde.zani@ensam.eu, [b]enrico.panettieri@endam.eu, [c]marco.montemurro@ensam.eu

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Abstract. Wire arc additive manufacturing an additive manufacturing process that allows producing large metal parts in a layer-by-layer fashion assuring a high deposition rate. However, the set of parameters that control the process leads to phenomena that are difficult to understand and predict. The work of this paper is to propose a metamodel based on basis spline entities to approximate the thermal response of the WAAM process for different combinations of deposition parameters. The aim is to reduce the computational cost, and obtain results without actually solve a complete FE model for any combination of parameters in the design space.

Introduction

In the aerospace industry, the amount of wasted material generated during manufacturing is called the buy-to-fly (BTF) ratio, which is defined as the ratio of the mass of raw material to the mass of the finished part [1]. In order to reduce material waste and thereby reduce the BTF ratio, Additive Manufacturing (AM) technology is an environmentally friendly manufacturing alternative to conventional manufacturing processes. Among metal AM processes, wire arc additive manufacturing (WAAM) is one of the most promising technologies in terms of deposition rate [2] allowing the production of large near net-shape metal parts with complex geometry by depositing weld beads in a layer-by-layer strategy [3].

Despite these advantages, the quality of parts manufactured by WAAM is highly affected by the thermal and mechanical phenomena occurring during the process, which are influenced by its main parameters. Furthermore, the understanding of the relationships between the physical phenomena and the parameters governing the process (together with the interaction between these parameters) represents a challenging task [2,4]. Accordingly, process simulation is a powerful tool to address such issues, allowing the simulation of the effect of different deposition parameters and, thus, optimising the process.

From a simulation perspective, WAAM technology is typically simulated using a transient thermomechanical Finite Element (FE) analysis with progressive material addition. However, the computational time associated with this analysis can become prohibitive, especially when the influence of process parameters on the thermomechanical properties of the material must be integrated into the design process. As discussed by Ding et al. [5] this usually results in a reduction in the effectiveness gains of WAAM process numerical modelling. In addition, due to the prohibitive computational costs related to FE non-linear thermomechanical analyses, such a modelling strategy cannot assess the sensitivity of the temperature field and residual strain/stress fields within manufactured parts to the main process parameters. Therefore, appropriate abaci should be used at the preliminary design phase to predict the behaviour of the resulting material in terms of stiffness, thermal conductivity, thermal expansion coefficients, etc., since calculated values of these parameters cannot be obtained in a reasonable time using this type of modelling strategy. Accordingly, Ding et al. [5], Montevecchi et al., [6], Michaleris [7] proposed different methodologies to reduce computational costs, while keeping a reasonable level of accuracy.

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Therefore, a trade-off must be found between the computational costs and the precision required for a given application [8].

In this context, metamodels are efficiently employed to capture the influence of the main parameters of the process on the manufactured parts and to obtain results having a level of accuracy as good as the one related to non-linear thermomechanical FE models. Generally, a metamodel consists of the definition of a parametric hyper-surface that is capable of approximating (or interpolating) some data [9,10] without knowing the explicit physical equations of the problem at hand. In comparison with other metamodeling approaches [10], Non-Uniform Rational Basis Splines (NURBS) entities offer many unique advantages [9].

This research proposes a metamodel based on Basis spline (B-spline) entities (a sub-class of NURBS hyper-surfaces) applied to thermal analyses of the WAAM process. The main goal is to analyse the thermal response of the process as a function of different deposition parameters. The temperature histories are monitored during the simulations at different points on the substrate and approximated through a B-spline hyper-surface. The hyper-surface is built as a result of an optimisation procedure generalising the one proposed in previous works [9].

The paper is organised as follows. Section 2 briefly introduces the main features of WAAM process and gives the description of the non-linear thermal problem that will be used to build the metamodel. In Section 3 the fundamentals of B-spline entities are recalled, and the algorithm employing for generating the metamodel is presented. The results are presented in Section 4. Lastly, Section 5 ends the paper with conclusions and prospects.

Finite element numerical model

WAAM is a Direct Energy Deposition process in which the material is directly deposed on a substrate and locally heated by a heat source. To better understand the process behaviour and improve the final quality of the part, FE models have been adopted to analyse and simulate the non-linear phenomena occurring in the WAAM process.

In this work, only the numerical model of the thermal problem is developed to analyse the thermal history as a function of different deposition parameters, notably the torch speed also referred to as travel speed (TS); the power of the welding Q; and the deposition rate expressed as the Wire feed Speed (WFS). Moreover, the material is deposed maintaining a constant volume for all the analyses.

The numerical model of the WAAM process deals with the progressive heating of the deposited material, the progressive material addition, and the thermal dependencies of the chosen material.

Firstly, a 3D transient non-linear heat transfer analysis is performed using the commercial software ABAQUS®. Moreover, the heat transfer from the arc to the molten pool is described employing an equivalent heat source model. Generally, for 3D AM simulations, the volumetric heat source proposed by Goldak et al., [11] is used as it capable of modelling the three-dimensional phenomena occurring in the molten pool. The Goldak heat source reads:

$$\boldsymbol{q(x,y,z)} = \frac{\boldsymbol{Q6\sqrt{3}f_\zeta}}{\boldsymbol{a_\zeta bc\pi^{3/2}}}\boldsymbol{e}^{\left(-3\left(\frac{x^2}{a_\zeta^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)\right)}, \tag{1}$$

with ζ =*f (front) for* $x \geq 0$ *and* $\zeta = r$ *(rear) for* $x < 0$, *and* $f_f + f_r = 2$ to ensure continuity at the source origin x= 0. A schematic representation of the Goldak double ellipsoid heat source is represented in Fig.1.

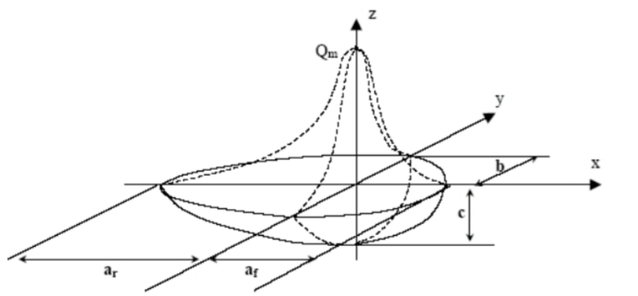

Figure 1 Double ellipsoid Goldak heat source) [11].

A second issue in the WAMM process simulation is the material deposition modelling. In this work, the progressive elements activation technique is employed [12]. This method, available in ABAQUS® software, allows activating the elements as a function of time and space and relating them to the movement of the heat source [13].

The FE model used to generate the database for the B-spline metamodel is built following the guidelines available in the work of [5]. It consists of a four-layer wall deposited along the centre line of the base plate, as shown in Fig. 2.

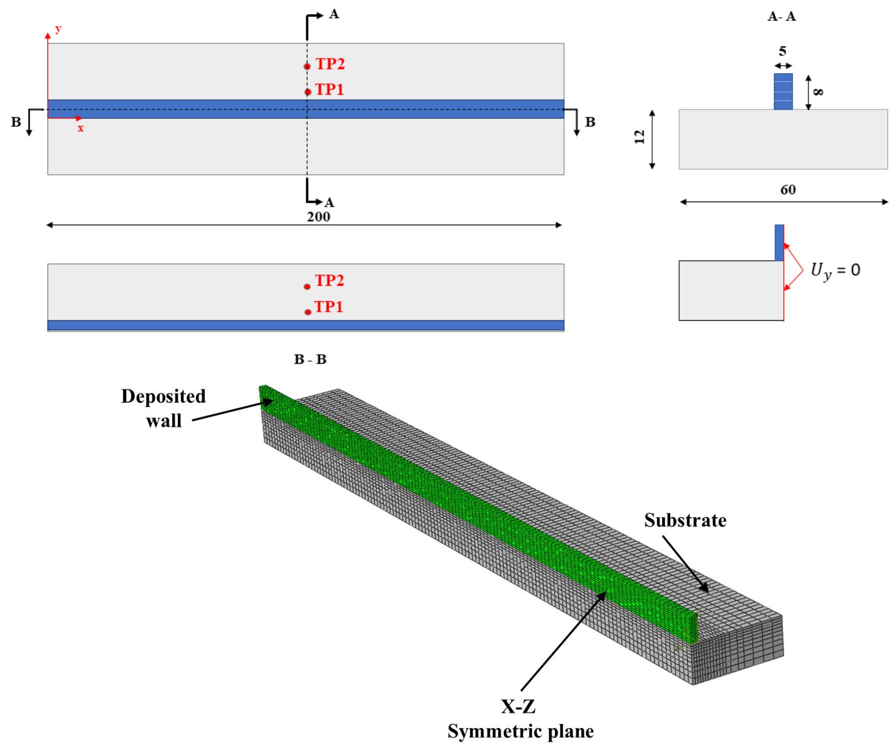

Figure 2 FE numerical model from [5]

The material used for both the substrate and the wall is a mild steel with material properties dependent of the temperature taken from literature [14].

To reduce the computational costs of the analysis, only half of the model in the X-Z plane is considered. Lastly, linear brick elements with eight nodes (DC3D8) are used for the thermal simulation with meshes of size 2 mm× 0.833 mm× 0.667 mm for the bead and the area near the welding line, and a coarsened mesh far from the wall to reduce the total number of elements.
The complete details of the FE model, together with the initial thermal and boundaries conditions can be found in [5].

The goal of the metamodel is to approximate the temperature value at given locations, i.e., on the nodes where thermocouples TP1 and TP2 are placed as illustrated in Figure 2, as function of

process parameters. Accordingly, a series of WAAM simulations is run considering suitable intervals of the main process parameters, i.e., the input variables of the metamodel.
The selected values are listed in Table 1, for a total of 1000 simulations.

Table 1 Values of deposition parameters

TS [mm/s]	*Q [W]*	t_{cool} *[s]*	*time [s]*
[4.4, 6.2, 8.4, 10,10.68, 11, 11.2, 12, 13.2, 16.4]	[364, 447.6, 571.1, 700.3, 849.4, 890.1, 1282.3, 1537.4, 1826.3, 2302.2]	*[2,5,10,15,20,30, 40,50,60,100]*	*[0,496]*

As the process parameters vary, there is a modification in the bead behaviour with a consequent change in its temperature history [2]. Inasmuch as the interest is creating a database for the B-spline metamodel, the heat source dimension and parameters are kept constants for all the simulations and equal to the one of [5]. Moreover, the heat step time increment is considered equal to 1 sec.
Finally, the geometry of the model, which should vary as the deposition parameters change is kept constant. This strong assumption is justified by the fact that the material is deposited at a constant volume and with the progressive element technique. For more details on this matter, the interested reader is addressed to [15].

The results of the temperature profile at the two thermocouples TP1, TP2 are presented in section 4.

B-spline metamodel of WAAM thermal problem
The B-spline entities are used as a tool for creating a metamodel that generates a response surface capable of fitting a given set of target points (TPs) $\boldsymbol{X}_i$. This section briefly presents the theoretical background of B-spline entities, and the basics of the implemented algorithm to evaluate the metamodel.

Theoretical background
A B-spline hyper-surface is a polynomial-based function defined over a domain of dimension N domain to a codomain of dimension M, , $\boldsymbol{H} : \mathbb{R}^N \rightarrow \mathbb{R}^M$ [9]. The mathematical formula of a generic B-spline hyper-surface reads:

$$\boldsymbol{H}(\zeta_1 , \dots \zeta_N) \coloneqq \sum_{i_1=0}^{n_1} \cdots \sum_{i_N=0}^{n_N} N_{i_1,p_1}(\zeta_1) \times \dots \times N_{i_N,p_N}(\zeta_N) \boldsymbol{P}_{i1,\dots i_N} \quad , \tag{2}$$

where $\zeta_k \in [0,1]$ is the kth dimensionless coordinate, whereas $\boldsymbol{P}_{\boldsymbol{i_1,\dots,i_N}} \coloneqq \left\{P^{(1)}_{i_1,\dots,i_N}, \dots , P^{(M)}_{i_1,\dots,i_N}\right\}$ are the control points (CPs) that constitute the control hyper net.

For each parametric direction $k = 1, \dots , N$, $N_{i_k,p_k}(\zeta_k)$ represents the Bernstein's polynomial of order p_k and defined recursively as discussed in [16].

The choice of using B-spline entities as a metamodel strategy stems from its ability to well approximate problem non-linearities, and to be applicable to MIMO systems. The first property derives from the local support characteristic of the blending functions. Indeed, thanks to this property, each control point affects only a restricted portion of the domain wherein the B-spline is defined. For more information about this topic, the reader is addressed to [16].

Implemented algorithm.

The algorithm, originally implemented by [9] has been generalised to any combination of dimensions *N* and *M* of the B-spline hyper-surface domain and codomain, respectively.

The algorithm main steps are schematically represented in Fig. 3.

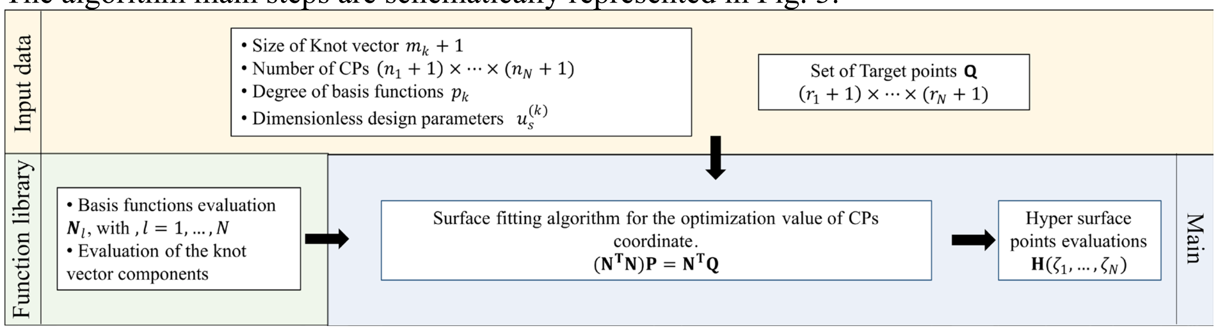

Figure 3 Algorithm flowchart. The hyper-surface surface fitting problem for the optimization of the CPs coordinates is taken from [9].

More precisely, once all the necessary input data have been provided, several routines are called to evaluate the basis functions, the optimal values of the CPs (constituting the control hyper-net), and then, the hyper-surface. The database of TPs is determined via numerical analyses conducted through the FE model presented in Section 2, and the metamodel will approximate the thermal history *T*(t,TS,Q, t_{cool}) at the two thermocouples for different combinations of input variables.

Results and discussion

This section presents the result of the B-spline metamodel in terms of thermal history *T*(t,TS,Q, t_{cool}) at the thermocouple TP1, TP2. For brevity, the results are shown only for TP1.

Fig. 4 represents the approximated temperature contour plots as a function of the inputs. The coefficient $R^2 = 1 - \frac{RSS}{TSS}$,, which represents a measure of the quality of the approximation of the metamodel, is equal to 0.977. RSS is the residual sum of squares and TSS is the total sum of squares. This means that the fitting capability of the B-spline metamodel is accurate (the closer R^2 to the unit the more accurate is the approximation).

Furthermore, the computational cost to obtain this approximation is well in excess of 100% lower than the computational time of the FE simulations.

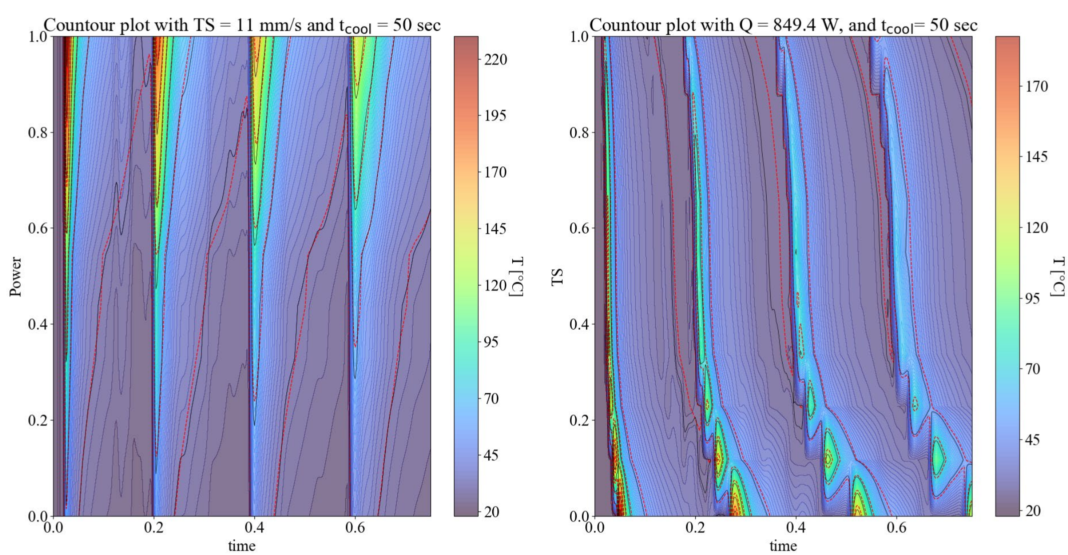

Figure 4 Contour plot of the nodal temperature for thermocouple TP1 resulting from the B-spline hyper-surface for a constant TS (on the left), a constant power (on the right)

However, the main purpose of the metamodel is to obtain the results for input values not included in domain described by the 1000 simulations, without solving the entire numerical model. For this reason, four sets of TS, Q, t_{cool} not included in the initial set have been chosen to test the accuracy of the approximated method. The results, together with the four parameter sets are shown in Fig. 5.

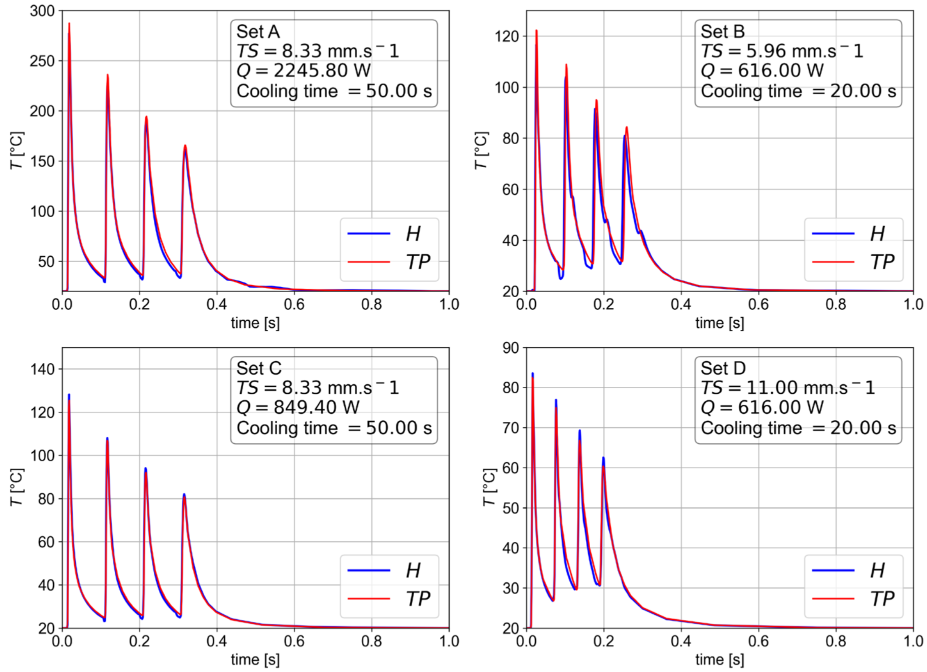

Figure 5 Temperature history at thermocouple TP1 for the four sets of deposition parameters constituting the validation set.

Overall, the approximated temperature history match quite well the simulated results.

Conclusions and Prospect

In this paper, a metamodel based on B-spline entities has been applied to the thermal simulation of the WAAM process to approximate the temperature history at different locations of a 3D model. The proposed metamodeling strategy allows approximating with a good accuracy the numerical results while considerably reducing the computational cost. Moreover, it has been possible to obtain temperature profiles for sets of values not included in the initial database. It must be highlighted that the generated metamodel is able to predict the results of the non-linear finite element model even if some discrepancies are present due to the chosen approximation method. Indeed, B-spline entities are not able to correctly approximate distributions of data characterised by strong non-linearities and/or discontinuities on the local tangent vector direction. To overcome this issue, the presented metamodeling strategy should be extended to the most general case of NURBS entities by including the weights related to each control point and the inner components of the knot vectors among the design variables. Research is ongoing on this aspect.

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